SIMULATION OF THE VISUO-MOTOR PROCESSES IN THE TRACKING AND INTERCEPTION OF A TENNIS BALL IN PLAY

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PREFACE

According to the Oxford dictionary, to simulate is to imitate the conditions of some situation with a model. Such a model might be analogue or digital, physical or conceptual. A digital computer model is digital-conceptual and takes the form of a program.

Development of such a program normally begins with an economic need to understand or test a system. One might, for example, simulate an aircraft in flight, or a spacecraft in a trans-lunar orbit. By means of the simulator, errors in design can be eliminated without the possibly great cost of producing a real system that fails.

In sports, one might wish to test new ideas regarding player movement, tactics, or strategy without subjecting the athletes to possibly wasteful or even harmful habit formations. If a method of simulation of the athlete can be devised, experiments might reasonably be conducted to evaluate the ideas independently of actual training or trail in the field.

Simulation of a complex system generally begins with a long period of analysis. During this time there may be mathematical and programming explorations and constructions to sharpen and examine different approaches. Meetings are usually held by the participants to try to define the task and explore alternatives. Ideas are amplified, possibly discarded as not feasible, or incorporated into the system package. Gradually there evolves a tighter and more acceptable formulation using logical and mathematical expressions.

In formulation one tries to reflect the key elements of the system being simulated. The model incorporates judgements about the system. Its equations identify the principle components and portray the interactions among these components as a function of time. This must be done with acceptable veridicality, yet with enough simplifying assumptions to keep the model from being too complex to be manageable.

In the task I set for myself, viz., to simulate the visuo-motor processes of a tennis player, I had no idea what kind of mechanization would be required. The only condition I imposed on the simulator was that both the player's personal experience of his playing arena and an objective view of that arena were to be represented. Otherwise, the nature of the program, the specific jobs it was to perform, the kind of structure it should have and the functional level at which the simulator should be carried out were merely vague notions, no more than a hunch, really, how the processes were to be formulated.

As it turned out, much time and a great deal of analysis were in fact needed before a model began to take shape. At a minimum, a setting for the simulation had to be established. Specific programs had to be defined. The overall structure of the program had to be worked out. Input-output requirements had to be specified. And above all, the many details of the psycho-physiological processes of the player's visuo-motor system had to be determined.

One ingredient of the simulator certainly had to be the motion of the ball. Treated strictly as an object moving without spin in a 3-space through a simplified gravitational field, the problem is merely an exercise in undergraduate physics. Far more complex, however, is the need, first, to deal with spin, and second, to represent the motion of the ball as the personal experience of the moving player, who has to be able to track the ball in its flight even as he races to intercept it. These actions engage many psycho-physiological mechanisms and involve bio-mechanical principles. For example, the player has to be able to rotate his eyes as he moves his body. To do this he must apply forces, torques, in various combinations.

There were mental considerations as well. The way the player sees the ball and reacts to it are characteristics involving personal skills. He has to detect and identify the ball. He is bound to estimate distances, time and speed. He must project force requirements on his movements. He has to make decisions and initiate actions.

Muscles have to be guided along one or another motor plan, according to the situation or need. And, among other decisions, he has to select an appropriate one of an available arsenal of shots or tactics.

Furthermore, his choices affect his movements, and the movements in turn feed back on, and affect, the decisions. This interaction certainly had to be reflected in the mathematical model and be incorporated into the program design, adding to its complexity.

A mathematical model is preliminary to program design, but before the model can actually be accepted, certain programming factors have to be considered. To design the simulator, provision had to be made for the way in which the computations implicit in the formulation were to be carried out. Choices in computation strategy can, and did, affect both the overall organization of the program and its detailed coding.

Concomitant with the decisions regarding the method of computation are those relating to input-output needs and data formats. In addition, starting conditions have to be specified. If the simulator is to generate quantitative data, the relevant features of the simulated entity have to be characterized as being in a certain starting configuration. For example, the player's limbs have to be assigned initial angles and angular rates of change. His torso would have to be given a certain weight. The center of gravity may have to be located. The player's line of sight would have to be directed and given a rotation rate. Before any simulator can generate output data, any and all independent variables in the model have to be configured for starting conditions. This simulator was no exception.

ORGANIZATION OF THE REPORT

The report is organized in the manner of the outline of program development discussed above, but it does not reflect the interplay that occurred in actual design of the simulator. Chapter 1 is an introduction to the problem. It states the aims and objectives of the project and sets the stage for the more detailed analysis or formulation to follow.

Part I represents the first major step in the construction of a conceptual model of the interactive process in which the player perceives his environment and moves around in it. The line of development in the text generally follows the plan of an illustrated information-flow model (Chapter 3) which is presumed to characterize the process. Physical energy from the environment is understood to impinge on the player's senses, is somehow transformed into his personal experience of the environment, and leads to actions which affect the environment and feed back on his perception.

Part II examines this interaction at a deeper level, making explicit many of the neuro-physiological details. Getting down to the nitty-gritty, the successive chapters show what is involved in the player's perception of the environment, how control centers in the brain seem to function, and how biological forces are generated by the player. Some mathematical modeling is evidenced at this stage.

Part III then extends the analysis and devises a scheme using standards, strategies, and competences to automate the player's movements. Based on this conceptual framework it develops a mathematical model and program for a prototype simulator. As might be expected for a first model, this is a greatly simplified version of the real thing; because of the design complexities, many of the details of the interaction had to be left out. However, the model does offer a basis on which to flesh out more realistic versions.

A summary chapter, finally, reviews the work done, evaluates its results, and identifies some of the great deal of work that yet remains to be done.

As can be seen from the Contents, the analysis recognizes and takes into account contributions from a wide range of disciplines. Some of the topics which are touched on are:

1) The mechanics of motion of deformable objects moving in a gravitational field -- the basis for a ball trajectory model;
2) The physics of light and its interaction with the molecular structure of the surfaces of objects in physical space -- the presumed source of information in the visual field;
3) Optics of the eye;
4) Physiology of the eye, the voluntary nervous system, and the musculo-skeletal system;
5) Mechanics of levers applied to movement;
6) Psychology of perception, especially the perception of space, time, and movement;
7) Perceptual-motor skills, in ball sports generally, and tennis in particular.

This unusual but essential mix of disciplines was a source of much consternation in writing this report. Many physical, physiological and psychological elements are involved in the athlete's sensory-motor processes. In addition, many logical, mathematical, and programming details are involved in the development of a simulator. Not only are there many facts, but there is also a complex organization overlying the facts; the facts come into play, not randomly but in a very orderly fashion. After all, the player's view of the playing arena and his movement in the arena are purposeful and meaningful. The simulator must reflect this characteristic.

I felt that to present the material properly, both the details and the organization were needed. Despite an already long report, even with significant areas missing, such as the perception of color, I also believed that if the work was to be at all useful to the research student, some background material had to be included. The reader will therefore find some brief introductory sections on related topics in logic, mathematics, mechanics, and electromagnetics. For the most part, these topics lead directly to required simulation details.

The Appendices contain the program listings for the prototype model and three extensions. To avoid further compounding of the problem of length, I omitted computer output for all but the last, and most comprehensive, of these programs. I believe that a need by the student to evaluate his own data can be met with this output.

A concerted effort was made to minimize spelling errors, but the reader is cautioned that American and not the Queen's English governs language usage. I can only hope that the variants are not too disturbing.

On the matter of units, I found the literature to contain many variations. In mechanics, for example, ft/sec is still in use for velocity and remains part of my own habit structure. In optics there are any number of unit designations. There are variations in the other areas as well, despite the attempts to establish uniformity. In this report I presented results in both the metric and English systems and constructed unit conversion tables where it seemed necessary. My reason for doing this is that the development of a realistic simulator depends heavily on the ideas coming out of the diverse fields of study, and I felt that communication would be better served this way.

ACKNOWLEDGEMENT

The range of topics in a project of this type is so extensive, one must rely heavily on the research of many specialists. In this regard, I am grateful to have had the -- shall I say indirect -- support of the authors listed in the Reference. At that, the list represents only a sample of the vast literature available.

More directly, I wish to thank my supervisors: Doug Coghlan, Senior Lecturer at Rhodes University; Herbert L. Pick, Jr., Professor at the University of Minnesota; and Michael T. Hyson, formerly at the California Institute of Technology and now private consultant in machine sensing (Hy Tech). My special thanks go to Doug, who kept the faith through this long effort.

CHAPTER 1

INTRODUCTION

During the course of any game the athlete more or less routinely performs a variety of tasks which he has learned to some level of competence. Almost without thinking he can, for example, scoop up a grounder to throw out a runner. Or he can loft a puck into center ice, or block his man in a scrimmage. Occasionally, however, he gets disoriented and, in effect, "loses his way" on the playing field. On the soccer field, for instance, or the hockey rink, swimming pool, or tennis court, he might find himself "out of touch" with his surroundings for a moment. He can lose contact with a teammate and miss a passing opportunity, or step out of bounds, or hit an outbound ball. Too often he fails to note a developing tactic by the opposition and is caught out of position. Or he may be unprepared for a slow return shot and miss an easy point.

Any mental lapse, misread situation, wrong information, poor tactic, or the like, can be a hazard. Well developed sensory-motor skills, good concentration, and a great deal of knowledge are required to manage the actions properly.

Bill Russell, the all-time great center for the Boston Celtics' basketball team, expressed the problem situation well. Commenting on the fast-pace action of a televised Boston-Philadelphia game, he said that the player must always know where he is on the court, and where the ball is; and he must always move with purpose, whether he is moving <u>with</u> the ball or <u>away</u> from it.

The player must be able to twist and turn without becoming spatially disoriented (Picture 1.1). He must be able to estimate direction and distance accurately. He has to identify and assess a developing situation quickly. And he has to know how and where to run, which means he must understand the game. In short, he has to <u>know his way around the court</u>.

Picture 1.1. Paul Westphal twists around a defensive guard to drive on the basket. (Photo by Associated Press)

This is a complex perceptual-motor process, requiring a well-developed mental representation of his physical environment. He must be able to identify key facets of his game, respond to critical items of information, and detect when and how to move. In other words, the player must have a good "feel" for the geography of his turf.

It is this aspect of human perception and movement with which I am here concerned. In particular, I examine the playing environment of the tennis athlete and aim at a simulation of his visuo-motor processes in that environment. In simulation the player has to visually track an oncoming ball and race to intercept it. The athlete doesn't carry with him, or use, such travel paraphernalia as road maps or compass; obviously, there are no roads or landmarks, in the normal sense of the words, on a tennis court. Nevertheless, he does seem to use maps of some kind or another; he does have a sense of direction; he does acquire the requisite sensory-motor skills; he does establish relationships with the elements of his environment; and he does somehow wend his way around the court.

A wide range of forces, human as well as physical, underlies his play. The various forces determine the way he moves on the court. They affect his interests, biases, and limitations. They influence the way he perceives his arena and they establish the pace of the game. It is these forces that make it possible and meaningful to simulate the player's sensory-motor processes.

Central here is the fact that the player is embedded in the playing environment; he is part of that environment and interacts intimately with it. He perceives the ball, his opponent, and the court. He moves on the court toward the oncoming ball, and thereby is influenced by, and influences, the behavior of his opponent.

To simulate the player's sensory-motor processes is thus to simulate his behavioral environment. We would like to delineate the mechanisms by means of which he constructs his space-time reference system, perceives the objects of his environment, senses their locations, judges distances, estimates direction, speed, and acceleration, maintains his stability, powers himself along, makes perceptual and motor decisions, hits the ball, and generally controls his movements.

Simulation can aid in this enterprise directly and indirectly. To construct a program it is necessary to be very explicit. Computer processes are logical and precise, so the statements characterizing the player-environment interactions have to be sharply defined. This fact induces clarity and understanding.

More directly, simulation is a proven useful tool in the analysis of operational procedures. For example, missile performance tests are conducted extensively by simulating missile dynamics in the operational environment. The missile is "flown" in simulation and its motion is studied under diverse missile-environment conditions.

In a similar way, simulation can be used in the analysis of performance in sports. By constructing detailed models of the athlete in his playing environment, optimization studies can be conducted for various player-environment conditions. In simulation, performance can be studied for actual or projected skill levels and environments.

Given a full-fledged simulator, we might study the effectiveness of, say, alternative forehand styles against a specific class of cross-court shots under certain environmental conditions. Conversely, we might examine the utility of a particular forehand style against a variety of shots under alternative environmental conditions. These tests could be run for varying levels of the player's visuomotor skills. In all such cases the tests would treat the athlete as if he were playing in his specialized behavioral environment.

As an initial step in the effort, the simulator might be designed to test the player's ability to track and intercept a specific trajectory. By providing parameters which can be modified for different runs, the tests could be made for a variety of sensory-motor skills. It would require some minimum representation of the ball moving in physical space, the player's awareness of the moving ball, his eye movements relative to his body, his body movement in physical space, and the visuo-motor interaction. That is the plan here.

THE PLAYER'S BEHAVIORAL ENVIRONMENT

The tennis athlete's behavioral environment is the environment in which he engages in his tennis activity. It is his turf, his zone of familiarity in his capacity as a tennis player. As such, it encompasses the physical environment consisting of the court, the net, surrounding screen, atmosphere, and people running after and hitting a ball in physical space-time; but it includes more than that.

The court region is a segment of the wider context of physical objects with its stimuli of physical energies such as electromagnetic radiation, molecular vibrations, pressure, and thermal flows. The player himself is understood to be one of the objects of that physical environment and is stimulated through his senses by the physical energies. Responding to the various stimuli, the player perceives, makes decisions, and effects motor responses, operating entirely within the physical environment.

What the individual sees or does depends on conditions inherent in his physical structure. His sensors, complex central nervous system and brain, consisting of billions of cells, collectively intervene to produce the response. The neural network interprets the stimuli and generates the appropriate behavior. The network is an internal or personal determinant of behavior and puts the player's cognitive-evaluative stamp on the physical environment. The resulting experience is his behavioral environment.

A similar distinction is made by Koffka (1935) between what he called the geographical environment (or absolute space) and the behavioral environment (relative space). As indicated by Downs and Stea (1973), Koffka held that the geographical environment is "stimulus providing," whereas the behavioral environment is behavior regulating.

Behavior is not a simple reflex-arc but depends on a complex framework of mental representations -- a cognitive-evaluative structure. We are dealing with a self-steering organism whose sensory and motor processes are highly interactive. The organism perceives its environment, interprets it, moves more or less freely in that environment, and in the process might modify it to some extent.

While we judge that perception is generally highly veridical and movement varied and far ranging, nevertheless we are aware of a difference between what we experience and what might be true about the world we experience. This is the difference between a personal and an impersonal world.

Consider the emotional shock the Kalahari Bushman would experience on being dumped onto the streets of New York and the comparable shock the New Yorker would feel if he were thrown onto the Kalahari. Although the traffic and the hustle and bustle of pedestrians of the city is a normal, patterned daily phenomenon to the city dweller, it would be a bewildering cacophony of sight and sound to the bushman. By contrast, the Kalahari would be a hot, barren, deadly wasteland for the urbanite, but home to the bushman -- a place where roots, blood, or hidden ostrich eggs provide life-preserving water; and berries, leaves, grasses and the occasional animal hunted down with poisoned arrows offers nourishment. The physical environment in and of itself is none of these things; it is impersonal. But the behavioral environment, on the contrary, is very personal indeed.

To a greater or lesser extent, each individual knows his way around his own element. He has a background of experience, information, concepts, values and skills which enable him to avoid pitfalls and satisfy needs. His internal maps or mental representations guide him through the terrain. Maps help him orient himself in his space, enable him to identify signposts, judge distances, and delimit and define his behavior. They determine his pattern of perception, the figures of attention and the broader, unattended background. And they configure his attitude, values and intentions.

The Kalahari Bushman somehow has learned to survive in the desert, despite the severity of its conditions. He has developed skills and knowledge which enable him to contend with an extremely barren land and sharply limited rainfall. He knows the vegetation, can read spoors, and without getting lost can track animals for days, relying on roots or hidden caches of water-filled ostrich eggs for liquids.

On the other hand, we in our society manage to survive in a jungle of machines. We drive motor cars comfortably at breakneck speeds along narrow asphalt and concrete pathways even as we chatter away with passengers, eat snacks, drink refreshments, or listen to radio reports or music. We use airplanes, trains, washing machines, computers, telephones, x-ray machines, volt-meters, television, and hundreds of other such objects routinely.

On the tennis court we directly encounter the concrete surface, the boundary lines, net, opposing player or players, the ball, the racquet and possibly a partner among the other artifacts and natural factors that determine the player's perception and influence his behavior. Because of the shape and structure of the racquet, and construction of the ball itself, certain methods of striking the ball and certain kinds of trajectories are possible; and certain choices of return shots are thus available. Clearly, a beach ball or a basket ball would produce a different set of perceptual and motor possibilities, as would a "court" consisting of a tangle of vines in a rain forest; under these unusual conditions the game of tennis would certainly not be the same as we now perceive it to be.

Similarly, the kind of lighting, the background against which the ball is tracked, the nature of the court's surface, the type of net, its structure and shape, the size, strength and gender of the players, their visual acuity, neural anatomy, and body structure, the clothes and shoes that are worn, the player's attitudes, objectives, experience, approach to the game and style of play, the degree of adherence to the prescribed rules of play, the type of coaching that is available, and the number and kind of spectator -- all contribute to the nature of the behavioral environment of the tennis player.

REGULATORY CUES

In the process of tracking and running to intercept the tennis ball, our player is confronted with a number of more specific tasks requiring information for their solution. On a continuing basis he has to detect or identify characteristics of himself and his environment, estimate distances, velocities and accelerations, activate his muscles, direct his movements toward some point of interest, and choose and make a return shot.

He has to contend with a real ball that could be moving at high speed and with an opponent who is constantly changing position and who very likely is using every stratagem to defeat him. The opponent might try to mislead him by faking or disguising a shot, using tricks, or simply employing good tactics, making him run. The player has the boundary lines to consider as well. And the net and the wind. In fact, there is the whole court and its background.

This is a familiar situation tennis players merely take for granted. But the familiarity masks a more penetrating problem, one that has occupied the minds of epistemologists for centuries. The problem, simply, is to gain accurate knowledge about the world. For the tennis player this translates into getting an undistorted image of his court activity.

From science we know that physical energies from the objects around us stimulate our senses and lead to our experience of those objects. We say we form impressions of them. So too the tennis player forms impressions of his court; he forms an image of it, and he has only this image to rely on to maneuver on the court. The image determines his perceptual discriminations and his selection of information, and it determines the nature of his responses, while at the same time being determined by what he does and by the objects he encounters. The image dictates the range of his possible actions. If the image is narrow and limiting, his range of skills will be limited; if it is rich with possibilities, his play will reflect the diversity.

The broader epistemological issue as such is of no particular concern to the tennis athlete; his interest lies in the specific actions of his opponent, the motion of the ball and the way he should respond, not in the manner that knowledge is acquired or tested. He is of course presumed to be playing a game characterized by well-defined rules. He abides by the rules and his responses are appropriate to the game. By the same token, the information he acquires must also be appropriate, or relevant. He needs the kind of information that leads him to specific and definitive action, namely, to intercept the ball with the racquet so that the ball is propelled back to his opponent's court in a most effective way relative to proper play. This relevant information is here termed regulatory information. It is the kind of data by means of which the player normally regulates his actions or makes appropriate decisions.

For example, he may put together a personality profile of his opponent. This is the kind of data usually collected to reveal the opponent's overall strategy or style of play -- whether he is a perpetual lobber, say, or a serve-and-volley type of player. One must of course be wary of pitfalls in such "historical" information, for it is a bit removed from the immediate decision-making arena; but "scouting" can still be a useful guide. Its aim is to understand the weaknesses and strengths of the "enemy." In this respect, "stats" are valuable. Nevertheless, the real story can only be told during a match, by the point-to-point or game-to-game tactics, which are discovered by direct participation.

At the level of tactics, our player needs to know what kind of shot the opponent is going to hit. Will it be a lob? a drop shot? a drive down the line? The sooner he finds out, the better. If he is at the base line, earlier information might gain him just the extra step he needs to reach a drop shot at the net, or, if he is at the net, to anticipate the need to race back for an offensive lob. Timely data might also enable him to poach effectively on a cross-court shot or be alerted to block a down-the-line hit.

For tactical data the player must direct his attention to certain characteristics of his opponent's behavior. Thus, for example, he may watch the opponent's feet, to see how they are positioned in preparation for a shot. Or he may wait to observe how the racquet face is positioned just before impact with the ball. Is the face set for a lob? Is the wrist cocked for a forehand? Is the backswing deep and ready for a hard shot? These and other bits of data offer cues as to the opponent's action.

But information at what I call the spatio-temporal level is also needed. The player has to be able to read distances, velocities, accelerations. And he has to estimate time. In other words, he has to be able to identify the state of the ball, how far it is and how fast it is moving, and the state of his opponent, where he is standing, how fast he is running -- that sort of thing.

This kind of information applies at the personal level as well. It is a form of body awareness. For instance, the player needs to be aware of the positioning of his own racquet. Failure to place it properly can result in poor contact with the ball. As he races across the court or runs back to the baseline for a shot, possibly turning away from the ball for a moment, he has to keep track of the extent of his body rotation, changes in direction of motion, or changes in speed. That is, he has to know where he is and he has to know where he is going. Only then can he determine what to do next.

To understand regulatory information is thus to understand the information useful to the player at various levels of interest. The player looks for information according to his need, though he may not always know what it is or how to find it. Certainly he wants the right kind of data; he wants to separate the relevant from the irrelevant. But this is not always easy to do. The process may even require an ability or awareness that he does not have. At the very least, getting the correct information presupposes a behavioral environment for the player that honors the information as an aspect of its organization. But beyond that it requires viewing his environment in an efficient and veridical manner relative to the pertinent court activity. In short, it

Picture 1.2 Martina Navratilova showing top form in return of a volley. (Photo by Brad Graverson)

requires practiced ability. (See picture 1.2 for a good demonstration of this ability.)

HABIT

Habit is a boon to the player. The less he has to think about the details of his game, about his information gathering, movements, ground strokes, serves, overhead smashes, and the like, the better off he is. Habit enables him to perform even complex actions routinely, leaving him free to plan his tactics.

Unfortunately, habit also gets in the way of necessary change. Bad habits are hard to break. The strongest pre-game resolutions fall prey to "old reliable" mental or motor mechanisms; and habitual perceptual and motor patterns prevail over the resolutions as the player "gets into the action." The very fact that the patterns are performed without conscious effort dictates that they will run as usual as soon as attention is withdrawn. Such changes require continuing conscious effort, something one cannot do during the game. Thus the player may continue to search for the same old information in the same inefficient way and continue to respond with the same inefficient responses.

He may, for instance, resolve to "keep his eye on the ball" as the opponent tosses it for a serve, but in the heat of the action may become enamoured as usual, say, with the opponent's unorthodox motion and fail again to watch the ball for a critical split second. Or he may tell himself that this time he is going to "charge the net." Yet when play for the point ends, there he is, still near the baseline where he started, not having moved a foot closer to the net. Again, if he is at the net in a doubles match, his partner serving, he may assure himself that this time, no matter how anxious he is to poach, he will not make his move precipitously, before the opponent makes contact with the ball; yet when the serve crosses the net and approaches his opponent's racquet, he is away too quickly once again, and the opponents have another easy point down the line.

To make the problem of habit correction more difficult, a bad habit is seldom, if ever, an isolated pattern. Rather it is usually an integral part of a complex perceptual-motor chain, much of which is executed without conscious effort. The complex pattern offers strong resistance to change, because modification of a part throws the whole pattern out of balance.

The larger pattern, too, is a component of the player's greater behavioral environment. This environment is like a four-dimensional jigsaw puzzle. If a piece of the puzzle is modified, adjustments have to be made in the rest of the puzzle to accommodate the change. Such an accommodation can be resisted fiercely.

Suppose that for years a player has relied almost exclusively on a back-court game and now wants to develop a serve-and-volley style of play. This is a drastic modification. Even to <u>think</u> about it as a real possibility requires a significant change in attitude. The player has to consider making movements such as racing to the net after his serve, cutting off hard passing shots, engaging in rapid-fire volleying, or hitting overhead smashes. To be viewed as prospective moves, the actions have to be given more importance, higher value.

And the movements still have to be incorporated into his game. This means practice and more practice, usually a painful and laborious process. A great deal of testing is done. There are many trials, and many failures. Old habits have to be eliminated. New regulatory cues have to be added. And all the modifications have to be integrated into new habit patterns.

The <u>new</u> player, too, is confronted with these problems. Like the established player changing his style, the novice brings a life-time of perceptual-motor habits to the court with him. These habits have grown mostly by dint of circumstance, like weeds, unsystematically. Too little is known of the psycho-physiological mechanisms to do serious pruning. The player can consider himself fortunate if he has only a few bad habits among his skills and if these bad ones are not too emotionally charged to prevent change. The player is enmeshed in a complex interaction with his environment, and highly charged factors can affect both his sensory and his motor processes. This is particularly true of patterns developed during his early years.

Formed in part by inherited neuro-physiological structures, these early habit patterns are highly resistant to change. Deeply rooted, elemental and typically unconscious acts in origin, learned without the benefit of self awareness, they are nevertheless basic components of the individual's perceptual-motor skills. They involve many subtle interactions that continue to be unconscious in adult life. Yet these processes are fundamental to the construction of the player's spatio-temporal experience; they are the yarn out of which is woven the fabric, the skills, tactics, of his behavioral environment.

"INNER"TENNIS

Self awareness is an important aspect, if not the key, to the teaching philosophy developed by tennis-pro Tim Gallwey, author of The Inner Game of Tennis (1974). This awareness is non-judgemental. It aims not to criticize but to "see." Its objective is to gather information, not to pass judgement on it. The idea is for the player to become aware of what his body is doing, to know how his feet are moving, to feel the extended racquet arm, without bringing up the right or wrong of the actions -- without jumping all over himself for making a bad shot or puffing up after a good shot.

The conscious self can be the player's own worst enemy, according to Gallwey. This is self number one, the boss, the self-appointed critic, the know-it-all. Self 1 wants to do things right, and he is willing to push and shove to do it. "Take your racquet back, you jerk!" "Oh Christ! Drop your elbow! Drop your elbow!" "You swung too early, you dummy!" "Oh what a rotten player you are!"

Self 1 is the <u>thinking</u> self, the ego-mind, and for Gallwey it is the constant cause of interference with the more natural processes of a second self, the <u>doing</u> self, or Self 2. To be less interruptive, Self 1 must eat humble pie. It must cease to be a tyrant and become more like a watchful, loving parent, willing to let his child (Self 2) learn on his own, happy to let the child make mistakes and profit from them.

Self 2 is the inner self, the unconscious doer. It operates best when it is free of interference from Self 1. It plays with relaxed concentration, with a kind of effortless, spontaneous performance that does wonders when the mind is calm and at one with the body, i.e., when Self 1 is unobtrusive.

The unconscious doer may be playing "out of his mind" or "over his head," as we say; but he is not playing without consciousness. To quote Gallwey, such a player

> is more aware of the ball, the court, and, when necessary, his opponent. But he is not aware of giving himself a lot of instructions, thinking about how to hit the ball, how to correct past mistakes or how to repeat what he just did. He is conscious, but not thinking, <u>not over-trying</u>. A player in this state knows where he wants the ball to go, but he doesn't have to "try hard" to send it there. It just seems to happen -- and often with more accuracy than he could have hoped for. The player seems to be immersed in a flow of action which requires his energy, yet results in greater power and accuracy. The "hot streak" usually continues until he starts thinking about it and tries to maintain it; as soon as he attempts to exercise control, he loses it. (1974, p. 20)

Dealing with inner tennis, Gallwey is concerned with the psychology of the game, viz., with what is happening in the mind of the player. In particular, he is interested in improving the relationship between the conscious teller, Self 1, and the unconscious doer, Self 2. He feels that Self 1 treats Self 2 like an idiot with a short memory, when in fact, in his view, Self 2 hears everything, never forgets anything and is anything but stupid. After hitting the ball firmly once, Self 2 "knows forever which muscles to contract to do it again. That's his nature." (p. 26).

This notion of a nearly infallible Self 2 may be a bit optimistic. But what might we make of such a conscious unconscious doer? One interpretation may be drawn from the philosophies of Cassirer (1946) and Langer (1953, 1957). In their view there are non-verbal as well as verbal symbols. Words are not the only vehicles of expression; one might use gestures, for example. In fact, most forms of art rely solely on non-verbal symbols. Painting, architecture, dance -- all use only non-verbal modes of expression. The individual is thus able to respond to non-verbal as well as verbal forms of information, or regulatory cues. The player may thus be "unconscious" in the sense that non-verbalized or non-speakable symbols are involved. But he is conscious in respect to the fact that he is aware of the symbols and can respond to them.

In Gallwey's view, Self 2 works best with non-verbal data. To Self 2 a picture is worth a thousand words. The player must learn to program Self 2 with images. The greatest efforts in sports come when the mind is "as clear as a glass lake."

A verbal picture often is not easy to grasp, and it becomes more and more difficult as detail is added. Yet the verbal always seems to contain less data than the visual, which is relatively easy to grasp.

What is the inherent difference between the two information modes? The verbal can certainly be made visual: one has only to print the words. But the verbal can also be rendered non-verbal. Each spoken or written instruction can be transformed into a visual sign, such as a flash card, each with a different color pattern, like the cards flashed by students at football games. A red sign could then mean "Get the racquet back earlier!" A green one: "Toss the ball higher!" Etc. The coach could then flash the necessary card. No words or verbal instruction would be needed.

Does this make life easier for Self 2? It does not. There is no change in information, so the response patterns should be the same. Even if the flash cards were snapshots of "correct" positions for the racquet, feet, or the like, the fundamental problem would remain unsolved: The player's smooth flow of motion would be interrupted. A succession of such cards would produce a robot-like performance, step, step, step, instead of a single continuous motion. Thus Self 1 interferes not simply because its information is verbal, but because its information is inappropriate.

A directive by its very nature draws attention to the component of movement that needs to be corrected. In a game situation this might occur just at the time when a smooth, undifferentiated flow of movement is desired. Under these conditions the information would not only not be useful, it would be counter-productive.

Self 2 can and should be given assistance, but the help should be given under appropriate conditions with appropriate images. Self 1 is crafty and subtle; it can sneak in an instruction under the very nose of the player, in the middle of a critical move. It must learn tolerance and patience, and Self 2 should be allowed to play the game.

"LEFT-BRAIN" SYNDROME

The brain is a complex mass of interconnected cells that regulates the activity of the human organism. Integral to the central nervous system, it is the quarterback of the organism, accepting signals from internal and peripheral sensors and transmitting messages to muscles and glands.

Much still remains to be learned about the brain's operation, but its structure has been delineated in considerable detail and specific functions have been associated with many of its components. The forebrain is the newer brain phylogenetically; it is seated above the more primitive brain stem, which is an extension of the spinal cord. The forebrain has two hemispheres, left and right, connected together by a cable of nerve fibers called the corpus callosum, and by other, smaller, cables, or commissures. Each half-sphere controls the opposite side of the body, generally speaking, and contains a frontal, temporal, parietal and occipital lobe.

Since each hemisphere controls the other side of the body, it is to be expected that most functions are duplicated in the two halves. This is generally true. For instance, a visual control center is contained in each posterior, or occipital, lobe (at the back of the head), and controls for voluntary movement are found in the posterior section of each frontal lobe (at the brow).

However, not all functions are duplicated in the two halves, and even if they are, the functions may not be developed equally on the two sides. For a particular task, one side or the other may be dominant. In the case of speech, for example, the left hemisphere is dominant for the vast majority of people. Speech control centers in the left half are usually very well developed, while only rudiments of control are formed in the right half. But the degree of this dominance varies from individual to individual.

In some instances there is a very strong left-brain dominance and this tends to produce what might be called a "left-brain" syndrome. Persons with this characteristic tend to take a Self 1 approach to everything. Their approach to tennis, in particular, is "intellectual." They rely on a continuous stream of verbal directives to play the game and in effect suppress their non-verbal or intuitive capabilities. The result is that their style of play frequently seems deliberate and mechanical.

The intuitive capabilities may possibly be a function of the right hemisphere of the brain, and there is some evidence to indicate this might be true. For one thing, there is an overwhelming tendency for verbal control centers to develop in the left hemisphere (in most right handers and about two thirds of the left handers) leaving spatial control to the right hemisphere. Recent split-brain experiments, pioneered by Dr. R. W. Sperry and his staff and students, have shown as well that the right hemisphere is also conscious and can recognize things despite the fact that it may have only very limited verbal knowledge. (Sperry 1975)

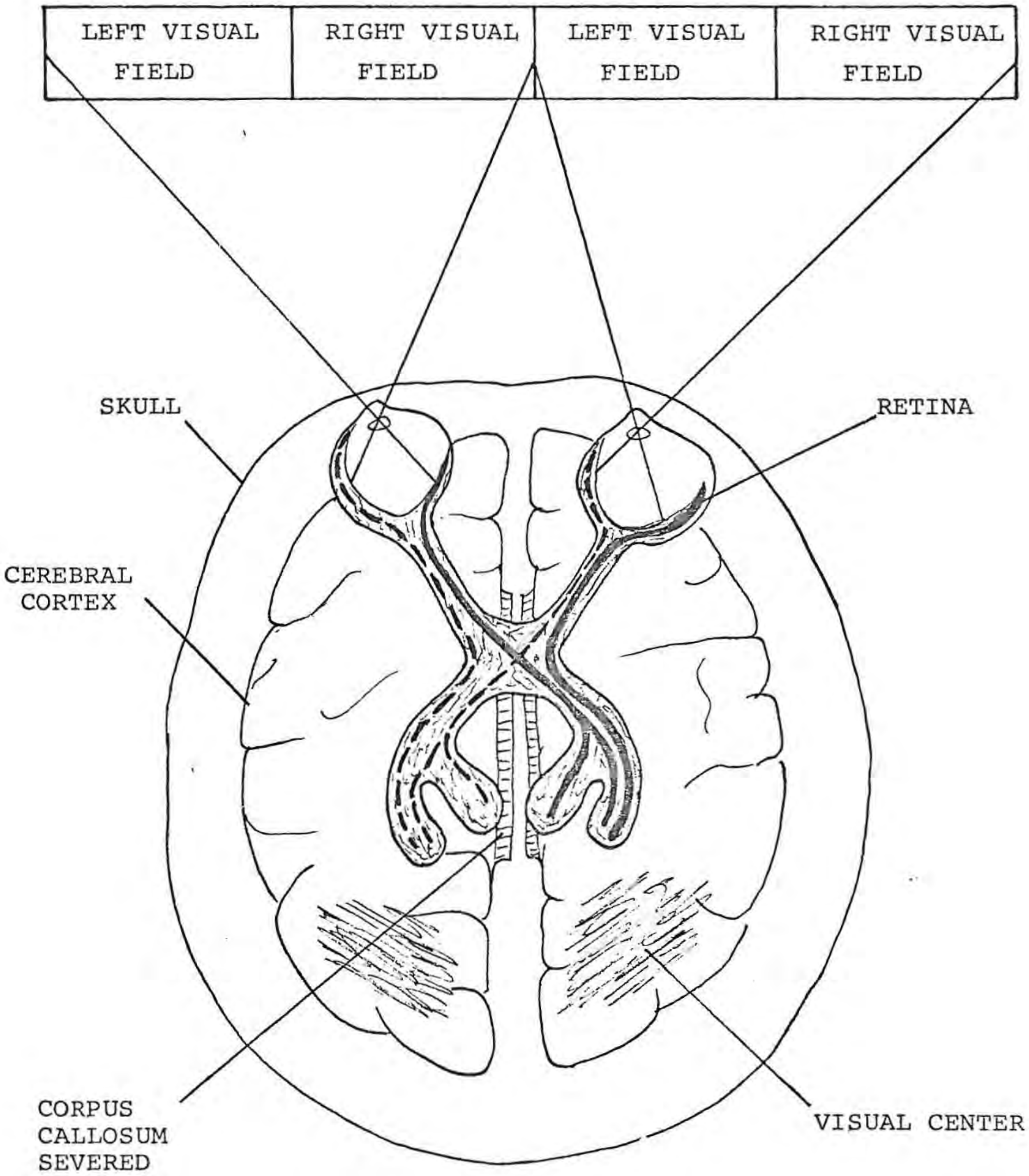


Figure 1.1. Schematic of cross-over of signals from left visual field to right brain and signals from right visual field to left brain. Corpus callosum is shown severed. (After Plotnik and Mollenauer 1978)

To test this condition, an image is presented to the right hemisphere but not to the left. This can be done by projecting the image from the subject's left visual field. Because of the crossover pattern of the visual fibers, signals from the left visual field, whether from the right eye or the left, are transmitted to the right hemisphere visual area; conversely, signals from the right visual field go to the left brain. Even though the right hemisphere may be mute, it can still point with its left hand (the hand it controls) or pick out an object. Thus, if it recognizes the image, it can pick out the correct one from a number of diverse objects, which it does. (See Figure 1.1 for the field-hemisphere relationship.)

These developments at first glance seem most encouraging for the existence of a palpable Self 2, one that is not out of reach of the researcher's equipment. To date, a number of fascinating experiments on the brain have been conducted. A number of inferences have been drawn, perhaps the most fundamental of which is that each hemisphere has its own mode of thought, the left using words, the right using sensory language, or images. The argument is that the left brain is analytic or logical, while the right is synthetic or spatial holistic. Thus it would seem, in this view, that the left brain is intellectually digital, while the right is analogue.

Considering this representation of the division of functions between the two hemispheres, might Gallwey's Self 1 and Self 2 be identified, respectively, with the left and right brain? It is clear that the highly verbal character of the left brain matches the nature of Self 1 and that the non-verbal aspect of the right brain reflects a Self 2 type. But there are a number of factors that work against adoption of such a simple correspondence.

For one thing, motor control centers of both frontal lobes are necessarily involved in all movements; muscles tend to work in pairs and both sides of the body operate in concert. Binocular integration brings the visual centers of both occipital lobes into play. These centers are active even while the body is moving. In fact, movement is necessary if the eyes are to see; at the very least, they have to be oriented or directed toward the object which is to be seen. In addition, signals to and from the medulla, in the brain stem, are essential for balance. And the cerebellum is required to smooth out the rough edges of movement.

Spatial integration, itself, is not the simple process it might appear to be. The visual field at any instant is relatively narrow, far too narrow to encompass anything the size of a tennis court at playing range. To produce the player's actual image of the court, spatio-temporal integration is needed. Without such a "manufactured" image, the player cannot establish his orientation on the court or have an awareness of direction. The eyes jump around, now looking this way, now that way. The successive "snapshots" have to be pulled together into a unified field that marks our normal experience. Many components of the brain are involved and many control centers have to be brought into play to produce the player's behavioral environment. Just how complex the task is, will be seen, in part, in the chapters following this introduction.

MANIPULOSPATIALITY AND LANGUAGE

The view that such basic processes as analysis and synthesis are <u>not</u> integral facets of the intellectual character of each hemisphere of man's brain has recently come under attack. Gazzaniga and LeDoux (1978) claim that this specialization theory fails when the processing requirements and real capacities of the hemispheres are considered.

Conducting their own tests, they found that the patient was able to select correct answers without using his hands. This suggested that the left hemisphere can <u>perceive</u> spatial features and that the left and right hemispheres are neurologically the same.

According to Gazzaniga and Le Doux, the left hemisphere is minimally involved in manipulospatial functions and the right minimally involved in language, because language is a late phylogenetic development. The language cells competed for space and for some reason sprouted in the inferior parietel lobe, the traditional turf of the manipulospatial function. The reason for this is not known, though it is possible that specialized language cells developed out of the use of tools, a manipulospatial derivative.

Gazzaniga and LeDoux (1978) use the term "manipulospatial" to refer to the mechanism by which a spatial context is mapped onto the perceptual and motor activities of the hands. Neither perceptual nor motor, strictly, it is the means of actively exploring and altering the spatial environment by using the hands. It is part of the more basic neural mechanism whereby the organism maintains and actively utilizes the spatial relationship between its body and the surrounding spatial environment.

This awareness of the relationships of the organism's bodily parts to the spatial environment seems to be a function of the inferior parietal lobule, because cells of the lobule were found to be activated by reading the manipulatory movements. That these movements were not simply motor was indicated by the fact that the cells fired independently of the speed of movement. Furthermore, "the cells were generally contralateral and specific for particular points in the immediate surrounding space" (p. 57).

The manipulospatial mechanism thus appears to provide a personal reference frame or map for manual exploration of extrapersonal space. Typically a function of both hemispheres in non-human primates, in humans it apparently lost the competition with language for neural space in the brain and now resides only in the right hemisphere. Consequently, according to this view, the dramatic dichotomy of lateralization of the brain seems to be language versus manipulospatiality.

THE PLAYER AS PROGRAMMER AND COMPUTER

In a sense, Gallwey's Self 2 is like a robot, an automaton -- a biological computer that is programmed by Self 1. Might such an interpretation have a physiological basis? In this section we consider the view of Wilder Penfield (1975), a neurosurgeon specializing in the treatment of epilepsia, who does in fact argue that there is in the brain an integrated, two-mechanism control center, one element of which is a mind-mechanism, which programs, and the other, an automatic sensory-motor mechanism, which is programmed.

The region of integration and coordination lies in the higher brain-stem -- the diencephelon or old brain, speaking phylogenetically, lying deep within the cerebral mass of gray and white matter, attached to the lower brain-stem, which extends the spinal cord. The mind-mechanism in the semi-independent pairing is the source of consciousness, and the other is a mechanism for sensory-motor coordination. In their combined action these units make sensory input available and motor output purposeful. "They constitute a centrencephalic integrating system that unites functionally the diencephelon (higher brain-stem) with the cortex of both hemispheres. To this integrating system, sensory impressions come, and in its action, thought, and behavior [sensory impressions] find expression." (p. 44).

Evidence for this view derives in large part from the bizarre and very unfortunate occurrences of epileptic fits. The network of the brain is such that natural or artificial stimulation in one area has disruptive effects in that area, but possibly also in distant, functionally related areas. Thus, if an electrode is made to pass current into a region of the cortex, the current interferes completely with the person's normal use of that area. But in the process, other, distant zones beyond the interfering influence of the electrode may be activated by normal neuronal conduction from the affected area. This phenomenon may also occur as the result of an epileptic discharge in the starting area. However, the first epileptic charge may be so severe as to be a bombardment, the secondary and distant effect of which is another explosion, or a continuing series of explosions, along the functional paths.

The effect of the epileptic discharge depends on the functional path affected, and this depends on the point of origin of the discharge. On occasion, an epileptic discharge will confine itself selectively to one functional system. When it does, says Penfield, it paralyzes that mechanism for any normal operation. "If the function of gray matter is highly complicated and only partially automatic, such as in the speech area of the human cerebral cortex, the epileptic fit produces nothing more than paralytic silence, e.g., aphasia." For this reason, observation of such effects for the selective identification of functional systems of the brain has considerable investigative value (Luria 1969).

If the epileptic discharge begins somewhere in the sensory or motor region of the cortex, it activates all of the motor area. The cortex of one side is then pitted against the cortex of the other, causing the person to stiffen his body and limbs, uncontrollably, under general muscle contraction. Consciousness vanishes.

However, if the epileptic discharge begins in certain areas of the cortex outside the sensory-motor region, in the interpretive cortex, as Penfield identifies the region, the mind-mechanism is paralyzed. The individual is then no longer a conscious, decision-making creature; he is converted into a mindless automaton.

The interpretive cortex is the phylogenetically newer part of the cortex, proportionately more fully developed in man than in other mammals. Some areas of the cortex, such as the sensory and motor areas, are committed as to function at birth, but the interpretive cortex is not. It is only after birth, with the acquisition of experience, that the latter is "programmed."

> When a child is born, the new convolutions of the temporal lobe are uncommitted and unconditioned as far as function is concerned. During the initial learning period of childhood, some of these convolutions will be programmed for <u>speech</u> on one side or the other, usually the left side in right-handed individuals. The rest of them will be devoted to interpretation of present experience in the light of past experience. This we have labeled the <u>interpretive cortex</u>. These new areas of cerebral cortex, both frontal and temporal, are employed in the mechanism of mind-action after the early period of what may be called conditioning or programming. (Penfield 1975, p. 19)

For Penfield, the interpretive cortex does for perception of non-verbal concepts what the speech cortex and the speech mechanism do for speech, the verbal and non-verbal mechanisms together forming a large memory file, access to which is gained either through conscious effort or by automatic processes. Included in the interpretive cortex is a group of cells in the inferior parietal lobule of the right hemisphere, whose function is to provide the capability for space orientation. Corresponding to the speech center of the left hemisphere, the space orientation cells provide a body-reference map of the surrounding spatial environment. These cells, as we have seen, are not part of the sensory-motor mechanisms. And somewhat like Gazzaniga's manipulospatial mechanism, they give a spatial interpretation of the sensory and motor activities, relating the bodily parts to the immediate environment. Gentle stimulation of this segment of the interpretive cortex may, for instance, ellicit a mechanism whose function it is to send signals that make the person aware that something is "coming nearer," say, or "going away," etc.

In general, however, a violent stimulation of this or any other portion of the interpretive cortex -- a stimulus such as that of an epileptic discharge -- knocks out the whole area, including the mind-mechanism, itself. But it leaves the sensory-motor control intact. The individual is no longer conscious, but he continues to function; i.e., he is capable still of carrying on in accordance with decisions or plans already made. For instance, he can continue to walk or drive home, if that had been his destination. But a novel circumstance can disrupt him completely. In general, if new decisions are to be made, an automaton cannot make them.

> In an attack of automatism the patient becomes suddenly unconscious, but, since other mechanisms in the brain continue to function, he changes into an automaton. He may wander about, confused and aimless. Or he may continue to carry out whatever purpose his mind was in the act of handing on to his automatic sensory-motor mechanism when the highest brain-mechanism went out of action. Or he follows a stereotyped, habitual pattern of behavior. In every case, however, the automaton can make few, if any, decisions for which there has been no precedent. He makes no record of the stream of consciousness. Thus, he will have complete amnesia for the period of epileptic discharge and during the period of cellular exhaustion that follows. (Penfield 1975, p.39)

Nevertheless, if an attack of automatism on a person occurs while he is in the act of planning a project, the automaton "may discharge the purpose in remarkable detail."

For Penfield, then, the evidence shows that operation of the brain is like operating a computer, which requires a program and a programmer. The programmer in the brain is the mind-mechanism, while the programmed computer is the sensory-motor mechanism, capable of doing what the programmer wants done. "A man's mind, one might say, is the person. He walks about the world, depending always upon his private computer, which he programs continuously to suit his ever-changing purposes and interests." (p. 61).

In a sense, too, this is how Gallwey's Self 1 and Self 2 are related. Self 1 is the programmer; it is the planner and decision maker. Self 2 is the "automaton," the competent slave; it is the programmed or programmable computer. To paraphrase Gallwey, once the computer (the automaton) is programmed to do a certain job of work, it should be allowed to do it; it should be allowed to run its course toward a solution without being interrupted continuously by some new program change, some irrelevant new plan or directive.

So if we aren't too fussy with the linguistic comparison of the two views, it would seem that Penfield's work does in fact support the Gallwey concept. There is of course that one nagging problem, namely that Penfield's automaton is unconscious, whereas Gallwey's Self 2 is really conscious.

The sense of Gallwey's unconscious-conscious Self 2 turns on the existence of the non-verbal interpretive capability of that entity. But the interpretive cortex is an integral part of the mind-mechanism functional system; it is not at all a component of the automatic functional system. This fact alone mitigates against a direct correspondence between the views.

Unfortunately for this argument, however, Penfield throws in a monkey wrench by giving the following summary of the capability of the automatic mechanism:

> Inasmuch as the brain is a place for newly acquired automatic mechanism, it is a computer. To be useful, any computer must be programmed and operated by an external agent. Suppose an individual decides to turn his attention to a certain matter. This decision, I suppose, is an act on the part of the mind. The brain response must be somewhat as follows: The highest brain-mechanism takes immediate executive action, which causes the sensory-motor mechanism to block, by inhibition, the inflow of information that is unrelated to the subject of the mind's interest. At the same time, it allows related data to pass through into the stream of consciousness. The data that enter the stream of consciousness may be sequences of sight and sound from the neighborhood, accepted with immediate interpretations, such as awareness of familiarity or of danger. Relevant memories may be added automatically from the individual's past experience.
>
> The automatic sensory-motor mechanism itself comes to be conditioned, as the years pass, for many purposes. It coordinates the action of many semi-separable mechanisms within the brain, such as reading, writing, speaking, and the dextrous skills. As time passes, it learns to take over more and more of the body's behavior. Each skill, acquired in the light of conscious attention, soon becomes automatic and runs itself even more skillfully than the individual could carry it out by conscious direction. (1975, p. 60-1)

The language in this passage is hardly different at all from that of Gallwey. Such a great deal of flexibility is allowed for the automaton, it might as well be Self 2. When the athlete is said to be "playing out of his mind," this may well mean that during that very fortunate interlude his skill levels are high and he is not being reprogrammed. For the correspondence to be complete, then, it seems that Gallwey need only admit that the non-verbal mechanism is an alternate vehicle to the speech mechanism for programming the automaton. The computer can then be programmed to any degree of sophistication desired, thereby preserving the respectability of Self 2. In this interpretation, however, real power actually shifts to Self 1, which now regulates both inputs, not just the verbal.

SENSORY AWARENESS AND MOTOR ACTION

A hemispherectomy patient is conspicuous by the fact that he tends to collide with objects located in that part of his visual field normally under the control of the missing hemisphere. For example, a right-hemispherectomy patient frequently collides with things on his left. In walking down a corridor, for example, he might bump into the left wall, or walk into a chair.

A reasonable explanation of this phenomenon is that the patient, from long accustomed practice, continues to rely on a source of information that is not now available to him. Momentarily forgetting his loss of the required sense mechanisms, or possibly unaware of their importance, he reads the <u>absence</u> of data in a positive way, namely that his path is clear.

In a similar way, an individual suffering from a loss of hearing might, for example, fail to notice approaching traffic. Say he is crossing the street and is thinking of other things or momentarily forgets his hearing problem, which may be a recent development. Out of habit he might depend as usual on his ears to detect the presence of cars, and the absence of the telltale sounds might lead him to believe, at his peril, that no car was coming.

Disease might affect perception in another way, creating a loss of body image. Such an image depends on integrating the many kinds of information normally available to the individual, not the least important of which are seeing and hearing. But a patient who loses this capability could be helpless when asked to show parts of his body. The loss may be so severe, in fact, that when asked to point to an ear or arm he may believe they are missing. His postural model may also be disturbed, and he may not even be capable of starting a movement (Granit 1977).

These examples point up the fact that the individual comes to depend on a normal flow of information, or sensory impressions. <u>His movements take place within a sensory envelope whose presence</u>

and stability is constantly confirmed by frequent renewal of the same experience. For Granit, this perpetual confirmation has created the neural organizations that engineer the constancies in experience, such as the constancies of size and shape of objects, and the frameworks of reference that give perceptual stability, particularly the uniformities of space and the regularity of time. These developments are habitually taken into account in movement.

> Within the surrounding space such as a room we move with the greatest ease between objects whose size is constant rather than variable with the retinal image. Because our movements are scaled to this invarient world, it should be possible to detect cells in the cortex that somehow have the properties of coordinating the motor and sensory spheres. In a sense the pyramidal cells of the motor cortex and the motoneurons of the spinal cord represent stimuli and movements combined. But, in looking for cells inserted into our established organizations for movement within spatial coordinates, a more sophisticated response pattern is required than that of pyramidal cells and motoneurons which deliver force and rate of change of force to commands from elsewhere. (Granit 1977, p. 182).

Cells that exemplify the required properties do in fact exist. They lie within the parietal cortex, the area we have seen to contain the seat of spatial reference. Clinical experience with these cells show them to be complex and varied. For example, lesions in this area show defects in the synthesis, interpretation, differentiation, and comparison of the elementary sensory experience. Such lesions also result in postural loss and defects in recognition of passive joint movements (Granit 1977).

In extreme cases, the effects of sensory deprivation can result in a disastrous loss of balanced control of behavior. But even in less severe cases, the results could be hazardous, unless some remedial action was taken. For instance, the person with the hearing reduction might have to depend more on his vision. The habit of listening for cars would have to be neutralized and displaced with the new habit of watching for cars. That is, the automaton has to be re-programmed, and this requires conscious awareness.

At the very least the individual must recognize the fact that he is still relying on his hearing despite the lack of information from that source. He must also become aware of the different situations in which the dependence occurs, such as at streets and parking lots. And when he is in these situations he must consciously inhibit the automatic unproductive method and apply visual scanning. He must continue to do this until the new habit is well established.

While our tennis player is not necessarily deprived of any of his senses, he may nevertheless be caught up in a similar problem in depending on information that is unproductive and performing actions that are ineffective. To correct a poor habit structure, he, too, must engage in remedial practices. First, of course, he must become aware of the habit. When it is possible he must consciously inhibit it and consciously substitute the more effective alternative, to the best of his ability. This practice has to be continued until the new technique is ingrained.

In the end he is faced with a two-fold task. On the one hand he must heighten sensory awareness in order to build up a better image of his behavioral environment, incorporating higher requirements, finer values, and better skills. As we saw earlier, however, this may not be easy. He may have strong emotional biases toward existing practices, and may not even wish to re-examine them. Perhaps the skills identify him with good friends, whose company he doesn't want to lose. Any one of a variety of factors might inhibit new sensory awareness.

On the other hand our player has to practice the new techniques until they are automatic. Like the skilled pianist or typist, in order to gain efficiency and smoothness he has to let his automaton handle the details. By sharpening his insights and by improving his motor acts, he can improve his game.

PART 1

THE PLAYER'S BEHAVIORAL ENVIRONMENT

CHAPTER 2

THE PLAYER'S PHYSICAL ENVIRONMENT

While history has had its share of solipsists -- those who hold that the self is the only knowable, or the only existent, thing --, most of us have suffered enough knocks on the shins to accept the contrary view, that there is an external world out there and that it is knowable. At least we behave as if that were the case. We certainly do not ignore the automobile that bears down on us when we cross the street. Nor do we ignore the opponent in a tennis match who slams the ball back. We acknowledge the automobile, the street, the player, the ball and the court as real entities in a real world with which we interact.

In physics the external world is expressed as a reality independent of a personal vantage point, although we realize objects can never be experienced except from a certain perspective. Space is represented via a system of three orthogonal, or Cartesian, coordinates, as shown in Figure 2.1, and time is added as a fourth dimension orthogonal to the other three.

Objects in the world are not presented to us in this way. We see the world in perspective; parallel lines converge; objects appear to be smaller when they are farther away. This is evidenced by the fact that very large objects, such as buildings or airplanes, can be obliterated from view by small physical objects that are close to the eyes.

We do not literally take the objects to be smaller. That is, we take for granted that the seemingly smaller things are not smaller in their physical nature, though at times we are fooled. Somehow we learn to recognize that an objective distance affects the visual presentation of the objects. This objective distance is a segment

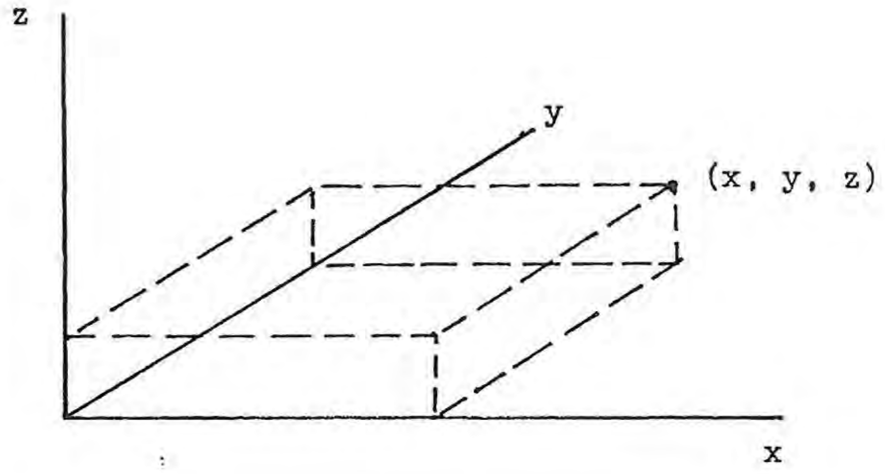


Figure 2.1. Coordinate reference system.

of physical space, and the space is such that equal segments have the same measure throughout its span. This is not true in our personal or subjective space.

We also recognize that motion occurs in this 3-space. Objects that move may exhibit velocity, which is a rate of change of position per unit time in a certain direction. The objects may also exhibit acceleration, which is the time rate of change of velocity. Since velocity has two components, namely, speed and direction, the acceleration may occur as a time rate of change of speed or a time rate of change of direction. We then have either linear acceleration or angular acceleration.

In this chapter we examine the physical nature of the tennis arena. The tennis ball is considered to be moving through an objective space, in real time, through an actual gravitational field, and we look specifically at the way it moves in that field.

We also examine the physical nature of light and consider how it interacts with the surfaces of objects in the arena to reflect into the eyes of the perceiver, who somehow constructs a highly veridical semblance of that arena in his visual experience.

INERTIAL FORCE

The step from velocity to acceleration provides the basis for the mechanics of motion. By virtue of the rate of change of velocity, a description can be given of the forces acting on an object. That is, the consequence of a net force acting on a body is that the body suffers acceleration. This is a most significant concept.

A body at rest or moving with constant velocity does not exhibit a net force. It is the acceleration that determines whether a net force is acting, not the mere fact that the body is in motion, as was thought to be the case in antiquity. The first principle of Newton states that an object will remain at rest or in constant motion provided no external net or unbalanced force acts on the object. This is the principle of inertia. In effect, it says that force is needed to overcome inertia.

To determine the amount of force required to speed up or slow down an object, Newton offered his second law, viz., that the net force, F, is the product of the inertial mass, m, and the acceleration, a. That is, presuming there is no resistance,

$$F = ma.$$

The greater the inertia, the greater the force required for a given acceleration. And the greater the acceleration, the greater the force being applied to the given body. In other words, F is proportional to m, and F is proportional to a.

For example, suppose a box-car on frictionless rails is being driven by an engine. Say the box-car weighs 5 tons and the acceleration is constant at 10ft/sec/sec. The force being applied is thus

$$\begin{aligned} F &= 5 \times 2000 \text{ (pounds)} \times 10 \text{ (ft/sec/sec)} \\ &= 100{,}000 \text{ pound-ft/sec/sec.} \end{aligned}$$

This expression of force is stated in English units. In the metric system it may be expressed in dynes (gram-cm/sec/sec), or in multiples of the dyne, using meters, kilometers, etc., in place of centimeters, or in Newtons, using kilograms and meters.

Note, too, that force and acceleration are vector quantities, having both direction and magnitude. On the other hand, mass is only a scalar; it has no direction.

GRAVITATIONAL FORCE

When working with the British system of units, weight is sometimes used in place of inertial mass to avoid the more complex unit of mass called the slug, or pounds/ft/sec^2. However, weight and mass are quite distinct and it is important to understand the difference.

Mass is an intrinsic property of an object; its value is retained even if the object is moved to a different environment. An object has the same mass whether it is on the moon or on the planet mars. This is not true for weight, however. Weight is an extrinsic property. On the moon the weight of a body of fixed mass is lower than it is when measured on mars. Its value is a function of the gravitational acceleration, g, which depends on the mass of the associated body. That is,

$$W = mg.$$

The reason for the interchangability is that in the normal environment of everyday living the gravitational acceleration is constant, so W is proportional to m. So long as the gravitational environment remains the same, no confusion results. However, if calculations involve a change in gravitational reference, care must be taken to keep the concepts distinct.

Weight, we say, is an unbalanced force. Yet there is no obvious exertion on weighted objects; nobody is seen to push down on them. Where then does the force come from?

In Newton's view, weight is the result of a natural force of attraction between bodies having mass. This force is expressed by the function

$$F = G \frac{m_1 m_2}{r^2},$$

where m_1 and m_2 are the masses of the respective bodies, r is the distance between them, and G is a proportionality constant. This expression is Newton's law of gravitation. It says that the force on an object, or its weight, is proportional to the product of the attracting masses and inversely proportional to the square of the distance between them. The greater the mass, the greater the weight; the greater the distance, the less the weight.

It is to be understood that the distance, r, is the center-to-center distance of the masses. For objects on the surface of the earth, for example, r is 4000 miles. This is already a great distance, so the object can be taken several miles farther, or several miles in altitude with only relatively insignificant changes in weight. This is another way of saying that the gravitational acceleration can be considered constant for most earthly practices.

FALLING OBJECTS

To say that an object is falling is to say that there is a net force acting downward on it. If we allow that the only force acting on the object is the gravitational force and that the object falls through a distance over which the force is constant, we can compute the time it takes for the object to fall and the velocity it has when it lands.

Since the force is constant, the velocity of the object increases in a straight-line manner and an average velocity of fall can be defined. This average, v_{ave}, is half the sum of the initial velocity, v_o, and the final velocity, v_f, viz.,

$$v_{ave} = \frac{v_o + v_f}{2}.$$

Using the average velocity, the distance, s, and the time, t, of fall are related as

$$v_{ave} = s/t.$$

And we know that acceleration is the change in velocity per unit of time, or

$$g = (v_f - v_o)/t.$$

We can now find the time of fall and the final velocity for different initial conditions. Suppose that the initial velocity is zero and that the starting height is 64 feet. We take the gravitational acceleration to be 32 ft/sec^2.

Substituting these values into our three equations yields:

$$v_{ave} = v_f/2,$$

$$v_{ave} = 64/t,$$

and

$$32 = v_f/t.$$

Eliminating v_{ave} and solving for v_f we have the two equations

$$v_f = 128/t,$$

and

$$v_f = 32t.$$

Therefore

$$128 = 32t^2,$$

or

$$t = \sqrt{128/32} = \sqrt{4} = 2 \text{ sec}.$$

The final velocity is then

$$v_f = 32 \times 2 = 64 \text{ ft/sec}.$$

In a similar way we can solve for the distance of fall if we know the time. The initial velocity may also be assumed to be non-zero, or we may compute this value starting with the final velocity. The initial velocity may be directed upwards or downwards.

BALL TRAJECTORY

If a horizontal component of velocity is added as a possible starting condition to those already mentioned for the free-falling object of the previous section, we have the possibility of a more general type trajectory. Such a trajectory is attained when a downrange missile is fired or when a satellite is launched into orbit. The trajectory is shown in Figure 2.2, in which it can be noticed that the direction of the force of gravity on the object is always toward the center of the earth.

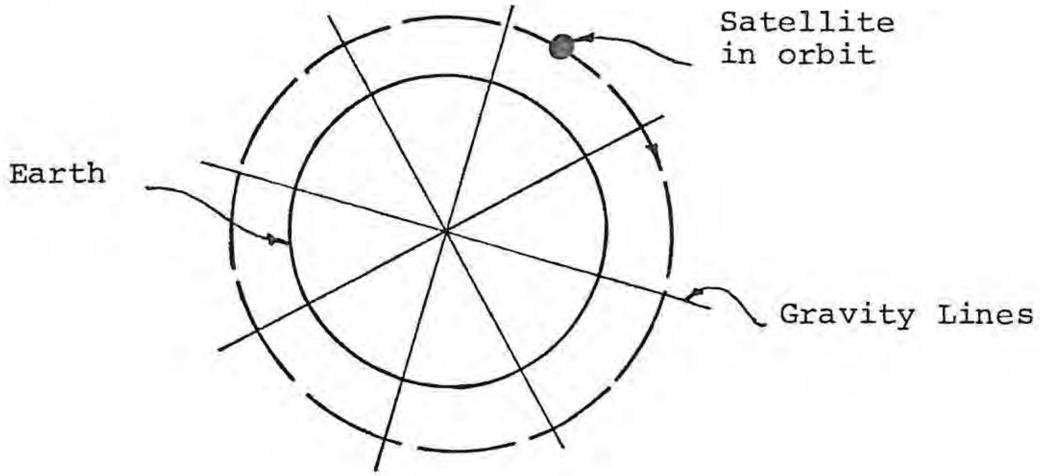


Figure 2.2. Satellite orbit. Gravity lines are directed inward.

At a more down-to-earth level, basket balls, tennis balls, golf balls, or footballs are given similar trajectories when they are hit or thrown, as the case may be. There can, however, be a difference in treatment in that the range of the trajectories involved is short enough that the gravity lines over the course of the trajectory may be considered to be parallel to each other. This simplifies the computations.

We would like to be able to determine the positions, s, velocity, v, and lapsed time, t, from start for free-falling tennis ball trajectories. This can be done using the formulas of the previous section and adding a computation for the horizontal component of motion. However, it is useful first to re-write the formulas in a slightly different but more tractable form. In this formulation air resistance is still considered negligible.

Rearranging terms in the expression for acceleration, we obtain

$$v = v_f = v_o + gt.$$

Then starting with

$$s = v_{ave}t$$

and substituting for $v_{ave} = (v_o + v_f)/2$, we get

$$s = \frac{v_ot + v_ft}{2}.$$

Finally substituting for v_f,

$$s = \frac{v_ot + (v_o + gt)t}{2}$$

$$= \frac{2v_ot + gt^2}{2}$$

$$= v_ot + 1/2\, gt^2.$$

If a ball is now assumed to be free to fall and it has initial velocity, $v_o = 0$, the position, s, measured from an arbitrary starting point, and the velocity, v, can be computed for successive seconds. Sample values are presented in Table 2.1.

t (secs)	s (ft)	v (ft/sec)
1	16	32
2	64	64
3	144	96
4	256	128
5	400	160

Table 2.1. Sample values for free falling object.

Suppose we now impose a horizontal velocity on the ball as a starting condition, letting v_o remain zero. The values of Table 2.1 will not be affected, because the imposed velocity is at right angles to the lines of gravitational force. However, the ball will suffer translation per unit time in the amount of the imposed velocity. Remember that the lines of force are assumed to be parallel, so we can use a Cartesian coordinate system to represent the vertical and horizontal motions, as shown in Figure 2.3.

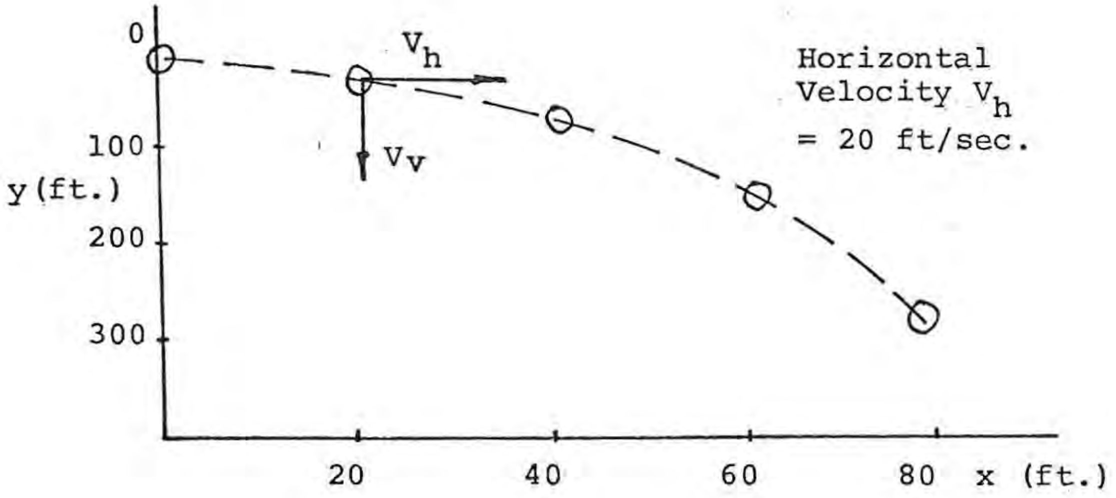


Figure 2.3. Falling ball with horizontal velocity component.

AIR, WIND, AND SPIN

In the previous sections it was assumed that there was no air resistance, wind, or spin to affect the motion of the ball. Under normal conditions, however, these are significant factors in games, particularly in tennis.

So far as air and wind are concerned, it is clear that air resists the motion of the ball and that wind tends to carry the ball along with it. Air resistance always opposes the motion; it is a force vector whose direction is opposite to the forces that cause the ball to move. Wind, on the other hand, is a force component that can cause the ball to slow down, speed up, or change direction, depending on its own direction. Clearly, a strong or gusty wind can produce major changes in ball trajectory and creates a physical condition that demands high concentration.

Spin, too, heightens the need for concentration, for it causes the ball to deviate from a trajectory which it would otherwise have had, and the ball can be spun in most any direction with varying magnitude. However, if attention is paid to the manner in which the opponent strokes the ball, the trajectory can be predicted to some extent, because it tends to curve in the direction of the spin. Thus, a ball hit with topspin will curve down, whereas a ball with backspin will tend to curve up, against the force of gravity.

Spin alters the trajectory because it causes a difference in air pressure which acts at right angles to the instantaneous direction of motion of the ball. This phenomenon is illustrated in Figure 2.4, using topspin.

In this illustration the topspin is considered to be in the plane of the page. Because of the spin the portion of the ball above the indicated line of motion has a greater speed than the mass center, and the portion below the center has a lower speed. The action compacts the air molecules at the top and rarefies them at the bottom. This creates a pressure imbalance that pushes down on the ball. The downward force adds to the force of gravity and causes the ball to fall faster than it would if there were no spin. With underspin, or backspin, a force imbalance is created toward the upside, tending to counter the force of gravity. This causes the ball to fall more slowly than it would if there were no backspin.

A factor that makes analysis difficult is that the differential of pressure due to spin, as indicated, acts normal to the path. But the path, itself, even without spin, already curves down because of gravity, alone. Since the normal to the curve changes as the curve changes, the direction of the net force due to spin must change. As a result, a component of the force begins to act in the horizontal direction. This component increases as the trajectory gets steeper.

The net force thus acts not only to change the rate of fall but also to change the horizontal speed of the ball. A topspin, for example, not only increases the rate of fall but also decreases the horizontal velocity. A backspin, on the other hand, decreases the rate of fall and increases the horizontal velocity. Consequently, a backspin shot travels farther than a corresponding topspin shot before it bounces, and it approaches the court at a steeper incident angle (the angle with respect to the normal to the court).

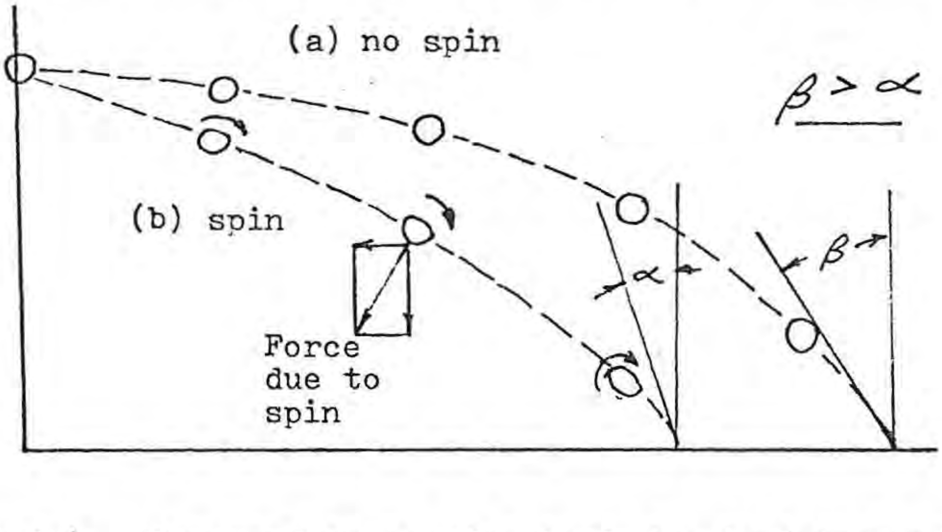


Figure 2.4. Downward curve of a ball due to (a) gravity alone, and (b) gravity and topspin.

EFFECT OF SPIN ON REBOUND

A perfectly elastic ball will rebound from a frictionless flat surface (court) with an angle of rebound equal to its incident angle. This is an ideal situation and is not met in practice. A real ball is not perfectly elastic, it does not bounce instantaneously, and the court surface is not frictionless. In consequence, the ball does not rebound as high as its pre-bounce height and the angle of rebound generally does not equal the incident angle.

To consider the effects of spin we assume that the ball is not distorted elastically, so that if it is simply falling, it will rebound along its approach line of motion, i.e., along the line of gravity.

If the ball is given a horizontal component of velocity, the rebound force must still be vertical; but the ball on rebound will translate in the direction of the horizontal velocity, the translation rate depending on the nature of the contact of the ball with the surface.

For a real ball on a real surface the contact is not instantaneous or elastic; it occurs over a finite interval of time and the surface offers resistance. This resistance, or resistive force, is in the plane of the surface and opposite to the ground speed or horizontal direction of the ball. Acting on the ball, the force reduces its horizontal velocity and produces a topspin. (See Figure 2.5 (a).)

Now suppose we add spin. We saw that the added force due to spin is at right angles to the spin axis and in the direction of the tangential velocity of the leading surface of the ball. The ball is already changing its direction of motion in the downward flight, and now the spin adds its own effects on top of that of gravity.

We let the spinning ball strike the court, where it encounters a resistive force opposite to the ground speed of the touching portion of the ball and roughly proportional to its magnitude. This ground speed is the resultant or combined effect of the horizontal velocity of the ball at contact and the spin.

There are many combinations of these motions. Some effects for the more familiar shots can be given. Consider a topspin shot. If the horizontal speed is greater than the linear speed due to spin, the net surface speed will be forward (in the same direction as the horizontal speed) and the resistive force will slow the shot and increase the spin. (See Figure 2.5(b).) If the horizontal speed

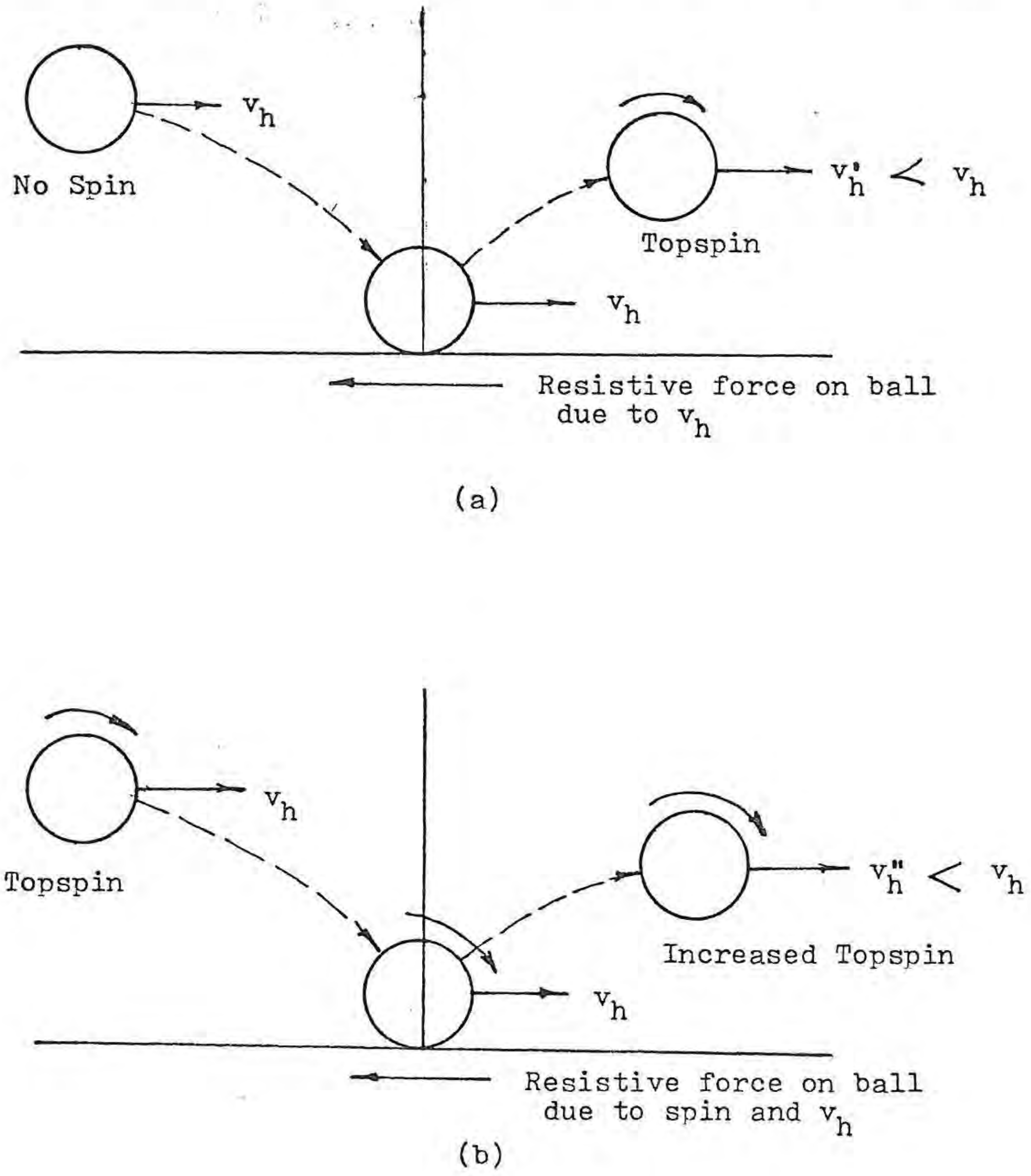


Figure 2.5. Rebound of (a) non-spinning ball and (b) ball having topspin.

is less than the linear speed due to spin, the net surface speed will be backward, and the resistive force will actually accelerate the ball forward, making it seem to "jump at" the receiver.

By contrast, the surface speed effect of a backspin shot is always to add to the surface speed. This increases the backward force, so the effect is always to slow the ball down and to decrease the spin rate. The result is that the player has to reach for the ball. If the relative linear speed of the backspin is high enough, the ball will actually bounce back away from the receiver.

LIGHT

The physical environment is liberally bombarded with radiant or electromagnetic energy, ranging on a scale of frequency, ν , from the high frequency cosmic rays, gamma rays and x-rays at one end to the low frequency TV and radio waves at the other. The spectrum of light waves, to which alone the eyes are sensitive and which act as the stimuli to vision, is a continuous band somewhat in the middle of the scale, roughly between 5×10^{14} and 5×10^{15} cycles per second. (The frequency is normally expressed in Hertz, abbreviated Hz.)

This energy may also be expressed or classified according to its wave length, λ , which is inversely proportional to frequency. The product defines the velocity of the energy. That is,

$$\lambda\nu = \text{velocity of the wave.}$$

In a vacuum this velocity is the same for all electromagnetic waves and thus equals the velocity of light, c.

In electromagnetic wave theory, the velocity of a specific wave is usually given a pictorial rendering as in Figure 2.6, which depicts the "movement" of the waves as a sinusoidal function of time, i.e., a trigonometric function. To be more specific, this movement is a

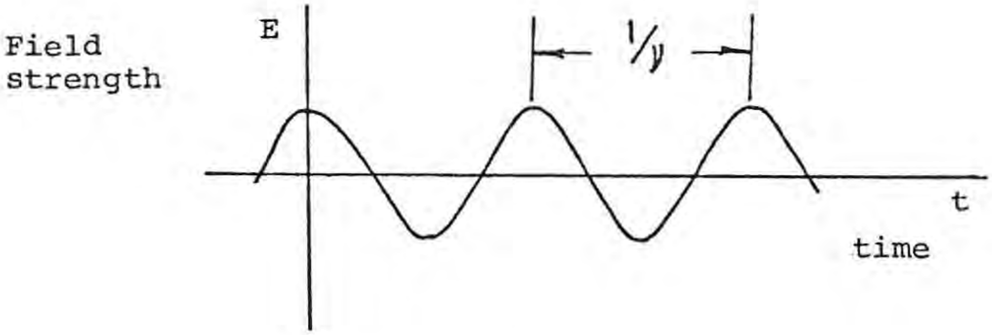


Figure 2.6. The electric field strength in an electromagnetic wave at a given point as a function of time, t.

transfer of energy from a source to a detector, somehow without transferring the medium in which the waves occurs (Welford 1976). That is, unlike sound or water waves, for example, electromagnetic waves do not seem to require a medium for energy transmission. They pass through a vacuum and don't seem to need even an "ether."

The so-called amplitude, E, of the wave is the electric field strength of the wave at a given point in the path of the wave at a certain moment. The field strength varies as a sinusoidal function of time and the wave is periodic, repeating itself in regular intervals. The wave length is thus the length of this periodic variation, and the frequency is the number of such cycles that pass a given point in a second. Since the direction of the electric field strength is at right angles to the "motion" of the wave, electromagnetic waves are classified as transverse waves.

The value for the electric field at a given point is given by the function

$$E = E_o \cos(2\pi\nu t).$$

with E_o being the maximum value of E. An alternative expression for E as a function of position, x, is

$$E = E_o \cos(2\pi x/\lambda).$$

An additive principal, or principle of superposition, may be used to account for the formation of overlapping waves which do not have very large field strengths. For these cases linear optics is adequate to explain both interference and diffraction phenomena, and compound waves can be analyzed into their linear components. These techniques are discussed in standard texts on optics. Analysis of high energy waves requires non-linear techniques.

The waves are referred to as electromagnetic because, in addition to the electric field, there is an accompanying magnetic field, which has a similar sinusoidal variation. Under simple conditions, when there is no transference of energy to the medium in which the wave is traveling, and where all parts of the wave are travelling in the same direction, the magnetic field and electric field variation are in step; the fields are at right angles to each other and to the direction of motion of the wave (Welford 1976).

This wave description of light, or electromagnetic energy generally, is only one interpretation of the energy and by itself does not fully explain all observed phenomena of the energy. An alternative description is a corpuscular theory, currently expressed via quantum mechanics. The quantum view explicates certain phenomena not adequately treated by wave theory but is by itself inadequate to account for other phenomena which wave theory handles nicely. The two representations tend to complement each other; there is, however, still no generally accepted unified theory.

In the quantum theory explanation, light is conceived in terms of a number of discrete quanta of energy radiated by a source. A quantum of energy is called a photon. The energy, E, of a photon is proportional to its frequency. That is,

$$E = h\nu,$$

where h is called Planck's constant (equal to 6.624×10^{-25}). In accordance with Newton's principle of mechanics, a photon tends to travel in a straight line unless acted upon by material forces in some way, thereby producing phenomena known as reflection, refraction, diffraction or dispersion.

ILLUMINANCE, REFLECTANCE AND LUMINANCE

When photons, or waves, of light energy interact with the configurations of atoms and molecules making up the surface of an object, the energy may be widely scattered, or dispersed. Most objects have this diffusely reflecting property, namely, that the angle of reflection of photons from the surface of the object is largely independent of the angle of incidence of the light to the surface. For this reason it is easy to characterize the light as belonging to the surface, thus to define its luminance.

Smooth surfaces, contrariwise, tend to reflect light uniformly. A mirror, for instance, reflects light almost completely in one direction, such that the angle of reflectance equals the angle of incidence.

We presume that light waves originate at some source. For the tennis player this is normally the sun, though indoor tennis under artificial light is a growing pastime. It is light from such sources that interacts with surface structures to produce what we know as visibility. The energy emanating from a source is generally called radiant energy, and in the special case of light, with which we are here concerned, the corresponding term is luminous energy.

This difference in terms recognizes the distinction between radiometry and photometry, disciplines which are concerned with measuring electromagnetic energy. Radiometry is the more general field, dealing with energy regardless of whether it can be "seen" or not; whereas photometry deals only with that segment of the electromagnetic spectrum that is the stimulus for sight. Over the years these two disciplines have generated different sets of corresponding terms to deal with the various concepts involved, and fairly recent agreements have established a quite common nomenclature. The terms are summarized in Table 2.2.

Radiometric terms apply to any portion of the electromagnetic range, but the photometric terms apply only to the visible spectrum. There is a fundamental difference between the two areas, because of the variation in visual effectiveness over the visible region of energy. The capability of the visual detector is not uniform over the spectrum. That is, equal radiant powers of different spectral energy, such as green and blue, for example, do not translate into equal brightness to the eye for these colors; the eye is more sensitive to green than it is to blue.

A luminous efficiency curve showing the variation in sensitivity is given in Figure 2.7. From this curve it is clear that the peak sensitivity is about 550 nm (nanometers, or billionths of a meter). The sensitivity fades to zero at about 400 nm at the low end and at about 700 nm at the high end. Outside of this range, electromagnetic energy is not generally visible, which is to say the energy does not stimulate the visual processes.

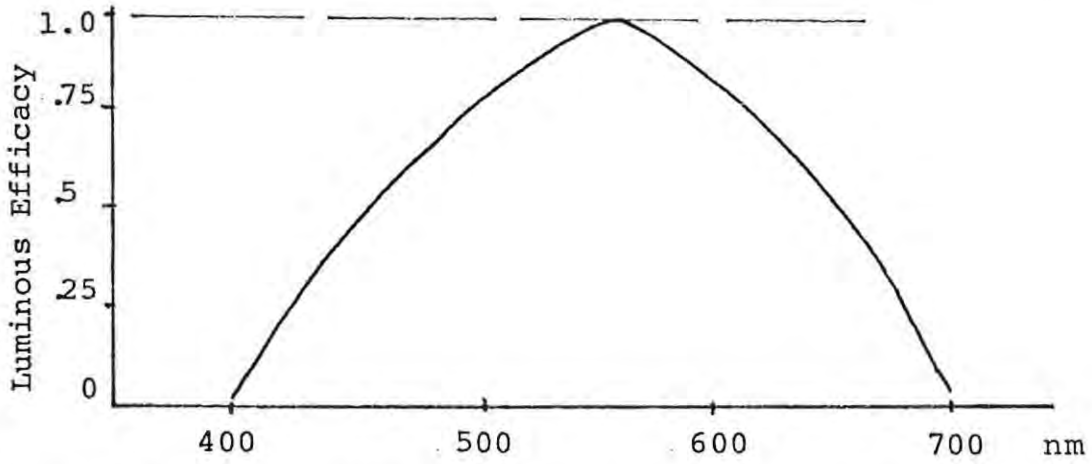


Figure 2.7 Relative sensitivity of the eye to light of different wave length. (From Kaufman 1974)

In order to convert radiometric values into photometric values for a given wavelength, the relative visibility of the light has to be considered. There is no standard sensitivity curve that applies precisely for all detectors (eyes), simply because eyes are different from one person to the next. But the curve of Figure 2.7 gives at least a first approximation, to which corrections for the individual case can be made.

Very few objects of ordinary experience are visible by virtue of being self-illuminating; most are seen because light shines on them and is reflected by them. Incident light illuminates an object, the object's surfaces redirect the energy flow away from them, and by virtue of the reflected light the object becomes luminous.

Luminous power is the quantity of radiant power, namely, the radiant energy transferred per unit time, that produces a visual sensation in the human observer (Meyer-Arendt and Jurgen 1972). The unit of luminous power is the lumen. Outside of the visible spectrum the term, lumen, does not of course apply, for no amount of radiant power can produce a visual sensation. Within the visible portion, however, the amount of radiant power required to produce a visual experience varies with the wave length of the energy. The variation is in accordance with the sensitivity curve given in Figure 2.7.

From Figure 2.7 we can see that below about 400 nm, no amount of radiant power can be effective; the effectiveness is zero. At slightly <u>above</u> 400 nm, however, the eye is able to see, but just barely. A relatively large quantity of radiant power is necessary merely to break the threshold of visibility. Luminous power is thus a very small fraction of the radiant power. At 410 nm, for example, the luminous efficacy is only .001. This means that one unit of radiant power produces only .001 units of luminous power.

For increasing wavelengths, up to about 550 nm, decreasing quantities of radiant power are needed to pass the visual threshold, the eyes being more sensitive to wavelengths in the middle range of the light spectrum. An equivalent way of saying this is that a unit of radiant power produces increasingly more luminous power with increasing wavelength. And at 550 nm, one unit of radiant power corresponds to one full unit of luminous power. A unit of radiant power, as can be seen in Table 2.2, is the watt, so 1 watt of radiant power corresponds to 1 lumen of luminous power at 550 nm.

The constant of proportionality between the watt and the lumen is 680, so one watt of radiant power at 550 nm actually equals 680 lumen. Combining the proportionality constant with the luminous efficacy for specific wavelengths, we can see that one watt of monochromatic light at, say, 410 nm is .001 x 680 = .680 lumen.

Above 550 nm, the sensitivity of the eye decreases, so a unit of radiant power produces lesser and lesser quantities of luminous power. Beyond about 700 nm, then, no amount of radiant power is productive of the experience of light.

The term, luminous power, characterizes the light emanating from an object. If the object is not self-illuminating, the quantity of luminous power depends on the power incident on the object, i.e., on the illuminance due to a light source, and on the reflectivity of the object, i.e., on its reflectance. For instance, under the same lighting conditions, white paper reflects more light than black cloth; it has a higher reflectance.

Illuminance is the luminous power per unit area incident on a surface. One common unit of illuminance is lux, measured in lumen/m^2. If reflectance is considered to be the ratio of reflected light to incident light, then luminance is defined as the product of illuminance and reflectance. Luminance is then expressed in lumen/m^2.

More commonly, however, luminance is defined as the luminous power that leaves a surface per unit solid angle and unit projected area of that surface, or luminous intensity per unit area. That is,

Radiometric Term	Unit Name	Photometric Term	Unit Name
Radiant energy	Joule	Luminous energy	talbot
Radiant energy density	Joule/m^3	Luminous energy density	talbot/m^3
Radiant power	Watt	Luminous power	lumen
Radiant intensity (power density)	watt/steradian	Luminous intensity (power density)	candela
Radiance	watt/m^2-steradian	Luminance	candela/m^2
Irradiance	watt/m^2	Illuminance	lumen/m^2

Table 2.2. Comparison of Radiometric and Photometric terms and units. (After Meyer-Arendt and Jurgen 1972)

$$\text{Luminance} = \frac{\text{Luminous power}}{\text{Solid angle x area}} = \frac{\text{Luminous intensity}}{\text{Area}} .$$

Luminous intensity is commonly measured in candela, or lumen per steradian. Taking square meters for area, luminance has the unit, candela/m^2.

Luminance is still expressed in several different units, such as millilamberts and candela per square centimeter. To reduce the confusion due to a wide variety of names and units, a table summary of the more important terms and their conversion coefficients is presented in Table 2.3. Conversion is accomplished by multiplying the item on the left by the coefficient to get the item at the top.

	candela/ft^2	lumen/ft^2 (ft-lambert)	candela/m^2 (nit)	lumen/mm^2 (millilambert)
candela/ft^2	1	3.142	10.76	3.38
lumen/ft^2	.318	1	3.426	1.076
candela/m^2	.0929	.292	1	.314
lumen/mm^2	.296	.929	.0318	1

Table 2.3. Conversion factors for luminance units. (After Meyer-Arendt and Jurgen 1972)

For white paper in sunlight, luminance ranges from 10^2 mL (millilambert) to 10^4 mL, while 10 mL is considered normal for comfortable reading (Haber and Hershenson 1973).

Illuminance is also expressed in a variety of different units. Table 2.4 gives conversion factors for some of them, such as foot-candela, which is really lumen/ft^2.

	lumen/ft^2 (ft-candela)	lumen/m^2 (lux)	lumen/cm^2 (phot)	1000X lumen/cm^2 (milliphot)
lumen/ft^2	1	10.76	1.076×10^{-3}	1.076
lumen/m^2	,0929	1	10^{-4}	.1
lumen/cm^2	929	10^4	1	10^3
lumen/mm^2	.929	10	10^{-3}	1

Table 2.4 Conversion factors for Illuminance.

Luminance is defined as the photometric brightness of a surface. This does not, however, characterize the light striking the retina. The light incident on the retina is the luminance at the cornea times the cross-section or area of the pupil (the opening of the iris).

If luminance is expressed in candela per square meter and the area of the pupil is expressed in square millimeters, then retinal illuminance is given in trolands. We first express millilamberts in terms of candela per square meters. That is,

$$1 \text{ millilambert} = \frac{1 \text{ lambert}}{1000} = \frac{1/\pi \text{ candela}}{1000 \text{ cm}^2}$$

$$= \frac{1/\pi \text{ candela}}{10^3 \text{ m}^2/10^4} = \frac{10 \text{ candela}}{\pi \text{ m}^2}$$

Retinal illuminance, I, is then given by:

$$I = \frac{10 \text{ candela}}{\pi \text{ m}^2} \times 10^3 \times 4\pi \text{ mm}^2 = 4 \times 10^4 \text{ trolands.}$$

This expression does not give the true illuminance of the retina for the given luminance, because there is a natural loss of energy in the eye due to corneal reflection and to absorption of energy by the fluids of the eye as well as by the wall of the eye. Thus, a transmission factor must be incorporated in the formula. This factor is the ratio of the intensities of light falling on the retina over the light falling on the cornea.

It should be noted that retinal illuminance is independent of the distance from which an object is viewed, except when the distance is large enough for the particles in the air to attenuate the contrast between the image and its background. Under these conditions, the decrease in intensity of light with distance is exactly balanced by the increase in density of the retinal image, which is decreasing in size (Kaufman 1974, pp. 36-7).

REFRACTION AND LENSES

In this section we continue to assume that light travels in a straight line unless acted upon by material forces. As we saw in the previous section, light can be reflected when it interacts with the surface molecules of a material object. Light can also be refracted. Electromagnetic energy, generally, and light in particular, has the property that when it passes from a medium of one density (such as air) to a medium of another density (glass, water, etc.), the velocity of the energy changes.

The velocity difference depends partly on the wavelength of the light, monochromatic light of shorter wavelength changing more than that of longer wavelength. That is, the change in velocity varies inversely with the wavelength. This can be shown easily by passing light of mixed colors through a wedge-shaped prism. A narrow beam of white light from the sun, for example, displays the whole range of colors of the visible spectrum.

However, we ignore differences in wavelength here. It is common practice in the design of many kinds of image-forming optical systems to consider differences in wavelength negligible and to use the concept of a ray of light in conjunction with wave fronts to deal with the systems. This practice of Geometrical Optics is followed for the discussion of refraction.

The velocity difference also depends on the relative optical density of the medium of refraction, and it is this property that we examine in more detail. If light passes into a higher density medium, its velocity is decreased; and if it passes into one of lower density, its velocity is increased.

To appreciate the effects of a change of velocity of light on its path, consider a beam of parallel rays in air incident on a boundary with glass at an angle, θ, as in Figure 2.8..

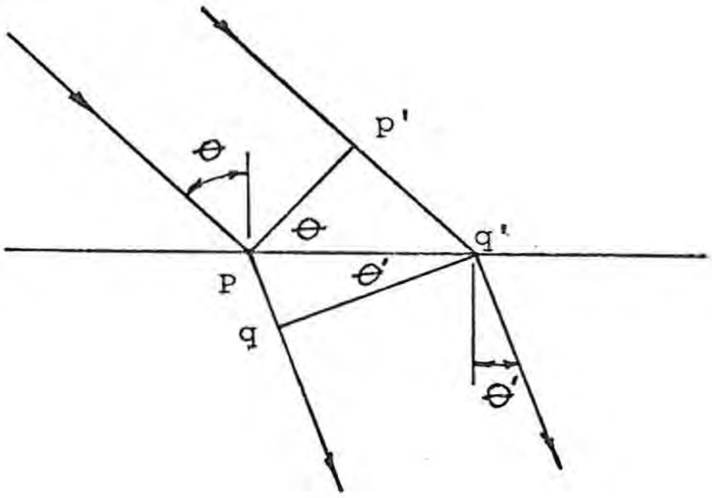


Figure 2.8 Snell's law obtained from wave theory. (After Welford 1976)

Glass is optically more dense than air, so the light is slowed on entering the glass. Let pp' be a wavefront of the incident beam which meets the surface at p at time zero, say. After a time t, p' has reached the surface at q' and p has moved on to q. We plan to equate equivalent expressions for time, so we write

$$p'q' = vt \qquad \text{and} \qquad pq = v't,$$

where v' and v are the velocities of the rays p'q' and pq, respectively. Replacing p'q' and pq with their sine equivalents we get

$$pq'\sin\theta = vt \qquad \text{and} \qquad pq'\sin\theta' = v't.$$

Elimination of pq' yields

$$\frac{\sin\theta'}{\sin\theta} = \frac{v'}{v}$$

which is Snell's law.

Relating each of the two media to a vacuum, we may put $v/c = 1/n$, where c, as before, is the velocity of light in vacuum and n is the index of refraction of the related medium. Substituting $v = c/n$ and $v' = c/n'$ in the above form of Snell's law yields another form:

$$n'\sin\theta' = n\sin\theta .$$

By virtue of this property of refraction, lenses may be ground to optical specifications. For instance, the convex lens in Figure 2.9, having two interfaces with air, converges parallel incident light rays to a point, the distance to which is called the focal length, f. Light rays that enter the lens medium (say glass, or plastic) are bent toward the normal of the point of entry, and rays that exit the medium are bent away from the normal of the exit point.

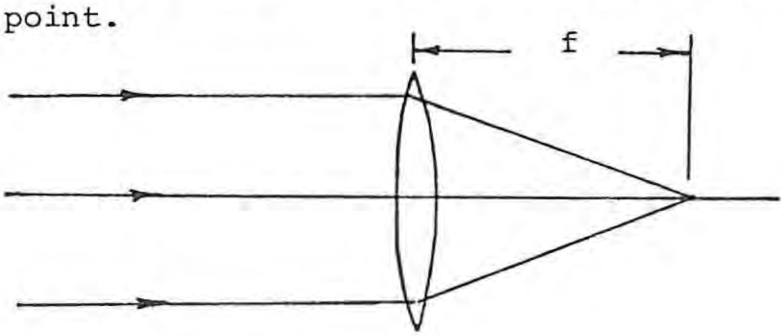


Figure 2.9. Convex lens.

Compound lenses may be constructed by joining together layers of properly ground materials. Lenses of plastic and glass may be joined, for example, perhaps with an intermediate layer of water, or air. The refraction of the compound lens, taken as a unit, can then be specified as a function of the indices of refraction of the separate layers making up the lens. With appropriate design, compound lenses of very high quality can be constructed, because defects like spherical abberration can be neutralized. (Spherical abberration is a distortion of most single element lenses because of which rays from the periphery of the lens fail to converge to the focal point. This produces a bluring of the image.)

THE EYE AS A LENS

We will see in later chapters that physiological or psychological optics has to be considered to account for the phenomenon of sight. Before our tennis player can actually "see" the ball, he must engage actively in a process of perception -- a complex personal response to a stimulus that acts on the rods and cones that form his retinas.

The stimulus itself is a light-density pattern or so-called proximal image that forms on the retinas. This is the result of a complex physical process involving the passage of light rays through the eye, a multi-layered, light-converging structure like a compound lens. The individual is not visually aware of this occurrence; he doesn't actually "see" the light striking the retinas. In fact, he need not even be alive for it to happen; the retinal image can be observed in the eyes of a cadaver, or in an eye which has been removed from the eye-socket. In this respect the eye, like the rest of the body, is part of the physical environment and is subject to the same conditions of visibility as other objects.

The optical layers of the eye consist of the cornea, the aqueous humor of the anterior chamber, the lens, and the vitreous body. These elements are shown schematically in Figure 2.10. The cornea and the lens are the principal optical elements responsible for sharp retinal image. Though they are living structures, their optics are similar to those of an advanced lens design.

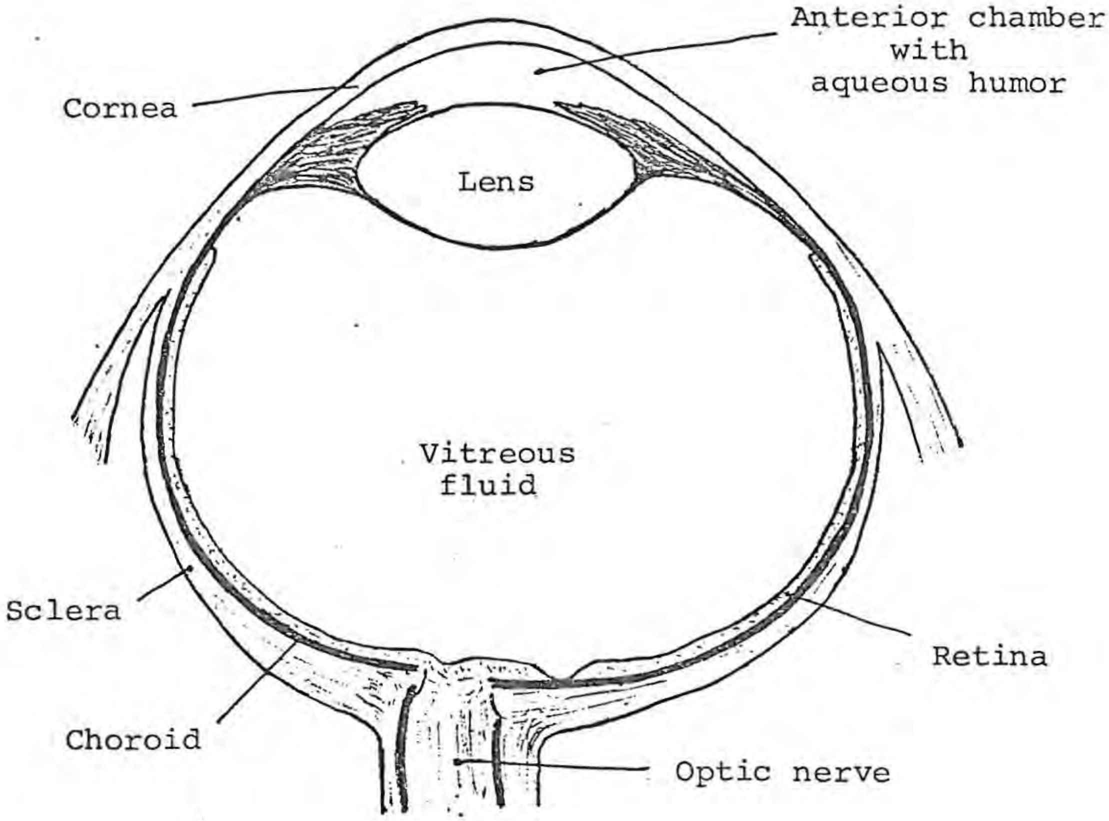


Figure 2.10. The eye. (From Kaufman 1974)

The cornea is the tough, front covering of the eye and is the most powerful of the focusing elements, being about three times as powerful as the lens (Miller 1979). It has a steep, spherical shape centrally and tends to flatten peripherally. Because of this shape it greatly reduces spherical abberration. The refractive index of the cornea is about the same as that for water; for this reason its refractive capability under water is practically neutralized; in passing from water to the cornea, the rays bend only very little.

The lens is a structure of densely packed, elongated, non-nucleated, transparent cells. As one would expect, its focusing power depends on its index of refraction; but it also depends on its shape, and this enables the eye, under control of the brain, to accommodate to objects at different distances, i.e., to change its focal length to bring near or far objects into focus. However, like a tree that accumulates rings as it grows, the lens adds new cells. This addition of cells thickens and stiffens the lens, making it less elastic, so the degree of accommodation decreases with age. The lens also yellows with age, and this tends to filter out bluish colors (Miller 1979).

The aqueous humor of the anterior chamber and the vitreous humor also contribute to the refraction of light rays, but their role in this regard is relatively minor compared to that of the cornea and the lens.

DISTAL AND PROXIMAL STIMULI

Dealing with stimuli, the psychologist makes an important distinction between distal and proximal stimuli. If the rays of light are considered to emanate from an object, pass through the eye and focus on the retina, the terms can be understood to refer to the distant and near "attachments" on those rays, viz., the object itself and the image of the object on the retina, respectively. The distal stimulus is the object of the environment; it is situated in physical space away from the sense organ. A proximal stimulus, on the other hand, is located at the sense organ itself, in this instance on the retina of the eye.

To perception psychologists the stimuli are physical. Only the distal stimulus is considered to be independent of the observer, however. The object has its own properties, which can be determined scientifically, or objectively, without regard to the observer. These properties do not come under the influence of that observer; they do not simply appear or disappear as the observer opens or closes his eyes.

The proximal image, however, is definitely affected by the condition of the observer's eyes or by how he moves them. If, for example, he changes his line of sight, the image would shift across the retina and possibly out of his visual field, though the object would not necessarily have moved. The image will be brighter or dimmer, according to the extent his eyes are open; closing his eyes will eliminate the proximal image altogether. If he moves away from the object, the image will get smaller; and the closer he is, the bigger the image will be.

It should be understood that this dependence of the proximal image on the state of the individual does not render the image non-physical or non-objective. To this extent at least, the observer is part of the physical world, and the image can be examined objectively. The relationship between the distal and the proximal images is strictly physical and can be expressed in terms of the principles of physical optics. This relationship is illustrated in Figure 2.11, in which the refractive property of the eye is represented by one double-convex lens, whose index of refraction is equivalent to the effective index of refraction of the eye, taking into account the indices of refraction of its various layers.

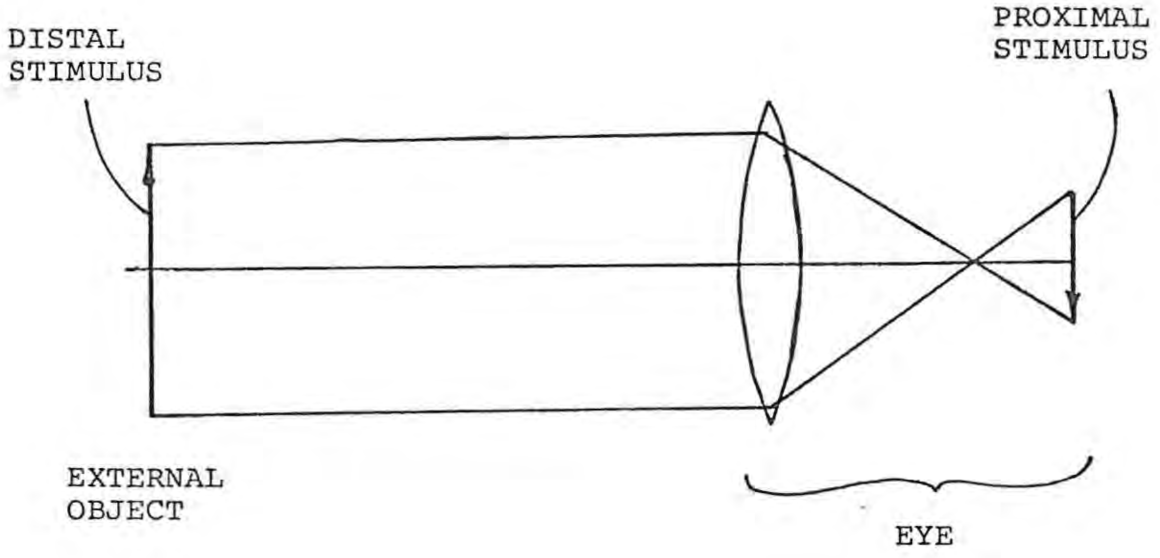


Figure 2.11. Distal and proximal images of the visual environment.

CHAPTER 3

TIES WITH THE OUTSIDE WORLD

The human being is a versatile organism that collects information about the world around him, remembers some of it, but also forgets. His sense mechanisms lack a high degree of accuracy, yet have great flexibility; eyes and ears that are unable to detect fine-grain detail can still identify a wide range of patterns.

His walnut-shape brain is an unlikely instrument for transforming incoming signals into organized behavior, but it has a remarkable facility for making on-the-spot decisions, and can render fine works of art and perform astonishing athletic feats, involving the phasing and coordination of many detailed movements.

In this chapter we examine the individual's connections with the outside world and look specifically at the interaction of the tennis athlete with his court environment. It is taken for granted that the objects of the environment are real, and it is also presumed that physical energy in one form or another stimulates his senses. The problem is to understand how the physical energy is interpreted, or coded. This presents certain difficulties.

In the first place, the eye, as the player's most important data source, provides only two-dimensional information; topologically, the retina is a plane surface. Furthermore, the energy that stimulates the senses is not the energy that is transmitted to the brain; it is transformed into electro-chemical energy. In addition, the energy to the brain is, itself, controlled and shaped by the brain. The organism influences what it perceives and can affect the way it behaves.

AN INFORMATION FLOW MODEL

One approach to the study of this individual-environment interaction is to configure it as an information flow problem with feedback. In a model presented by A. J. Welford (Figure 3.1) the flow of information has three stages: perception, translation, and action. Feedback lines from action to perception through the environment and the individual close the loop.

In the first stage, external and internal stimuli act on peripheral and internal sensors, respectively, and are coded by the perceptual mechanism; i.e., data is synthesized, or integrated, into meaningful psychological units by the eyes, ears, nose, skin, and the kinaesthetic sensors in the muscles, tendons and joints. Both spatial and temporal integration occur.

In the second stage, the translation mechanism selects data for retention and combines perceptual data with stored information to elect a course of action. In the third stage the central effector mechanism converts the choice into phased and detailed muscular action. Incoming data is thus integrated in the perceptual mechanism, coded into memory, coded again for decision-making, and finally converted into appropriate messages (rules or plans) for detailed muscular action. Consequences of the action on the world (which includes the actor) are "fed back" to be perceived by the actor, and the cyclical process continues.

In the contact with the "outside world" some of the converted energy appears to be retained by the organism for future use, encoded as memory (possibly by means of reverberating circuits, as discussed below). Fresh inputs, evidently with the support of memory, employing decision rules and rules of action, are integrated into perceptual experience. This is to say that a source of intelligence uses knowledge and skills actively to interpret the energy and create a semblance of the real world.

To effect the integration of our present situation, we appear to apply categories of organization, or schemata, derived from

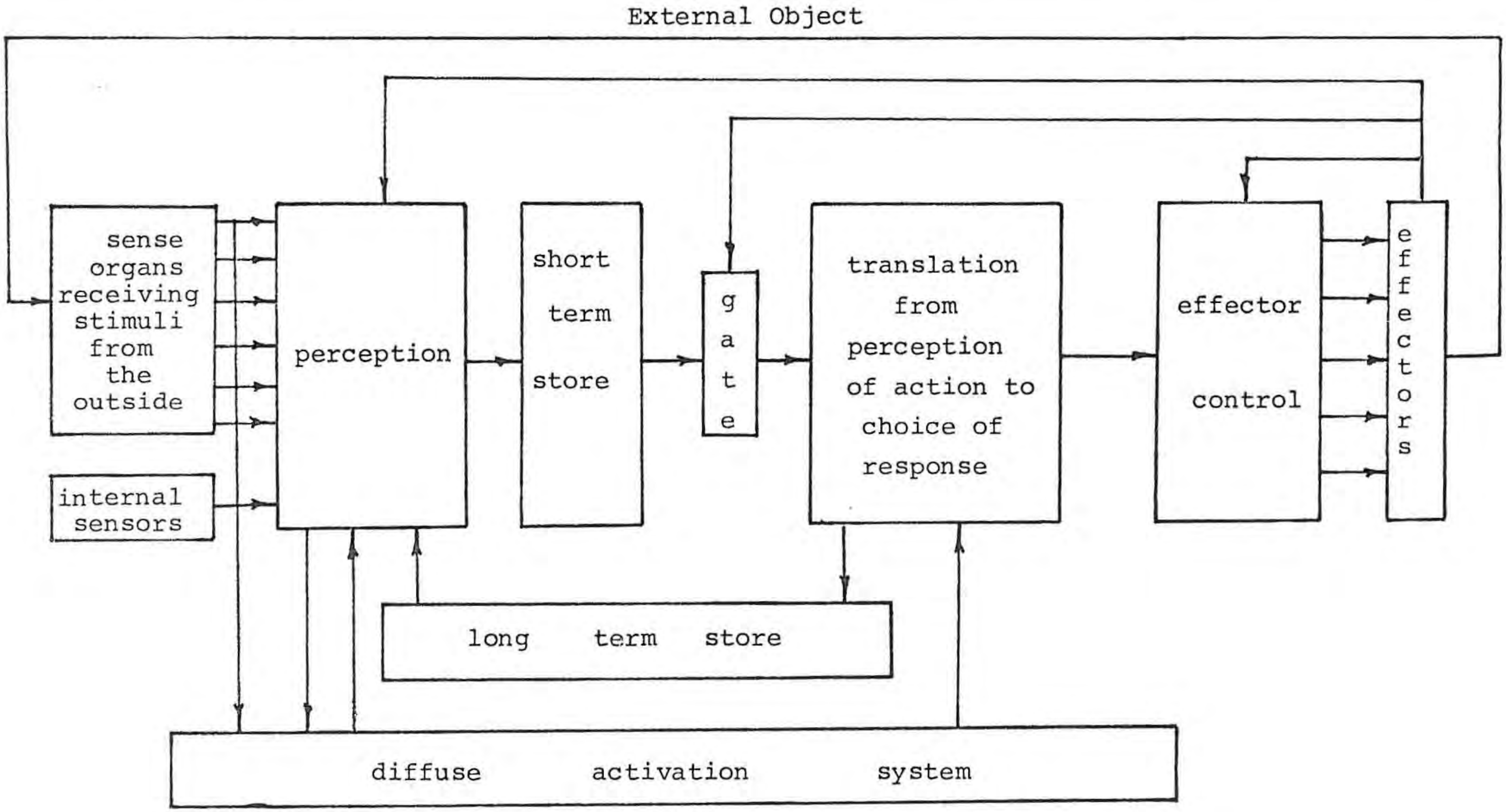


Figure 3.1. Hypothetical information flow model in the human. (From Welford, 1976)

our knowledge of previous events. We do so in a practical or economical sort of way, according to the dictates of the particular situation; the resulting experience has operational value but doesn't necessarily correspond with the real world.

> (We) often neglect data actually present but not in the imposed schema, and 'perceive' data in the schema which are not in the actual situation. Any data which do not fit the general schema but are nevertheless striking, tend to be specified separately. Thus, if we see a car of a particular model, we may fail to notice that one of its usual features is missing, or that an extra feature has been added unless it is very striking, in which case we recognize it as a deviation from the standard article. The whole process can be regarded as an attempt, albeit usually unconscious, to account for the maximum data in the minimum terms.
>
> Similarly, motor performance does not consist of a miscellany of discrete actions, but depends on coherent, learnt sets of rules for translating from perception to action. A simple example is the relation between written and spoken language which, once learned, becomes seemingly automatic. At a more complex level, rules of this kind are the basis of techniques and procedures which we tend to apply as wholes although with minor modifications to suit the circumstances. For example, there is a fundamental core of technique in any motor performance such as athletic exercise or the playing of a game, although many details of method and strategy vary according to circumstances, and some parts of the routine may not always be appropriate. A striking example of this last point is when an experienced cyclist attempts to ride a tricycle: the co-ordination of balance with movements of the handlebars essential for riding a bicycle is no longer appropriate, and a rider quickly finds himself with the tricycle handlebars held firmly in an extreme turning position.
>
> Analogous integration occurs in effector control, where the detailed actions of, say, throwing or jumping are automatically adjusted in a way that takes account of factors such as initial posture and firmness of stance. (Welford 1976, p. 55-6)

Economy of effort in the perceptual-motor processes can be achieved by combining many small items of data into fewer larger ones, or by taking actions in terms of a relatively few rules rather than by making many ad hoc decisions.

> Even if the perceptual schemata and rules of action we apply have to be modified to suit particular circumstances, the effort involved will often be less than that required to construct an entirely new schema or rule. (Welford 1976, p. 56)

Another economic factor is the precision with which coding occurs. In perception, the degree of discrimination appears to depend on the peculiar requirements of a given task. Thus, if one is crossing the street, it may be sufficient merely to note whether cars are coming and not take much notice of their make or color. However, if one were waiting for a friend's car to come by, finer distinctions between the cars would be needed.

> Similar relationships between precision and requirement can be seen in the ability to identify 'absolute pitch' acquired by musicians. This ability appears to imply that the internalized scale against which musicians judge any incoming note is much more detailed than that of those less professionally involved. The same kind of refined ability is seen in other occupational settings, for example the discrimination of hue by dyers, or by furnacemen who judge the temperature of molten metal by its color. The capacity of such judgements seems to have little to do with basic auditory or visual capacities except insofar as these may be limiting if they are very poor: it seems to be much more a result of learning. (Welford 1976, p. 56)

In the motor function, the economy appears to be reflected by the relations between speed and accuracy of movement. For simple hand movements, for example, the time taken from a starting point to some target depends upon the length of the movement and the precision required for its termination, i.e., the size of the target at which it is aimed. The subject tends to act by making a series of submovements, which tend to be progressively shorter and slower. The larger the target, generally, the fewer and faster the sub-movements. These submovements

> more or less run into each other, but can be distinguished by slight accelerations and decelerations in the course of the movement as a whole. (Welford 1976, p. 56)

Greater economy in movement is attained by learning 1) to adjust the balance between speed and accuracy so that the movements are neither too slow due to excessive precision nor too inaccurate and 2) to be more precise and reliable in the operation of the translation and effector control mechanisms in initiating movements, so that the required degree of accuracy can be attained without having to monitor and visually correct the movements. (See Picture 3.1 for a good example of professional coordination of speed and accuracy of movement.)

> When this stage is reached time is saved, not only because attention does not have to be diverted from the task as a whole to monitor the details of actions taken, but also because action can flow smoothly without having to be interrupted or modified to correct errors. As a result, the practiced, skilled performer has less to do than the novice. His performance becomes less jerky, appears to be more leisured, and its efficiency makes it less liable to fatigue. (Welford, 1976, p. 57)

It is evident that temporal as well as spatial integration is involved in these processes. In visual perception, integration over time is important with regard to moving objects, sequences of events and the comprehension of structures too large to be observed in a single glance. It is the mechanism whereby one is able to recognize a pattern running through a succession of spatially coded items.

In motor processes, the effect of temporal integration is to combine sequences of muscular contractions into unitary wholes.

> Just as in perception a whole sequence of events is coded into a single complex event, so on the motor side a complex action is a coding of a series of detailed movements as a unified sequence. These so-called motor programmes are necessary for three reasons. First, the time required to decide about each detailed movement separately would be so long that the performance as a whole would be extremely slow and uncoordinated. Second, the fact that it takes an appreciable time to react to any event means that, in a developing situation, such as shooting at a moving target, or running to intercept another player at football, or placing the racquet to return a ball in tennis, action is required not in response to the situation that exists when the need for

Picture 3.1. Brian Quinn giving Tommy Kristianson a sample of skillful ball handling. (Photo by Brad Graverson)

> it is perceived, but in order to meet the situation as it will be when the action becomes effective. Third, the time required to react means that an ongoing action cannot be modified immediately, but has to run on for a brief period after an error has been detected before corrective action can become effective. (Welford 1976, p. 57)

Occurrence of reaction time and the operation of the gate (as in Figure 3.1), whose function is to protect the activity of the translation mechanisms from interference by new data before the effects of previous data are completed, forces the conclusion that the player is committed to actions for a short time ahead of their initiation and cannot adapt immediately to changed circumstances. The interval may be very short in absolute time -- perhaps no more than a fraction of a second -- but for the tennis player this could be crucial. If during an exchange of volleys, for example, the receiver places his racquet where he expects the ball to be, but the ball just ticks the top of the net and is deflected over the racquet, he may find it impossible to recover sufficiently to make a good shot. Or he might slip, accidently, and not be able to recover his balance before falling.

> These limitations can sometimes be reduced by practice which reduces reaction time, but they can never be completely eliminated. Experience and skill resulting from practice exert their effects rather by improving prediction and rendering the movements in the programme more accurate and better coordinated. Opportunities for improvement with experience also exist on broader scales of performance. The very short-term programmes . . . have counterparts in procedures, plans and strategies of performance which guide actions over much longer periods of time. In these cases there is, of course, opportunity to modify action in the light of intermediate results, but the benefits of practice and experience in bringing improved prediction and more accurate execution of action apply in these longer-term cases also. (Welford 1976, p. 58)

PARALLELS WITH A MACRO SYSTEM

As Welford points out, the short-term programs of the athlete have counterparts in the procedures, plans and strategies guiding the actions of longer-term systems. These larger, macro systems have visible intermediate stages which might generate information useful to the study of the less visible "micro" systems, like the athlete. With this in mind, we compare our tennis player with a mobile man-machine complex, viz., a submarine.

Like the tennis player, a submarine has a variety of sense mechanisms. For example, it uses sonar, radar, and direct visual sightings to detect the presence of targets, each information source having its own type of coding, or mode of data representation. It uses inertial guidance, stellar sightings, or the traditional sextant, among other techniques, to navigate or keep track of its position and heading. Again, each of these techniques has its own method of coding data, its own language. And the submarine has a memory bank, containing such data as patterns of ships and other submarines it might detect.

We can assume that the information from the sensors is fed to the control room of the submarine, where the Commander can select whatever data he wants. By channel select switching he has access to -- can attend to -- past or present information, relating either to the external environment, the internal environment (such as fuel, weapons, or personnel), or to navigation and guidance.

Given his mission and the current location and status of his vessel, the Commander "reads" his current situation and decides what action is appropriate. Since his "mission" is normally characterized by a <u>set</u> of different objectives rather than a single one, he is faced with a multi-decision problem, the components of which are very likely to be interdependent, the solution of one depending on the solution of the others. In this event he has to rely on some kind of "feel" to cut through to a solution.

The tennis player is confronted with a similar task, though the alternatives are generally less obvious. Like the Commander, he has to contend with a number of objectives simultaneously, and he has to decide quickly and accurately what best to do in any given situation, relative to those objectives. That is, he must be attentive to the regulatory cues, evaluate their significance, and select a course of action that meets the demands of the current conditions of the game. These decisions are made on an on-going basis and may be determined ad-hoc or in accordance with rules and principles.

Based on his decision, the Commander issues an executive order to the system's response units -- the system's power and steering units and/or his fighting units, such as surface guns or torpedos. The comparison here with the tennis player's muscular structure and his racquet is apparent. Computations are involved in both the submarine steering command and in the orientation of the submarine's firing power. The computations must take into account the target's motion. This is, the Commander must anticipate where the target will be at the presumed moment of intercept of shell or torpedo with the target. If for instance, he fires at the point where the (moving) target was last seen to be, the target will have moved from the location before the moment of intercept. Circumstances thus dictate a feedforward computation.

The action that the Commander takes occurs in the physical environment and the result is reflected in what is next observed by the submarine's sensing devices. The result may be favorable or unfavorable. The target may have been damaged or it may not have been affected. In any event, the results are viewed by the submarine Commander on his display screen, and this knowledge of results, normally understood as feedback, directs his continued response. To be more precise, the feedback is a comparison between the Commander's <u>desired</u> result of the attack and the <u>actual</u> result, and it is the work remaining to be done that directs his continuing response.

An important property which characterizes both the submarine system and the tennis player is one already discussed in part, viz., reaction time. In the detection, identification, pursuit and attack of enemy craft, the time in which the system can respond is of the essence. It can mean the difference between success and failure and must be reduced as much as possible. So too for the tennis player; if he is too frequently slow picking up the trajectory of the ball or moving to intercept it, he could easily lose the game. By the same token, once an action has been committed by either system, there is difficulty altering it. Time is required for the submarine to set up for attack, for instance; and it takes time to recover from that attack profile if circumstances warrent a change. For the player as well, it takes time to get a muscle group into action and then to redirect the energy into another action. It is clear that in both cases the reaction time can be reduced, through training, say. But it is equally clear that one cannot get around the fact that submarines have physical limitations and that players have analogous biological restrictions. Each system has its inherent refractory nature.

In the course of the tracking and intercept functions, certain other actions have to be taken by either the Commander or the player. For example, the direction and speed of the object under surveillance have to be established and a point of intercept has to be estimated. For the Commander the target may be an enemy cruiser; for the tennis player it is the ball. As either makes his move toward the object he must update his estimate of the state of the object, update his estimate of his own status, continue to predict an intercept point and adjust his response accordingly. Meantime he must keep tabs on other pertinent items in his field of responsibility.

The Commander must maintain the appropriate state of alert of his forces; he has to have the latest figures on the state of his reserves; and he needs to keep track of such things as the amount of fuel remaining, ammunition, estimated time to intercept and the relative positions of other tracking units. The tennis player, similarly, has to keep tabs on his opponent, the wind conditions, location of the sun, and the relative location of the net and boundary lines, among other things.

It is clear that each system is an active, self-organizing or adaptive complex. Neither may properly be viewed strictly either in terms of a communications model or a control model, though both communication and control elements are part of the process. Both learning and unlearning, or forgetting, occur in the systems, so there is a continuing change in the quality of the related skills and the nature of the activities. In each there is a great diversity of skills and typically a wide range of competence from one skill category to the other. The Commander may have excellent torpedomen, for example, but only mediocre radarmen; the tennis player may have a great forehand shot but a terrible overhead or backhand. Each system may change its style, the one perhaps by replacing its Commander, the other possibly by getting a new coach. Each may adopt new techniques or pick up new equipment -- the one, hot new torpedos, for instance; the other maybe a new high-tension racquet. As changes occur in style, technique or equipment, there necessarily occur changes in the elements of the class of skills and the competence levels of those skills. Under the circumstances, only an adaptive or self-organizing framework can properly be used to characterize the system. So this kind of structure must be formulated for the simulator.

EMOTIONALLY CHARGED INFORMATION

Study of the information loop in the human organism is made more complicated by the fact that information can be emotionally charged. Reaction to data may differ greatly according as it is pleasant, unpleasant, or neutral in value.

According to Thomas (1964),

> our gaze is averted from something that is distasteful; alternatively, something that has been perceived only too well may be barred from fully conscious awareness. Studies undertaken at the University of Pennsylvania by Lester Luborsky, Barton J. Blinder and Norman Mackworth have shown that people may tend to avoid accepting and remembering visual information that is not associated with heightened emotion (as measured by an increase in the well-known galvanic skin response). They may deny

> that they ever looked at some emotionally charged feature, even though their eye-movement record shows that they had. (p. 148)

When an observer's interest is aroused by what he sees, his eyes tend to move more and more often and there appear to be more corrective jumps serving to bring the image of the object of interest toward the center of the fovea. Relating observations of eye movements of drivers in actual traffic, Thomas (1964) says:

> We saw how the driver's eyes dart about in their search for information. When an automobile is moving, the driver's eyes are constantly sampling the road ahead. At intervals he flicks quickly to the near curb, as if to monitor his position, but for such monitoring he seems to rely chiefly on the streaming effect -- the flow of blurred images past the edges of his field of vision. The edges of other vehicles and sudden gaps between them attract visual attention, as do signs along the roadway and large words printed on trucks. If something difficult to identify is encountered, the fixations are longer and the eyes jump back to view it again. (p. 150)

Not only does much of the incoming data get filtered out at the retina, but also a great deal of the information that reaches the brain fails to become conscious. As Thomas (1964) expresses it:

> In this connection it is startling to watch a film of one's own eye movements. The record shows hundreds of fixations in which items were observed of which one has not the slightest recollection. Yet the signals must have reached the brain because one took motor action and even made rather complex decisions based on information that was received during the forgotten fixation. Parts of the brain appear to function rather like a secretary who handles routine matters without consulting her employer and apprises him of important points in incoming letters -- but who at times makes mistakes. (p. 154)

This kind of behavior must also characterize the conduct of our tennis player and makes evident the effort required to concentrate on his game.

QUANTITY OF INFORMATION

Energy from the outside world impinges on our senses,is transformed into electro-chemical energy and somehow our perceptual world is formed. Physical stimuli such as electromagnetic waves, molecular vibrations and pressure are experienced, respectively, as light, sound and touch. Distances and motions in the physical world have psychological counterparts. We detect odors, feel pain, experience taste. In this complex process we somehow gain information about the world, including ourselves.

Figure 3.1 schematizes the flow of information. The flow is conceived as a three-stage process in which physical stimuli are encoded into percepts, transformed into the language of decision-making, and encoded again in the motor or output phase. But what is this information that is encoded? How are we to understand it?

One approach to a study of the problem applies a theory of information developed by Shannon and Weaver (1949) and Wiener (1948). In this theory, information is expressed as a measure of the decrease in uncertainty produced by a transmitted message over some communication channel. It says nothing about the contents of the message, its importance, or the context in which the message is given, but deals only with the quantity of information. It is a function of the number of possible alternatives from which the message is drawn. For noise free and equally likely alternatives, it is usually expressed as $I = \log_2 n$, where n is the number of alternatives, based on a binary representation of the message.

In the application of the theory to perception, the observer is presumed to be the information carrier. He takes in information from the environment, processes it and executes the appropriate response. If he is a single-channel carrier of information, he can only process one stream of data at a time. But even this involves activating the senses, relating the stimulus to a response and energizing the muscular system.

Each phase of the process takes time to complete and therefore contributes to the overall reaction time, which the player desires to minimize. Time is needed both to identify the stimulus and to translate the information into an appropriate response. But additional time is consumed if there is uncertainty regarding the nature of his stimulus. The uncertainty apparently inhibits early preparation, so the response time is increased. The response time is even longer if the number of stimulus alternatives is greater.

The uncertainty, or correspondingly the amount of information, derives from the probability of occurrence of the chance stimulus. The implication for perception is that, to gauge the probability, one must know the set of alternative stimuli and responses against which the chance event occurs. This entails knowing the properties or features that define the set and differentiate its members. These significances vary according to the perceptual strategy, which may change depending on the phase of perception (discrimination, recognition, identification).

SIGNAL DETECTION

Of critical importance to both the submarine Commander and our tennis player in his excursions through the environment is the ability to detect a target. Detection is a minimum condition for experience. But detection might be faulty. Extraneous information, or noise, can create the impression of the existence of an object in the perceptual field when none is there. And noise can obscure the presence of a real target.

Noise might originate in the environment or in the perceiving mechanism. It might be the result of spontaneous neural firings in the nervous system, for example. Or it could stem from extraneous reflections or reverberations of energy from various features of the topography. There might be deliberate man-made noises to hide an aggressive move. An enemy Commander could be setting up a smoke screen, or the opposing tennis player could be faking a certain shot. There are many possible sources of noise.

The theory of signal detection admits the presence of some degree of noise in every perceptual experience. This means that the target of perception always occurs against a background of noise and that, even when there is no target as such, the stimulus level does not drop to zero. The perceiver is thus always in a position where he has to decide whether the nature of the stimulus warrents a decision in favor of the presence of a target or a decision against its presence.

The theory also maintains that decisions regarding the presence or absence of an object are contingent on the perceiver's detection goals and on the risk he assigns to the two types of error that can be made, i.e., detecting a non-existing target, or <u>not</u> detecting a <u>real</u> one.

Expectation plays a role, too. A submarine Commander moving into a battle zone would be on alert, prepared to encounter an enemy ship at any moment. On the court, too, our tennis player is set and waiting for the oncoming ball. Away from the zone of combat these expectations would be drastically curtailed.

Signal detection theory is thus a statistical detection theory. It is based on the probabilities of occurrence of events in the real world and the perceiver's expectations, or his estimates of the probabilities of those occurrences. (A perceiver with unrealistic notions about the objective probabilities is going to err to the extent of that lack of realism. But good estimation procedure will have an error curve that matches the occurrence probabilities. In that event, a high probability occurrence will yield a high probability detection.)

Signal detection theory is basically statistical decision theory applied to detection. (There are any number of texts on this subject to which the reader may refer. See, e.g., Tanner and Swets (1954, p. 401-9) for its application to visual detection.) In this theory, a normal or bell-shaped distribution curve is presumed to characterize the sensory effects produced either by signals or by noise. Hence, if a signal is added to noise, the result will be a distribution pattern similar to that for noise alone but shifted upward in value in proportion to the magnitude of the signal. This is illustrated in Figure 3.2.

The decision problem is then as follows; Suppose that an observation, 0, is made on a given trial. That observation will have a certain magnitude, according to the circumstances of the signal. There is then a certain probability that an observation of this magnitude is produced by noise and a certain probability it is produced by the signal. In this case, was it noise? Or was it signal?

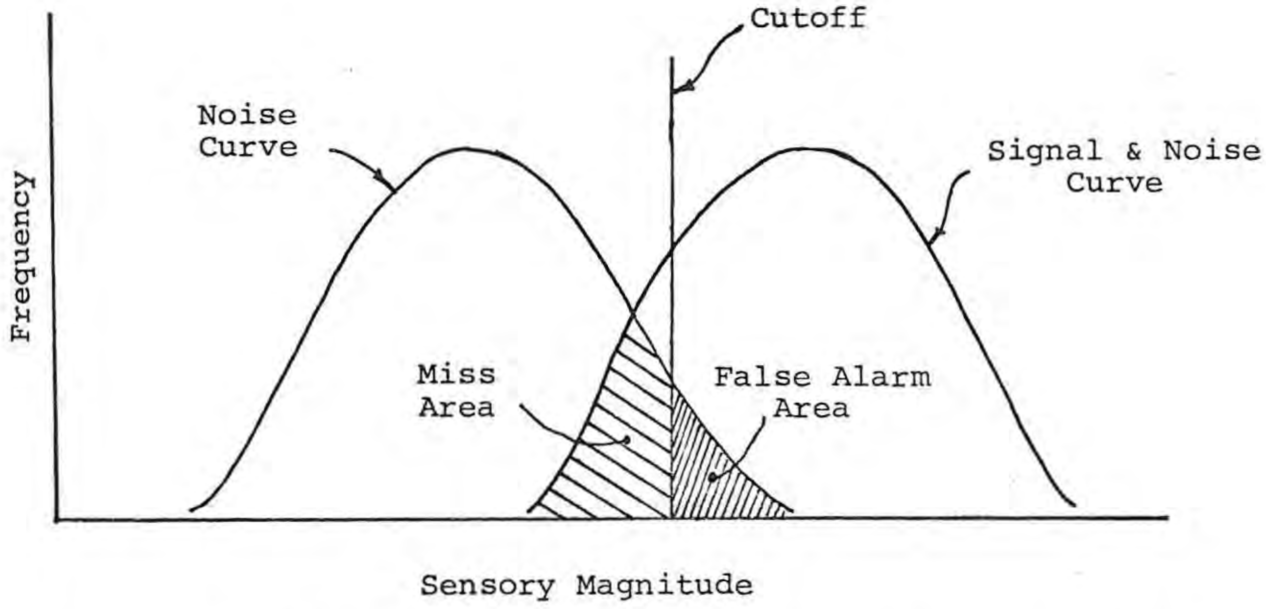


Figure 3.2 Hypothetical sensory effects for noise alone (left curve) or signal plus noise (right curve). Observation magnitudes are given along the horizontal axis, and the relative frequency of the magnitudes is given along the vertical axis. The shaded area identifies the false alarm area; the cross hatched, the miss area.

The procedure specified by the theory to reach a decision is to compute a <u>likelihood ratio</u>, which is the ratio of the probability that 0 was produced by <u>signal plus noise</u> to the probability that it was produced by <u>noise alone</u>. This ratio is compared to a cutoff value. If the ratio equals or exceeds the cutoff value, it is concluded that a signal was present. Otherwise it is concluded that no signal was present.

The cutoff defines the minimum magnitude that can be allowed to indicate that a signal is present. Choice of a cutoff value turns on the tolerance the perceiver has for the rate of false alarms and on his willingness to miss targets. A higher setting indicates greater reluctance to accept false alarms and less concern over failure to detect a real target. For the submarine Commander this is a policy more likely to be followed in peacetime; the cost of a false alarm could be a dangerous international incident. Consequently, should his sonar detect a possibly hostile action by a potential enemy, he would wait for further information before committing himself to an attack. In wartime, however, he would be willing to accept false alarms as the price for vigilance. The setting for a cutoff value would thus be lower.

For the tennis player, a higher setting could reflect a desire on his part to avoid embarrassment. For example, if the ball is moving through a haze or glare, he might prefer simply to let it go rather than risk looking foolish swinging at air. Or, he might rather give up an occasional point than get caught going for a fake shot. With a lower setting, however, he throws caution to the wind. The relative value of a hit is now greater and he is more likely to sound his inner alarm at every feint and swing out at every shot, regardless of the consequences.

LIGHT AS A SOURCE OF INFORMATION

Vision is mediated by light. It is light that irradiates. It is light that interacts with objects in almost limitless variety and detail and moves in a complex pattern to engage the eyes. It would seem, therefore, that light is the means whereby visual information is obtained. If so, what is the nature of the information and how is it obtained?

Two possibilities present themselves. One is that the information is derived from the spatial frequency pattern of the impinging energy wave, the patterns serving more or less as "fingerprints" of the external objects. However, to recognize the many thousands of objects in the visual field, a very complex matching process would be required. Since the objects to be encountered could not possibly be anticipated physiologically, the system would also have to be subject to adaptation through experience. The various patterns must somehow be learned.

The second possibility is that the visual system is directly responsive to the general nature of the irradiation pattern. Not to objects individually, but to all of them collectively. The product could take the form of an underlying metric, or scale of space, within which individuation could then occur.

Granting such a method of spatial referencing, what is there in the nature of the irradiation that provides this kind of information? And what physiological mechanism allows the information to be so derived?

Although we speak of irradiation interacting with our eyes, the fact is that we don't "see" the irradiation at all; it is "invisible". We see objects that are illuminated, and we see colors. But these things can only be phenomenological products of the interaction, not the raw material that goes into their production. Irradiation has a physical counterpart that can be detected by sensing devices other than the human eye, and these devices detect rays well outside the range of wavelengths with which we interact visually. If our perception were not the product of such an interaction, why is not the whole range of rays visible to us? Some kind of interpretation, or coding, is required. It seems clear that the human system is restricted in this respect. But what kinds of information are coded?

An analysis by Haber and Herschenson may help to clarify this point. They ask:

> What are the qualities of visual stimulation that we need to know about in order to perceive the visual world? We must know something about the location of objects in space, where they are, and whether they have moved. We need to know something about their spatial extents, their sizes, shapes, and texture. We need to know something about the scale of space, the distances between objects and their relative sizes, and the

> organization of space. We need to know something about serial order, about what happens before and what is happening next. And we need some way to integrate across the successive retinal projections that occur when our eyes open.
>
> It is obvious that the individual receptors themselves cannot tell us anything about this kind of information. To show that this is so, let us look at the limitations of an individual receptor in providing even the simplest information about the light that falls on it. Where is the light source? From which direction in space did the light come? Where on the retina did the light fall? What is the light's intensity, what is its wavelength, how large is it? What is its duration? For all of these simple characteristics of light, only two can be partially specified by a particular receptor alone -- the intensity of light and its duration. All of the other properties require more complex coding than that available in a single receptor. (1973, p. 36)

If more complex coding than that obtained from single neurons is required in order to generate information about the world, where might it come from? Is there something in the nature of light that enables us to construct a composite, a mosaic, over the set of cells? Is this a characteristic that would be useful in establishing a scale or metric of space?

According to Wald, light only serves to trigger a response.

> The point of vision is excitation; there is no evidence that light does work. The nervous structures upon which the light acts, so far as we know, are ready to discharge, having been charged through energy supplied by internal chemical reactions. Light is required only to trigger their response. (1964, p. 108)

The pigments which absorb the light that somehow stimulates vision are made of Vitamin A, in the form of retinene derived from carotenoids, joined with retinal proteins called opsins. The curious fact is that vision in all of its forms on this planet has come from the same group of molecules, the A vitamins. Wald believes that the key to the special position of carotenoids is their capacity to change shape profoundly on exposure to light:

> They do this by a process known as cis-tran isomerization. Whenever two carbon atoms in a molecule are joined by a single bond, they can rotate more or less freely about this bond, and take all positions with respect to each other. When, however, two carbon atoms are joined in a double bond, this fixes their position with respect to each other. If now another carbon is joined to each of this pair, both (of) the new atoms may attach on the same side of the double bond (the cis position) or on opposite sides, diagonally (the trans position). These are two different structures, each of them stable until activated to undergo transformation -- isomerization -- into the other...
>
> We have learned recently that all the visual pigments known, in both vertebrate and invertebrate eyes, are made with a specifically bent and twisted isomer of retinene. Only this isomer will do because it alone fits the point of attachment on the protein opsin. The intimate union thus made possible between the normally yellow retinene and opsin greatly enhances the color of the retinene, yielding the deep-orange to violet colors of the visual pigments. The only action of light upon a visual pigment is to isomerize -- to straighten out -- retinene to the all-trans configuration. Now it no longer fits opsin, and hence comes away. The deep color of the visual pigment is replaced by the light yellow color of free retinene. This is what is meant by the bleaching of visual pigment by light.
>
> In this succession of processes, however, it is some process associated with the cis-trans isomerization that excites vision. The subsequent cleavage of retinene from opsin is much too slow to be responsible for the sensory response. (1964, p. 111)

Sterling Hendricks agrees that production of this change to an all-trans state is the one and only role of light in vision. But he says:

> The change is followed by several rapid shifts in the structure of the opsin and also changes in the relation of the (vitamin-A; 11-cis retinal) to the opsin. To judge by the time it takes for a retinal-cell signal to arrive at a nerve ending, the signal is induced by the shifts that take place in the first thousandth of a second. (1964, p. 116)

There are actually four types of opsin, one in the rods and three in the cones (each found in a different cone cell), and all four change in the same way on excitation by light.

Combined with 11-cis retinal, they respectively form rhodopsin and three kinds of iodopsin. Absorption spectra curves for the latter show peaks at wavelengths of 450, 525, and 555 nanometers (blue, green and yellow regions, respectively). "The singularity of the nerve associations with the rod and cone cells preserves the retinal detail, or register, in the transmission of the visual signal; the differences in absorption among the three kinds of cones retain the color pattern of the image" (p. 117). The absorption curves for the three classes of cones are shown in Figure 3.3.

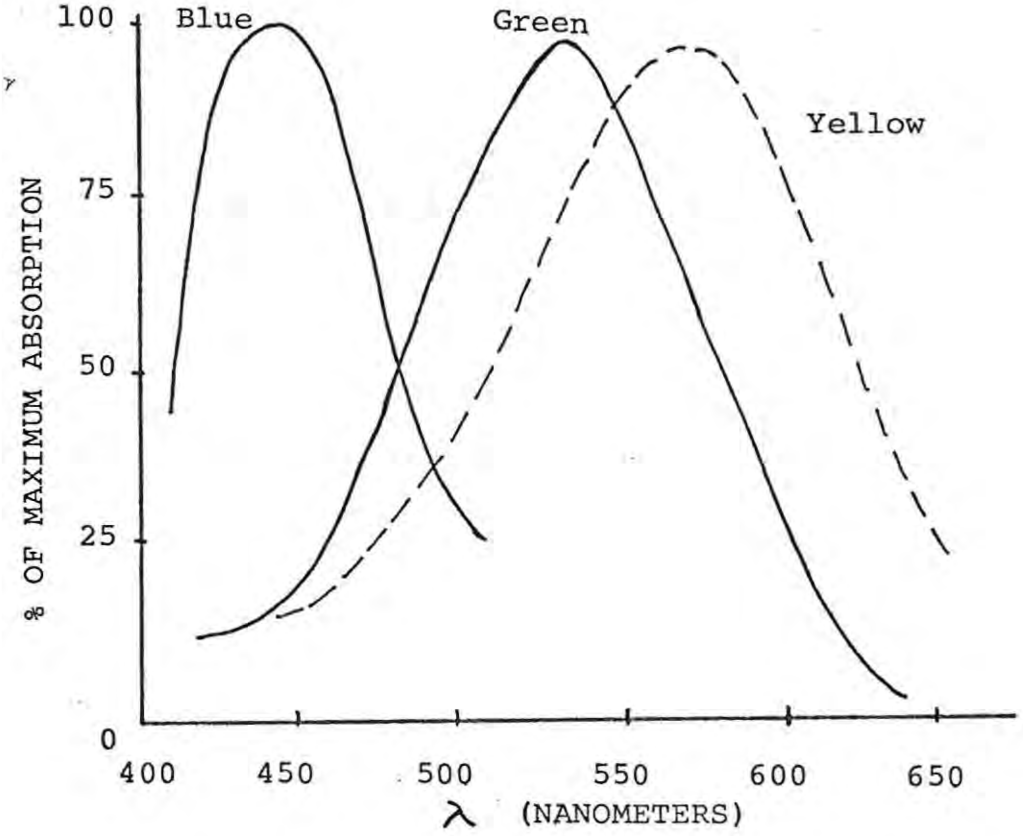


Figure 3.3: Absorption curves for the three different iodopsin pigments. The differences between the signals from each group of cones reflect the color pattern of the image. (From Hendricks 1964, p. 120)

In each case, light acts as a trigger to initiate processes that depend for their energy on the organism's own metabolism. This is another way of saying that the visual system is active, not passive. In other words, the organism does the work.

However, it is one thing to say that the organism does the work, but quite another to identify the work that is done. Common sense tells us that we do indeed interact with real objects and that we are able to acquire, and have acquired, complex knowledge which provides detailed characterization of the objects. Some of this knowledge is concerned with light.

We know that light interacts with objects in different ways. Thus, light is either reflected, refracted, absorbed, or diffracted, depending on the surface characteristics of the objects. The nature of the objects must therefore determine in part the quality of perception. For example, a highly polished surface would reflect light and possibly produce glare. This is common experience on a very smooth tennis court. Again, selective absorption affects the color of objects, so that if, say, the background screen has the same absorbing properties as the ball, the ball would be difficult to track.

Scattering is another important phenomenon. It is due to an interaction of light with a highly irregular surface. Simple reflection will account for some scattering. A coarse-grained playing surface may so scatter the incident rays that essentially no blind spots of reflection occur.

Scattering can also occur because of the absorption and re-emission of light by atoms. For instance, the sky is predominantly blue because higher frequency photons are re-radiated at a greater rate than lower frequency photons. The molecules of oxygen and nitrogen in air vibrate under the influence of any light frequency, but the absorption and re-emission of higher frequency photons is greater by far.

Scattering also occurs because of diffraction, which tends to bend the path of light. It is difficult to separate those photons being scattered by diffraction from those being scattered by absorption and re-radiation by the atoms, but the effect is somewhat less, apparently.

These modes of interaction account for some of the visible properties of surfaces, but they don't fully account for texture, which appears to be due as much to the interplay of light and shadow on the visible objects as to the interplay of light with their molecular structure. But quite apart from the fact that surfaces reflect light, texture itself seems to give perceptual existance to them. Surfaces appear to be real and clearly different from the light, which alone reaches the retina.

Might the overall pattern of light and dark in the field of vision be the source of the metric of space? Perception of depth is certainly enhanced under high-contrast lighting. On a tennis court, for instance, the ball is far easier to see on a bright, clear day than it is on a hazy day when shadows become indistinct. Loss of depth is also evident in photographs of scenes taken with low-contrast lighting.

Unfortunately, however, depth loss can occur as well when the objects are not sharply outlined. In a photograph it is only necessary to use a very grainy photographic process on an otherwise normal scene to reduce the feeling of depth. And the loss of depth on the tennis court may be due as much to the reduced contrast between the ball and its background as to the occurrence of low-contrast lighting. In both situations there is a loss of distinctiveness among objects in the field of view and this alters the feeling of depth.

The blurring can also be caused by myopia or astigmatism. When I look at the world with a naked eye, near objects stand large and vivid against a mushy background of color. In its outer reaches, the scale of space is greatly contracted. Edges of the distant contiguous objects become bundles of overlapping blur lines. For instance, the coffee cup on the far table in the room appears to be embedded in the table surface. The room with its splotches of color seems like an impressionist painting. Why is this? Why the loss of depth?

We saw in Chapter 2 that the eye is a compound lens and that rays of light are refracted as they pass through it to converge on the retina. In a glass lens, if the image screen doesn't coincide with the focal point of the lens, there is a loss of image sharpness. So too in the eye: when the image fails to focus directly on the retina, blurring occurs. A point might then image as a blur circle, and objects will image as overlapping blur circles. We can expect, therefore, that vision will be blurred under these conditions. Due to the overall blurring, objects will be indistinct and so too will be the distance between them. Consequently, there should be a loss of depth.

Since far points blur just as much as near points, far objects will suffer a greater loss of depth, because perspective lines converge with distance and blurring has a proportionately greater effect on object distinctness and distances between them.

This argument seems reasonable enough to me, but the puzzle still remains how perception can be integrated if individual receptors are limited to information about light intensity and duration. Whether vision is blurred or not, information from one cell still has to be conjoined with information from the other cells to generate a unified experience. Some kind of work seems to be required by the perceiving organism. We turn now to the mental side of the individual to try to understand what the work might be.

CHAPTER 4

THE PLAYER'S PERCEIVED ENVIRONMENT

Having examined our tennis player from the point of view of an information processing system, or a comparable man-machine system, we see that he is engaged in a complex interaction with the outside world, collecting information about it, as we say, interpreting or encoding that information, transforming the data into various forms, and generating signals to muscles to effect movement in that world. This all appears rather obvious. Except that now the nature of his ties with that world is not so evident as at first it seemed.

That the player does somehow gather information about the world would hardly be disputed by anyone with common sense. Nevertheless, the manner in which this is done, if it is done at all, is a moot point, requiring considerably more investigation. Whereas, for example, light would appear to be the source, and the only source, of information for the eye, its effect, apparently, is only to trigger chemical reactions in the retina. In this respect it yields no information at all. In this respect, our player cannot know where the ball is. If he cannot know where it is, he cannot track or intercept it. Yet he does so.

Taking a common sense attitude toward the player, it is evident that he is a conscious individual and that he does track the ball and run to intercept it. Now, if he is to track the ball, he must attend to it -- he must detect and identify the ball as a component of his environment and maintain consciousness of it long enough to be able to bring his racquet to bear on it.

In this chapter we examine some of the psychological aspects of this tracking problem. In Part II (Chapters 5 through 9) we will take a more detailed look at the underlying neuromuscular components involved in the visuo-motor processes. But here the emphasis will be on the nature of consciousness, mental representations, and information as understood within the context of the player's mental space -- the mind that intervenes between the stimulus and the response and places its stamp upon them.

CONSCIOUSNESS

Orientation of the eyes, alone, is not a sufficient condition for the occurrence of visual attention. A person must certainly be looking at least somewhat in the direction of an object if he is to be aware of it, but he could be staring at the thing without being conscious of it at all. An inattentive person might be "a million miles away." Viewers of a boring television show will attest to the fact that their attention wanders away from the screen even as they are staring at it. Tennis players exhibit the same phenomenon when they are presumed to be watching the oncoming ball. Just ask the lady player who begins to think about the evening meal she has to prepare!

More than orientation is required. The viewer must of course be able to discriminate the object from others around it; he must have the mental apparatus to pick it out of the environment. But even that capability is no guarantee that he will see it, even if he is looking in its direction. Something else is needed. Mental awareness of some sort or other. But what is this awareness? How can it be characterized? What can be said about it?

If we turn attention to the conscious experience, itself, we see that it never appears to be conducted in part, but always as a unified whole. It has the character of a finished product, and we are aware neither of the mobilization of forces involved in the experience nor of the stimuli which lead to the experience. As I sit at the desk and note my attention transferring smoothly from one word on the page to the next, with an occasional jump to the itching in my nose or to the sound of hammering on the roof, I am aware of no electromagnetic waves striking my retinas or neural impulses coursing through my nervous system. What I perceive is a continuum of objects and events in space-time. Common sense tells me that I am experiencing real things in a pulsating world, and there is no awareness that those things are there because my "mind" acts on certain "stimuli" which are bombarding my senses. But one simply cannot ignore the experiments of scientists, which argue strongly in favor of the view that we only experience the end results of the neuro-physiological processes.

Sayre expresses the notion well when he says:

> It is interesting and not irrelevant to note that it is our visual responses to configurations in our visual environment which have the properties of figure and form celebrated by Gestalt psychologists, and not the configurations themselves. The Necker cube, which reverses under continued attention, is not the two-dimensional configuration of lines on the blackboard or printed page. What alters in perspective and orientation is the pattern that constitutes our visual response to this configuration. What remains constant in shape as the kite bobs to and fro in the wind is not the flapping and twisting surface of paper reflecting light into our retinas from the sky above, but rather the patterned visual responses of the viewer who knows the kite is shaped like a diamond, and knows this in a sense that does not require his ever thinking about it. Color constancy, by which surfaces appear to remain the same color under changing conditions of illumination, is a constancy of color response and not a constancy of wave lengths delivering information to the retina. And the very phenomenon of figure-ground differentiation has to do with the patterns that emerge in our visual responses to information delivered to an essentially flat configuration of retinal receptors. There is no dominant figure in the complex mass of electrons interacting with the light reflected off the surface of an object, no background or recessive field focused through the lens of the eye, and no closure or symmetry in the retinal firings that convey the visual data to the higher levels of the visual tract. Where the patterning occurs is in the brain stem, perhaps, and in the visual cortex. And it is with an understanding of the data processing that occurs at these levels that we will understand finally how the world comes to appear structured in semipermanent objects with semipermanent spatial relationships, and with relatively constant colors and shapes, and characteristics of depth and perspective. (1969, p.141-2)

The manner in which the individual mobilizes his perceptual forces in generating the patterned responses which constitute his experience will certainly affect his approach to the game of tennis. Insofar as the game is part of the living process, the behavior involved in watching and chasing down the ball with the intention of hitting it back into the opponent's court is a facet of his perceptual experience. It is pregnant with all of the emotional, habitual, and purposive traps and pitfalls found in any other facet of life. Organizing the visual data and responding to the moving ball is a complex of activity that can take many forms, depending on the player's visual acuity, his physical skills, his interests, attitudes and values, indeed his total mental structure. As Sayre puts it:

> The patterns in terms of which the organism's visual data-processing system renders objects presented to it depend upon the demands the organism makes upon its visual environment. With the worm, frog, and cat, these demands are expressions of the organism's needs for livlihood. With man, these demands reflect as well the organism's interests, whims, and idle curiosity. A glance at a bare wall reveals nothing but a flat expanse of color. But subsequent glances, involving retinal stimulation different in no specifiable way from before, reveal many different colors and shadings, forms suggestive of familiar objects, a few cracks, spots and specks, textured areas, and more than can be comprehended in any single field of view. A window is a single object; except that to a window washer it is a multi-layered field of smudges and imperfections; except that to a glazier it is eight, twelve, or twenty separate panes, separated by many distinct pieces of wood; except that to a painter it is far more complicated than one hundred separate shingles on the side of the house. What one man will see, another man will try to see, but unsuccessfully, another will look through, and yet another will entirely overlook. (1969, p. 141)

Pursuit of the tennis ball suffers no less from variations in the organism's interests, whims, and idle curiosity. Tennis is but a single game; except that to the occasional duffer it is perhaps an opportunity to vent his pent-up frustrations; except that to a Club player it is a chance to restore some of the skills he lost during a long layoff or an opportunity to get reacquainted with his croneys; except that to the professional player it is a means of livelihood. What each person perceives in the game, in its set of rules, movements and challenges, depends on his feelings of the moment, on his plans and objectives.

Tennis is a game in which the most difficult shots can be accomplished only with a high degree of concentration, or in which the simplest can be missed for the lack of it. Given adequate visual acuity and the proper physical apparatus, the ability to concentrate is probably the singlemost critical aspect of the game and frequently marks the difference between the great players and the not-so-greats. This ability to concentrate may be the meaning behind the common statement that tennis is eighty percent mental.

In Sayre's view, shifts in concentration, which is one of the forms of the more general activity known as 'attending,' cause alterations in consciousness.

> The phenomena associated with concentration offer telling illustrations (of alterations in consciousness). When a person first glances at a painting on the wall, his attention may well be shared by several other visual ventures at the same time. But when he becomes engrossed in the painting and begins to pay more detailed attention to its lines and colors and to the modulations they embody, his attention is drawn away from other concerns and absorbed in the task of exploring the pattern incited by the picture alone. To become fully conscious of the picture is to devote his information-processing capacities to more detailed and highly structured responses to the data passed from the picture through his sensory channels. Coincidentally, to lose consciousness of other objects in his environment is to cease reacting to their stimulation in coherent patterned responses. To ignore an object or happening is not to cut off stimulation from that quarter upon the retina. And to fail to be conscious of the presence of a friend is not to shut one's eyes when looking in his direction. As often as not, what one overlooks is as fully within one's range of visual stimulation as the thing occupying one's direct attention. Failure of consciousness of this sort, rather, is failure of the sensory information-processing systems to honor the stimuli arriving from the slightest object with a fully patterned response. (1969, p. 145)

Consciousness, according to Sayre, involves the discrimination of different forms or objects. To discriminate different forms or objects means to generate patterned neural responses to stimuli at the senses. A person who, at any given moment, cannot discriminate anything at all is not aware of anything. And a person not aware of anything is not conscious. Noticing, watching, scrutinizing, inspecting, and concentrating, all of which are particular modes of 'attending,' count as forms of consciousness.

> The same, however, may be said for the generic term 'thinking,' under which fall deliberating, considering, contemplating, musing, and reflecting. But thinking is not a generic form of consciousness, and neither for the same reason is attending. It is the case, rather, that attending is one among many further specifiable ways in which one might exhibit the fact of one's being conscious. (Sayre 1969, p. 115-6)

It follows, therefore, that, for example, cessation of thought, in and of itself, is not unconsciousness. Neither is cessation of imagining, dreaming, or sensing. Rather, a person ceases to be conscious only when he fails to exhibit his consciousness in any one of its varied forms, i.e., when he is not conscious in any respect.

It appears, too, that the various forms of consciousness submit to different levels or degrees of intensity. For example, communication with others, or even talking to one's self, could represent high degrees of conscious awareness, as would the volleyball play in Picture 4.1; whereas watching television while half asleep might be a type of low intensity awareness.

> It would not be surprising if normal levels of consciousness in a population were determined by a Gaussian distribution curve. Some people seem to maintain a much higher level of conscious awareness than others. However, we have not yet the methods for testing my hypothesis. (Granit 1977, p. 82)

The split-brain experiments to which reference was made in Chapter 1 also raises the possibility that different kinds of conscious awareness are exhibited by the separated hemispheres.

Picture 4.1. Gary Hooper braces for a dig in volleyball. (Photo by Bruce Hazelton)

We saw that the so-called dominant hemisphere (usually the left) is capable of speech but that the other hemisphere is generally mute, in the respect that its communication by language is undeveloped. "The right hemisphere perceives and comprehends something but cannot express itself verbally" (Granit 1977, p. 81), though it can use the hand at its disposal (the left) to pick out objects represented in words.

We saw in Chapter 1 that Penfield (1975) places the locus of consciousness in the higher brain stem. Considering that consciousness seems to develop in parallel with the expansion of the cerebral cortex (Sherrington 1947), that it can raise to the level of awareness most sensory experience and many engrams, and that, given time, it can deal with vast amounts of information (Granit 1977), even if its locus is in the brain stem the quality of consciousness might still be significantly different in the two hemispheres solely by virtue of the cells used for speech. Sperry (1975) in fact ascribes to the right hemisphere a consciousness different from the verbalized type of the left, though precisely how the difference might be established is quite another matter. Consciousness does, however, implicate a vast number of cells (Granit 1977), and the quality of awareness could vary with the organizational structure of the interconnecting cells.

For Sayre (1969), consciousness is a particular manner in which information deriving from the organism's sensory environment is processed by its nervous system, and this of course depends on the inherent structure of the system. Playing tennis might therefore be a very highly concentrated mode of processing, whereas dreaming, or day-dreaming, could be inattentive forms. Perceiving or imagining might be more or less vivid, or dim, or acute, or fuzzy, or penetrating. Pursuit of the ball might be frantic, lazy, or nonchalant. Shot selection could be inspired, or it might be unimaginative. The player might participate in the game with enthusiasm, or he might play listlessly, depending on the manner in which the life forces are mobilized, depending on the way in which the complex organism interacts with the sensory stimuli. Such close attention as concentration involves a high expenditure of energy, a high degree of vigilance. The intensity of the expenditure may range from a low as in deep sleep, to a high as during the excess of anger.

A detailed description of the visual responses is especially useful in the explanation of consciousness and Sayre obliges by considering a situation describable as "watching an airplane move against a clear sky." The analogy is apparent to the situation in tennis describable as "tracking a lob against a clear sky."

> If one's gaze is directed above all ground objects to the airplane, then most of one's retinal receptors are responding to stimulation relevant to the sky and relatively few to the airplane itself. But since the sky is clear, there is no reason for the eye to distinguish among its various sectors; and most of the information present in the activity of the retinal receptors is in the task of watching the airplane. The information is redundant in a way deterimental rather than beneficial to clear visual perception. One of the basic processes involved in the patterned response is to block this useless information entirely out of the picture. Redundancy of the same sort is present, to a lesser degree, on one's retinal responses to stimulation from the airplane itself. If the viewer looks carefully, he can perhaps count the engines, determine the type of craft, and even gain some indication of the windows in the cabin and the markings on the wings. For purposes merely of watching the airplane move against the sky, however, these details are inessential; and the information that would bring them to one's attention would be blocked out until it becomes relevant. Indeed, only information indicative of the boundary of the airplane is required for the task of following its motion through the sky, and this is only a small fraction of the total information available at the retina at a given moment of perception. Watching an airplane against a clear sky places only a minimal load upon one's visual information-processing system. Yet such an activity shows all the basic characteristics of a patterned response.
> (1969, p. 159-60)

This quotation is taken from a context in which the human nervous system, particularly, is viewed as a "cascade of many information channels from which is systematically eliminated all save information directly relevant to the needs of the organism at the given moment of consciousness" (p. 156). Unlike such creatures as the frog, in which specific areas of the brain seem to be wired for specific functions, the brain is a biological adaptation in which a high degree of adaptability has been programmed. As Sayre argues:

> The needs and interests of the human being require for their satisfaction the ability to respond selectively to sensory situations that seem both countless in number and unlimited in degree of complexity. If separate areas of the brain had been set aside for processing information in each of these sensory situations, the human brain might have developed into an organ larger than the rest of the body together. This obviously would not have been an expedient evolutionary development. What apparently happened instead was an enormous increase in flexibility rather than an enormous increase in size. Instead of responding with separate parts of the brain to each data configuration of potential importance, the human information-processing system appears to be capable of responding with more or less the same brain areas to many different sensory configurations. The ability of the human nervous system to operate in this fashion is its ability to emit patterned responses. The first major process toward this end is the discrimination of contours with high information content within the retinal field. (1969, p. 161)

Since the information content and redundancy of visual perception is very high, the brain could easily be overloaded unless a significant amount of filtering along the cascade of channels takes place. Common sense tells us that in such situations as watching for a friend's car, observing a bare wall or a painting, watching an airplane move across the sky, or tracking a tennis ball, the amount of detailed discrimination that <u>could</u> enter the patterned responses is far more than normally appears; the bulk of it for the most part is ignored as irrelevant. Thus,

> it is clear that not all informational contours present within a percipient's retinal field at a given moment figure in his final patterned response. Somewhere between the operation of discriminating informational contours and the final visual response there must occur a sorting process that determines which contours will be passed on for incorporation within the finished pattern. In the human visual system, this "clearinghouse" operation might take place within the brain stem. (Sayre 1969, p. 162)

Consider a situation in which a tennis ball is moving from the opponent's racquet toward the percipient's court. The problem from the percipient's point of view is to follow the ball visually against the background, say, of a wire-mesh fence set in front of a cluster of trees. The task is to retain continuity of representation in the visual area of the cortex in the face of variations in contour configurations stemming from the edges of fence posts, trunks and branches of the trees, the net over which the ball is passing, and the opposing player, who may be racing to a defensive position.

In this example, the receiver is required to expend more energy in careful attention to the tracking than would be necessary if, for example, the backdrop were a smooth, uniformly dark screen. This means, in effect, that the information content at the cortex must be higher for the screen of shrubbery than for the dark screen. More complex neurological activity must therefore be brought into play. The consequence is an increased demand upon the entire visual processing system. If the player fails to muster the necessary capacities to meet the demand, the momentary loss of perception could result in a missed shot.

Additional complexity arises due to the fact that the percipient at the same time has to converge with the trajectory of the ball, bring into play neural activity needed to select a return shot, and maneuver into the best possible position for the shot. Thus he has to watch the ball in flight, project its motion, predict an intercept point, move toward that point, make corrections on his estimates, adjust his body position to maintain visual contact with the ball, consider the alternative shots available to him, keep track of his opponent's position on the court, maneuver into striking position, and address the ball. In the face of such incredible complexity, the wonder is he can hit the ball at all.

While the player attempts to "keep his eye on the ball," which requires sending appropriate signals to his eye muscles and any other portion of the body that needs to be adjusted to accommodate changes in perspective due to ball and body motion, he must activate the processes required to estimate the speed and direction of the ball and extrapolate its position into the short term future. It may, in fact, be necessary for him to turn his head away from the ball for a moment, when he receives an offensive lob, for instance, in order to run to the baseline to be in position to continue the play.

Meantime, he must "reach into his memory" to select from his assortment of shots the one he wants to use. The choice of shot and its execution are practically coincident. Should he, as a right hander, for instance, "see" the ball approaching him on his left, his first reaction may be to "prepare for a backhand shot," calling for signals to his muscles to swing the racquet to the backhand preparation position. Nevertheless, he may not yet have settled on a particular one of an assortment of backhand shots.

If the player is to play winning tennis, it is essential that he be alert to the kind of shot being hit by his opponent. He must gauge the position and pace of the ball accurately and thus be aware of any air currents over the court. And he has to be highly selective in his own shots.

Depending on his position on the court and on the position, speed and capability of his opponent, depending on whether he is playing "singles" or "doubles" (men's or mixed), depending on his own capabilities, personality and temperament, his attitude and mental state, ...he may proceed with a drop shot, a chip shot, a cross-court smash, a drive down the line, or even a soft lob, among a variety of possibilities. All this he must do, and still continue to track the ball. This requires a great deal of concentration.

Furthermore, a high level of attention must be sustained for long periods of time. A complete match may take two or three hours. It may be exciting to play; it may be full of surprises, with a strong mix of good shots, in which case the orienting response continually heightens attention and concentration remains relatively high. But the game may become very boring, as in doubles when two players enter into long and drawn out lobbing matches. The game then loses interest and players become inattentive.

ABILITY TO ATTEND

Development of the capability to attend is a significant step in man's evolutionary history. According to Granit (1977, p. 77-8), "the trend of evolution seems to have favored the capacity of making conscious use of attention. We feel it in our power to direct our attention to anything we choose to consider." Being able to choose which objects in his field to view is a human achievement in perceptual experience fundamental to the capacity of a tennis athlete. Unless the player can direct his attention to, and identify, the bits and pieces of information in his environment which contribute to efficient behavior and not attend to those that are irrelevant, he is subject to random influence by every stimulus that comes his way. It is the selection and processing of appropriate data that produces the unified action of the trained athlete. The ability to do this is well recognized. But just how the information is isolated from the welter of sights, sounds, smells, etc., which he can experience is not fully understood.

Examining the nature of the selective process, Dember and Warm (1979, p. 127-31) isolate for study several determinants of attention. These include physical and collative characteristics and the orientation response. They indicate that size, intensity, and motion are important physical determinants, with the advantage going to large, bright and/or moving stimuli, though the reason for the advantage is not entirely clear.

Collative characteristics are properties which depend on comparison of stimulus elements such as novelty, suprisingness, incongruity, and complexity. Dember and Warm cite studies which reveal that novel and incongruous objects are almost always selected or fixated in preference to others. Describing work with a "whirling propeller," they say that people, in viewing visual forms, attend predominantly to discontinuities, corners, contours, and the brighter sides of contours.

The orienting response is familiar to observers of animals. Dogs and cats pick up their ears or "point" in the direction of a sharp sound or threatening gesture. Pupils of the eyes may enlarge. There may be a decrease in the galvanic skin response. Breathing may stop for a moment and begin again with slow, deep breaths. Or the heart rate may slow.

The orienting response also habituates, which means that it diminishes with repeated presentation of a stimulus. But sudden changes in the quantitative or qualitative properties of the stimulus will reinstate the orienting response. We will see below that Pribram (1971) interprets these findings to indicate that the brain continually fabricates neuronal models of external events. Any event that doesn't match what is expected will trigger an orienting response, whereas the neural effects of events which do match will be inhibited. The implication is that the perceptual system attempts to reconstruct the external environment in an effort to cope with the mass of information which it encounters.

The Pribram theory means that the tennis player constructs and continually updates a model of the circumstances at the court. The surprise element, or the mismatch between the actual occurrences of the real events with the expectations established in the model, has a reorienting function. An overhead smash that was unexpectedly returned by the opponent would have this effect.

The element of surprise is closely linked to information. We saw above that information is defined as the logarithm of the number of alternative responses to an input; it is a measure of the amount of uncertainty the player has in making a choice.

In its more general form the alternatives are presumed not to be equally likely. Information is then expressed as an inverse function of the likelihood of occurrence of the event; the lower the probability of the event, the higher the amount of information conveyed by the input. It is still a measure of uncertainty. Thus, an input which surprises the player leads to an unexpected response. This is a low-probability event. So an input which surprises is one with high information content.

MENTAL REQUIREMENTS FOR PERCEPTION

The ability to attend is fundamental to the ability to organize experience into a conscious, meaningful unity. It is the means by which knowledge is gained. Exercise of the power to attend stimulates learning, leaves its imprint in the neural mechanism and thus provides the responses which characterize experience. In Penfield's terms:

> There is the record of conscious experience that we have discussed. It makes possible voluntary and automatic recall of past experiences, and it includes those things to which the individual paid attention, nothing he ignored. One can only conclude that conscious attention adds something to brain-action that would otherwise leave no record. It gives to the passage of neuronal potentials an astonishing permance of facilitation for the later passage of current, as though a trail had been blazed through the seemingly infinite maze of neurone connections. The same principle applies to the acquisition of speech skills and the storing of non-verbal concepts. Permanent facilitation of a patterned sequence in those brain mechanisms is established only when there is a focusing of attention on the phenomenon that corresponds to it in consciousness. (1975, p. 74)

Considering further the manner in which memory is affected by attention, it is instructive to examine Sayre's remarks:

> Classification as a sensory response pertains not to the lapse of time between stimulation and response but rather to the origin of the information that leads to its occurrence.

> In this respect an afterimage clearly is a sensory response. So, by the same token, is an image of an object or experience formed in imagination long after the information reflected in the image was presented to the senses. The same may be said of a dream image familiar to the dreamer from past consciousness involving information deriving from sensory stimulation that has been stored for an extensive period and then made available for further processing at times when the informational content of current sensory activity is minimal or uninteresting to the conscious organism.
>
> The most highly regulated form of delayed sensory response is what we call "remembering." Memory, like knowledge, is normative in that it admits among its objects only what is or was the case. Just as being known is a sufficient condition in the realm of possible states of the world for being factual, so being remembered is a sufficient condition in the realm of possible past events for actually having occurred. (1969, p. 173)

According to Sayre, what distinguishes the several activities are the circumstances under which they are performed and the criteria by which they are evaluated. In effect, all are products which stem from the stimuli emanating from physical objects.

> The facts of the matter are that each of the various organisms is confronted with the same physical objects, receiving information about its structure through propogated light waves, and each emits retinal reactions comparable to those of the others. Each, however, responds visually in its own unique way: and each patterned response reveals features that are significant only to the organism responding in that particular way. (1969, p. 140)

Again we see that visual perception is a product constructed out of stimuli. The individual receives information about the environment through propogated light waves and emits retinal reactions. Then he responds visually to the information in his own style. That is, he <u>integrates</u> the data in his unique way, according to his special interests and capabilities.

But we found in Chapter 3 that light only acts as a trigger, or that, at most, the individual receptors only provide light intensity and duration. The data from the separate cells still have to be organized. How is this accomplished? At the very least it would seem that the intensity and duration from one cell have to be compared with the intensity and duration from the other cells. Some kind of comparative logic has to be available. Rules of combination of some kind are needed.

Are these integrating rules somehow learned through experience? Or is there something in the organism to begin with, some integrating logic, wired-in or pre-programmed, that is activated by the stimuli? E.J. Gibson (1969) argues that nature doesn't turn out an infant with knowledge and strategies ready-made for perceiving the complexities of all the information. That can hardly be disputed; a great deal of learning surely takes place. But how is the infant to acquire any experience in the first place without some mechanism, however rudimentry, which enables it to put the tiny pieces of the information puzzle together?

This problem is analogous to the one that confronted Immanuel Kant, although it was presented in a slightly different way (1872).

Kant had to contend, on the one hand, with the legacy of the empirical school of philosophers who held that the origin of all knowledge lay in the empirical immediacies of experience, viz., the elements of sensation. These elements are the building blocks of knowledge and the constructions can only be learned through experience. Further, any test of these constructed knowledges can only be made by dipping back into that experience to make a comparison.

Kant also had to deal with the arguments of the rationalists, who held that the origin of all knowledge lay in the clear and distinct intuitions of the mind. Empirical experience is faulty. It is not to be trusted. It changes from moment to moment, and constructions out of it can only be statistical summaries. The true source of knowledge can only be in the insight provided by the mind, itself.

Kant agreed with the empiricists that knowledge stems from the constructions of experience, but he did not accept the view that the ground for the construction lies in empirical factors solely. In his thinking, sensations without the unifying principles of the mind would leave us intellectually blind. Similarly, he accepted the rationalist's judgment of the relevance of intuition so far as truth was concerned, but he was convinced that thoughts alone, without data, would be empty of content -- mere shells of knowledge.

Thus, for Kant, human perceptual experience is constructed by the percipient in accordance with certain principles of the mind -- categories of the understanding and the intuitions of space and time. But the construction is dependent for its content on facts provided by the state of the world at the time.

Our tennis player brings this mental framework to the court as part of his natural "equipment." The context of the player, including himself, the ball, net, racquet, playing surface, sky, etc., is thus a complex relationship, whose content is specified by the prevailing environmental circumstances and whose form is determined according to the human mental representations.

Contemporary scientists typically adopt the stimulus-response language when modeling human behavior and associate one or another of various physical energies with the stimulus (electromagnetic waves impinging on the eyes, sound waves striking the ears, etc., as we have seen), generally accepting the theoretical formulations of modern physics in this regard. But significant differences within this point of view arise when the individual's influence in the production of responses to the stimuli is considered.

Some of these behavioral scientists theorize solely within the causal framework, hoping thereby to heighten our ability to predict human behavior. They do, however, admit to a certain amount of ignorance of causal chains, but claim that there must exist some intervening variable to take up the conceptual slack in their model. The variable represents that-something-or-other still missinq in their understanding of the stimulus-response structure which, once filled in, will provide a strict causal relationship.

Others, holding the position that a teleological approach is not incompatable with causal principles, argue that the theory of the intervening variable is simplistic (Downs, Pribram, Neisser). They feel that human responses are far too complex to be explained simply by incorporating the intervening variable, particularly in light of the discovery of the ubiquitous servo-mechanism in the human organism found to be under control of the brain. For this group, nothing short of a complex system of mental representations (cognitive maps, forms, schemata,....) is adequate to bridge the gulf between stimulus and response.

This is the view of the cognitivists, who tend to follow the lead of Kant. There is an important difference, however. For Kant the mental framework was an immutable human characteristic. But current thinking presents no such fixed unified collection of mental conditions. Modern representations are considered to be in a state of flux, being influenced as much by experience as determining it. This is the stance adopted in our study of the tennis player.

In his interaction with the environment, the player is presumed to behave in a purposeful manner, i.e., that he is presumed capable of making decisions and acting on them freely, according to plan, using skilled behavior. This does not mean, however, that he can circumvent physical laws. On the contrary, purposiveness involves a selection among alternative future possibilities, a condition which implicates predictability, and this recognizes and requires the cooperation of causality (Granit 1977).

Once the player has developed the requisite skills, he can race with confidence to intercept the ball and can accelerate or decelerate at will, because muscle forces act predictably in the application of torques to move limbs. These are real forces operating in causal chains. And our player chooses freely within a framework of mental maps to initiate the choice.

COGNITIVE MAPS

Proponents of cognitive psychology do not agree uniformly on nomenclature when referring to the elements of mental space considered here. The terms "schemata" and "mental maps" are frequently used, as are the expressions "mental representations" and "mental image." At least one investigator uses the more neutral term "frame." The expression "cognitive maps" was used for the caption of this section just as a matter of convenience, though it seems now to be more favored.

The cognitive map, or schema, etc., is a mental element akin to, but not to be identified with, a map, or format or plan. As already noted in the previous chapter, we appear to impose schemata onto the environment in perception and we seem also to use them to guide or organize behavior. As Neisser expresses it,

> A schema is that portion of the entire perceptual cycle which is internal to the perceiver, modifiable by experience, and somehow specific to what is being perceived. The schema accepts information as it becomes available at sensory surfaces and is shaped by that information; it directs movements and exploratory activities that make more information available, by which it is further modified.
>
> From the biological point of view, a schema is a part of the nervous system. It is some active array of physiological structures and processes: not a center of the brain, but an entire system that includes receptors and afferents and feed-forward units and efferents. Within the brain itself there must be entities whose activities account for the modifiability and organization of the schema: assemblages of neurons, functional hierarchies, fluctuating electrical potentials, and other things still unguessed. It is not likely that this physiological activity is characterized by any single direction of flow or unified temporal sequence. It does not just begin at the periphery and eventually

> arrive at some center, but must include many kinds of reciprocating and lateral patterns. Nor does it begin at one moment and end at another; the continuities of different subsystems overlap in varying ways, providing for a host of different kinds of "information storage." (1976, p. 54)

It is conceivable that individuals may be able to think visually in cartographic terms. But in general, mental expressions are not dependent on the sense of scale, orientation, or the symbolic paraphernalia normally found on maps -- the collection of dots, lines, colors, etc., used to describe cities, highways and topographic features of an area.

Schemata are not strictly like maps in another sense, as well. According to Neisser, the latter incorporates a sharp distinction between form and content, while schemata do not. While the schemata do specify the form that information must take for it to be accepted as such, and although they direct movements according to a plan, the information that fills in the format at one moment of the cyclic process actually becomes part of the format in the next, determining how further information is accepted. The schema is not only the plan but also the executor of the plan. It is the pattern of action as well as a pattern for action. (1976)

This concept of a schema is similar in interpretation to the idea of a "frame" developed by Minsky and applied in artificial intelligence. The essence of the view is given in his own words as follows:

> When one encounters a new situation (or makes a substantial change in one's views of the present problem) one selects from memory a substantial structure called a frame. This is a remembered framework to be adapted to fit reality by changing details as necessary.
>
> A frame is a data-structure for representing a stereotyped situation, like being in a certain kind of living room, or going to a child's birthday party. Attached to each frame are certain kinds of information. Some of this information is about how to use the frame. Some of it is about what one can expect to happen next. Some is about what to do if these expectations are not fulfilled.

> We can think of a frame as a network of modes or relations. The "top levels" of a frame are fixed, and represent things that are always true about the proposed situation. The lower levels have many terminals -- "slots" that must be filled by specific instances or data. Each terminal can specify conditions that its assignments must meet. (The assignments themselves are usually smaller "subframes.") Simple conditions are specified by markers that might require a terminal assignment of a person, an object of sufficient value, or a pointer to a sub-frame of a certain type. More complex conditions can specify relations among the things assigned to several terminals.
>
> Collections of related frames are linked together into frame systems. The effects of important actions are mirrored by transformations between the frames of a system. These are used to make certain kinds of calculations economical, to represent changes of emphasis and attention, and to account for the effectiveness of "imagery."
>
> For visual scene analysis, the different frames of a system describe the scene from different viewpoints, and the transformations between one frame and another represent the effects of moving from place to place. For nonvisual kinds of frames, the differences between the frames of a system can represent actions, cause-effect relations, or changes in metaphorical viewpoint. Different frames of a system share the same terminals; this is the critical point that makes it possible to coordinate information gathered from different viewpoints. (1975, p. 212-13)

The frames also include expectations and other kinds of presumptions, and a great many details whose supposition is not specifically warranted by a situation. When a proposed frame cannot be made to fit reality, an information retrieval system, which links frame systems, provides a replacement frame.

> Once a frame is proposed to represent a situation, a matching process tries to assign values to the terminals of each frame, consistent with the markers at each place. The matching process is partly controlled by information associated with the frame (which includes information about how to deal with a surprise) and partly by knowledge about the system's goals. (1975, p. 213)

The notion of an active, as opposed to a passive, perceptual process implies that the perceiver contributes something to the formation of his experience, that the act presupposes the use of vehicles of construction of some kind. Frames are just such vehicles. They are the organizing principles, the clusters of constructive forms, by means of which experience is possible and meaningful.

Experience as we know it hardly seems possible without some objective agency being the source of inputs, either through internal or peripheral sensors. But it is not reasonable, either, to think that the experience can be meaningful without the individual somehow having organized it. Stimuli must certainly be offered up as content for the experience, but if the stimuli are to have any significance, a logical or organizational form of some sort is needed as well. Even the humblest blur must be organized in some fashion if it is to be a meaningful product of experience.

Each aspect of experience, as a patterned response, may be considered to be a problem situation which has been resolved in a particular way, as a percept of some kind, with a high or low level of attention, or consciousness. The specific colors or shapes of an object, the movement of a limb, the organization of speech, the execution of a particular play in tennis, . . . each constitutes the organized response of the individual and can be said to define a choice of experiential representation in problem space.

Even the manner in which the tennis player "eyes the ball" as he tracks it in its trajectory can be considered a solution -- one among many ways to resolve the matter of the objectivity of the moving ball. In Minsky's terminology, tracking the ball would mean, I should think, that a succession of frames is called into play to effect the perception, each frame structuring a different segment of the task, part of which means viewing the ball from a succession of different perspectives. Other problems, such as moving the body, selecting an appropriate shot, making feedback comparisons, detecting and identifying objects, or simply keeping tabs on items of related interest, would draw from other systems of frames and thus yield different solutions, each solution involving some sort of chain of mechanization.

Application of the cognitive maps (frames, forms, schemata...) is not without its hazards, unfortunately; problem solving does have its risk of failure. As noted in Chapter 3, schemata applied successfully in one sport may fail in another. For example, the techniques of bicycling cannot be applied to tricycling without modification; the method of co-ordination of balance on bicycles is inappropriate on tricycles. Similar difficulties arise when, for example, the tactics and techniques of squash are applied to tennis. Failure to adjust to the differences in stroke techniques, methods of approaching the ball, style of play and the like can lead to disastrous results. In general, when cognitive maps (motor plans, frame systems...) are misapplied or are not fully developed for the situation, there usually results a hitch -- an error.

In this respect, perception of the world is a simplification -- a model -- and as such is subject to error. So, too, is the tennis player's world of the tennis court. Watching a player miss a ball he was certain he had, an astute observer might note that at the moment of expected contact with the ball the player turned his head ever so slightly to glance at his opponent only to raise his racquet several inches higher than it should have been to meet the ball properly. It is reasonable to think the player was not aware of doing this, unless it is presumed he missed deliberately. The more likely possibility is that his perception of the situation was orderly and efficient, that he thought he was doing everything properly. But there was a hitch, nevertheless. His perceptual model was inadequate.

The problem is largely a matter of skill. It requires the ability on the part of the player to sneak a glance at his opponent without raising his racquet away from the ball, and it calls for skill in constructing his perception. Cognitive maps are not fixed, unchanging categories of the mind but are subject to modification through learning. Nor are the links among cognitive maps frozen; they, too, can be altered in the learning process, through experience. Groupings of cognitive maps which at one stage of development can only produce divided attention and behavioral disruption may eventually be synthesized, or coded, to yield experiential unity. This is the case when the player learns to track the ball and otherwise keep tabs on the other relevant items, as in a juggling act. It is also the case when he learns to make the appropriate decisions. And it is true as well when he learns to effect the necessary shots and movements smoothly and efficiently.

POSSIBLE TRACKING CUES

To simulate the visuo-motor processes of our tennis player, it is presumed that his percepts, decisions and responses stem from a unique qualitative base -- from his personal feelings, or intuitions. His behavior incorporates schemata, which offer a possibility of development along certain lines. The precise nature of the development can only be determined through his interaction with the environment. The schemata establish a point of departure and direct perceptual activity, but it is only the interaction of the schemata with the available information in the environment that yields perception. What kind of information does the tennis player encounter and how might it be represented in the simulator? Specifically, what kind of tracking information can he obtain?

An answer may be gleaned from the statement by A.J. Welford, above (p. 3-5) referring to the refined ability of the musician to identify pitch, the dyer to interpret hue, and the furnaceman to judge the temperature of molten metal by its color. In none of these instances is any type of objective measuring device employed, yet very fine distinctions are made and very precise responses are effected.

Welford's statement says, in effect, that the expert, because of his special talent, training and experience, is capable of the most subtle distinctions when dealing with properties central to his profession. Translating this into the language of tennis, it would mean that the master player is capable of the most subtle distinctions pertaining to the state of the tennis ball. He is able to "read" the trajectory in far more subtle terms than the novice. How is this possible and what form does the appropriate information take?

To see what information might be available to the player, consider the events he might observe as the opponent hits the ball to him. He might, for example, note the angular velocity of the racquet, which could tip him off to the impending speed of the ball. The relative position of the ball to the opponent could provide information as to the direction of the flight path (whether it was in his lateral plane, i.e., to his side; or whether it was well out in front of him). Our player might be aware of the angle of the racquet face, which could indicate the projected height of the trajectory.

The momentum exchange relationship between the racquet and the ball might also be of use to the player. Given the effective mass of the racquet, its angular velocity and torque arm, the mass of the ball and the pertinent coefficients, he might be able to calculate the momentum and thus the speed of the ball. But the computation is by no means trivial, even if he knows the conversion formula. It is certainly not one that the player can be expected to use.

The angle of the racquet face and the relative position of the ball at the moment of contact might give him some indication of the direction of the impending trajectory, but the assignment of specific numbers or values for these properties is all but impossible during play, particularly since the racquet can make a brushing motion over the ball during contact. Nevertheless, this relationship could well be the singlemost important piece of data available to the receiver.

Information that might compete in importance with this data is the velocity of the ball immediately after contact with the racquet. Given only the impact velocity for the ball, ignoring aerodynamic drag, the entire trajectory is established for any specific starting height. Furthermore, the velocity is unambiguous. So the intercept point is completely predictable within the estimation accuracy of the velocity.

If the ball is moving too fast, however, or is out of reach, the information does the player no good. Otherwise, he can continue to track the ball and update his position and velocity estimates. But spin and wind now become important factors in shaping the ball trajectory.

Information about the spin may be obtained by noting the way the opponent brushes the ball with his strings. A motion up and over the top of the ball produces a top spin, which tends to dip the trajectory and makes it bounce farther. But a motion down and under the ball tends to keep it aloft longer and makes it bounce less far.

Information about the spin is also available through direct observation of the ball, but this is very subtle and beyond the capability of most players. Also difficult to obtain is data on the effect of wind, since unpredictable gusts can and frequently do counter his expectations. Now he has to be more alert and watch for subtle movements of the ball away from its normal trajectory.

There are of course natural limits to this type of information, corresponding to the objective values of the associated physical properties. But the player imposes his own limits as well, according to the level of his ability to discriminate, which depends on his structural development and degree of learning with respect to the required skills. Featured in this development is the richness of his mental space, i.e., the complexity and subtlety of his system of cognitive maps, or schemata, which determines his behavioral environment.

The cognitive map is the means whereby the player is able to construct his perceptual space and find his way around it. It provides the reference frame within which his estimates and decisions are made. Only through some such reference can he identify his environment and orient himself in it. And it is the cognitive map that guides his movements.

But what is this reference frame? What is the nature of the mental representations that offers such a remarkable reference?

It is apparent that the player's perceptual field does, in some sense, include such properties as the direction and speed of the ball. But does he rely on some abstract reference frame such as a Euclidean coordinate system? Or does he use a more personal reference system? For instance, can he make use of the fact that, say, the ball has a speed of 97.5 mph with a heading of 192 degrees?

To obtain this kind of measure, the player would have to incorporate a reference frame which in effect lies outside the bounds of his court. For one thing, he would have to identify "north" precisely. And he would have to be able to estimate the angular separation from that abstract reference line.

At the common sense level, the player most certainly can identify in a minimal fashion some such property as position. He might, for instance, say simply that the ball is "over there," referring to a point off the right shoulder, possibly. Using similar body standards, he could characterize the direction of motion of the ball merely as, say, "away from me," or as "toward me," or moving with such and such another property. As for the speed of the ball, he might perceive that it is "very fast," for instance, or that it is "slow."

These properties can be meaningful to the player. As aspects of his conscious, patterned response, they are signs whose signification is evidenced through his behavior. In Neisser's view they afford various possiblities for action. They carry implications about what has happened or what will happen,belong coherently to a larger context, and possess an identity that transcends their simple physical properties. The meanings can be, and are possibly, perceived by our player, who responds by racing to intercept the ball.

To examine this response in greater depth, let us assume that the player has read his opponent's delivery, has expectations for the type of shot being hit, and has a first look at the oncoming ball. His immediate response might be to "compute" an expected intercept point -- the point on the court where he is likely to meet the ball. How might he do this?

One method might be to solve a system of simultaneous equations involving trigonometric expressions. This is a formidable process, requiring the distance, speed and direction of the ball. And it also assumes an intercept strategy. It is not a method which can be used on the spot by the player. This or any equivalent method is simply too difficult. Yet somehow the player does manage to intercept the ball, not just once in a while but over and over again. The question is, how does he do it?

I think it is reasonable to say that the player never really attempts such a one-shot computation. It seems far more likely that he solves the problem in stages, that his discriminations yield signs which guide his movements to an intercept point. The signs, themselves, yield to a degree of subtlety commensurate with the player's competence.

Somehow he learns to discriminate. The more he plays and studies the game, the more he learns and the more subtle become his discriminations. A novice will employ relatively crude schemata. His information will therefore be coarse and his responses will be crude and lack precision. But the expert will make fine distinctions and will respond with great precision and accuracy. He will have developed a vast array of schemata pertaining to the game, which is to say that his perceptual space is rich in content and that he has a wide range of responses.

Applying the discrimination process to trajectories, we can generate different morphological classes. Thus for instance, at one level we might have the groups: serves, overhead smashes, drop shots, lobs, volleys, half-volleys, and forehand and backhand shots. At this level, each service, for example, would be the same as any other serve; each overhead smash would be equal to any other; etc. This is obviously a very narrow and limiting partition on the space of all trajectories. And the system of cognitive maps would be equally narrow and limiting.

Going further, however, each class may be divided into subclasses. A flat serve might then be differentiated from a spin serve and handled in a different way. A forehand shot with top spin might yield one set of responses; one with underspin might be dealt with in another way. Similarly with the other classes of shots. To the degree that the differences in trajectories are considered to be significant, to that degree they are partitioned into different classes and to that degree they result in different responses.

In effect, the player learns to guide his actions on the court in increasingly subtle ways by incorporating into his perceptual model of the playing volume -- the specialized behavioral environment of the tennis player -- increasingly finer-mesh systems of cognitive maps. His capability can thus be measured by the nature of these mental representations.

In the simulator, the responses can be structured in accordance with accepted principles of the game. One such principle is to cut short the trajectory whenever possible. By closing rapidly on the ball, a player gives his opponent less time to prepare for his return shot. For a volley at the net, one is advised to hit with the racquet well in front of the body, keeping the racquet face open to the ball. A lob beyond midcourt may best be taken by gliding backwards for the overhead smash rather than turning, racing back to the base line and turning again to take the shot. Other situations call for other types of response.

It should be apparent that the player does not wait for a ball to run the course of its trajectory before responding to it -- that would be tantamount to watching it fly by. Rather, he responds on a continuing basis, reacting to elemental aspects of the path, such as position and velocity, or more subtle properties such as acceleration. The novice who is unable yet to hit the ball, likely has not refined his schemata to encompass the more subtle information, whereas the expert has already built up a set of expectations and can anticipate its motion with greater accuracy. In large part this is a matter of practice, and concentration.

> Don Budge once said he only saw his opponent twice -- when they walked on the court together and when they shook hands at the end. When his opponent served and came to the net, Don never saw him. He was too busy watching the ball. Billie Jean King will literally look at the ball for five minutes at night; she wipes everything else out of her mind and sees only the ball. The next day she claims she can watch the ball that much better. Now ask yourself if your tendency is to watch the opponent perform his strokes or to watch the ball only.
>
> The harder your opponent hits, the more intensely you must concentrate -- or you will lose the ball through the fact that it is coming back to you so quickly. When you serve, it is almost impossible to watch the ball's flight, but you can pick it up with your eyes as soon as it bounces on the other side. Try to follow the ball through four rallies, six rallies, ten rallies, without losing sight of it. Then see if you can do it for two games, four games, a set. Concentration is achieved only by consciously working at it. (Segura 1976, p. 107-8)

As Sayre pointed out, above, concentration on the ball brings more of one's processing capabilities to bear directly on this critical aspect of the game and can only enhance player development. Gallwey puts it well when he says:

> The tennis ball should be watched as an object in motion. Watching its seams helps to focus your attention on the object itself, but it is just as important to increase your awareness of the <u>flight</u> of each ball as it moves toward you, and then again as it leaves your racquet. My favorite focus of concentration during a point is on the particular trajectory of each shot, both mine and my opponent's. I notice the height of the ball as it passes over the net, its apparent speed, and with utmost care the angle at which it rises after bouncing. I also observe whether the ball is rising, falling or at its apex in the instant before the racquet makes contact. I give the same careful attention to the trajectory of my own shot. Soon I become more and more aware of the rhythm of the alternating shots of each point, and am able to increase my sense of anticipation. It is this rhythm, both seen and heard, which holds fascination for my mind and enables it to focus for long periods of time without becoming distracted. (1974, p. 93)

Following Gallwey, we have another source of information: at the level of the trajectory itself. We thus have information at the global as well as at the local level. The player with appropriate schemata is able to recognize the specific trajectory even while he is gauging the position and velocity of the ball at a given moment. Just as the ball is part of the playing volume at any moment of time, so it is part of a trajectory. A system of hierarchically embedded schemata reflects this condition.

Behavior can be viewed in a similar way. Sub-movements are embedded in larger movements and are motivated by anticipated consequences at different levels. At one and the same time, then, a certain action can be viewed as an overhead smash, for instance, or as a sequence of moves such as: gliding backwards, raising the racquet to a strike position, and swinging at the ball. To the extent that the player is aware of these aspects of the game, i.e., to the extent that he has developed a system of cognitive maps with which to note them, to that extent will he acquire the corresponding information.

By focusing attention on the subtle aspects of the moving ball, such as its seams or color, which are normally ignored as irrelevant, the mind becomes absorbed to the point where outside factors fail to distract. However,

> seeing the ball better is only a partial benefit of focusing on its seams. Because the pattern made by the spinning ball is so subtle, it tends to engross the mind more completely. The mind is so absorbed in watching the pattern that it forgets to try too hard. To the extent that the mind is preoccupied with the seams, it tends not to interfere with the natural movements of the body. Furthermore, the seams are always here and now, and if the mind is on them, it is kept from wandering to the past and future. The practice of this exercise will enable the tennis player to achieve deeper and deeper states of concentration. (Gallwey 1974, p.91)

Concentration on the regulatory cues (the specific sources of environmental information that govern effective movement) certainly improves the efficiency of a skill, and if, in particular, it is of some considerable advantage to focus on the seams of the ball, then by all means, the seams should be watched. But note, too, that a great deal of information is available in such a phenomenon as a spinning ball. The information is there for the taking, if only the player had the cognitive development, the richness of mental space, a sufficiently subtle image of his behavioral environment, a fully attentive consciousness, with which to see it!

PART II

THE PLAYER'S VISUO-MOTOR PROCESSES

CHAPTER 5

THE VISUAL SYSTEM

Living organisms are an integral part of the real world but are different from physical objects, both in structure and function, though the difference can be hard to define. Living organisms above the simplest metazoans have a nervous system by means of which they sense and respond to other objects in the environment. This nervous system exhibits the primary phenomena of irritability and conductivity (Matzke 1972). Sensory fibers arising from peripheral receptors conduct electro-chemical impulses into the central nervous system, where they are shaped and integrated via a large mass of internuncial or connecting neurons and are then directed to appropriate motor neurons to act on muscles.

In the human, the central nervous system, principally the brain, is a major component in the loop and is able to influence strongly the electro-chemical innervation pattern and thus dictate the spatio-temporal flow of muscle contractions. The human is thus able to develop skills, which is the ability to organize and coordinate combinations of specific movements into desired behavior (Jensen and Fisher 1975). The coordination of movement into exact patterns is a highly complicated physiological process, involving input, or afferent, signals from many sensors, including sensors in muscles and tendons, and output, or efferent, signals to the muscles.

Functionally, the nervous system can be divided into two broad categories: the autonomic or visceral nervous system and the somatic or voluntary nervous system. We shall not be concerned here with the autonomic system, whose function is principally housekeeping, such as maintaining the beat of the heart or the activity of the glands. The voluntary nervous system controls the skeletal musculature, which is involved in movement. The segment of special interest is the visuo-motor segment. While hearing may be important for the tennis player, most of his information comes from the eyes, so attention is restricted to the visual link with the skeletal muscles.

STRUCTURE OF NEURONS

The human organism is made up of many different groups of cells that have separate, special functions. Among the groups are the epithelium, blood cells, bone, cartilage, muscle, endothelium and nerve cells. All cells are excitable, but none so excitable as the nerve cell or neuron, the cellular unit of nervous tissue (Easton 1974). Figure 5.1 shows a schematic of the three-part structure of a neuron.

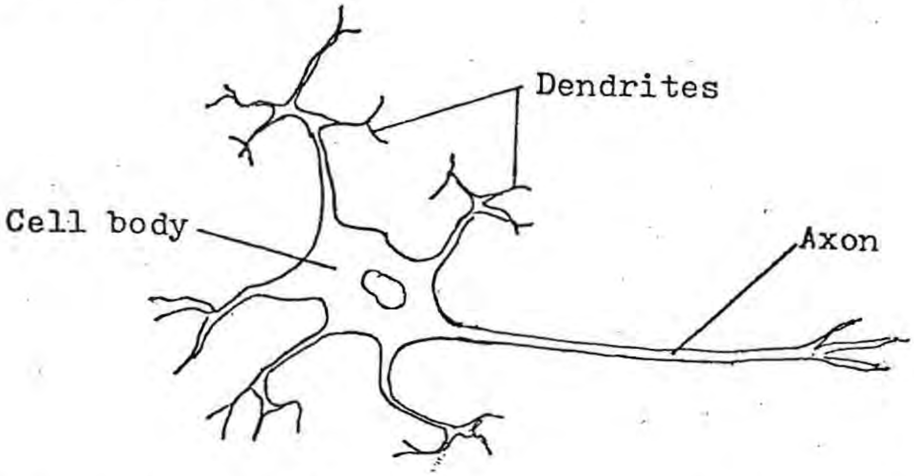


Figure 5.1. A schematic of a neuron, showing the dendrites, cell body, and axon.

The most characteristic difference between a neuron and other cells is that the neuron typically has a large number of branches. Short but profuse numbers of dendrites occur at the leading end of neurons; they receive impulses from other cells and transmit them inwardly to a cell body. This body serves to maintain the life of the cell. Branches at the terminal end sprout from an axon. The axon is usually long and untapered and transmits impulses to other nerve cells or to effector organs such as muscles or glands. This ability to send electro-chemical impulses through its branches and trunk is the most obvious special attribute of the neuron.

Signal transmission is a complex process, the detailed study of which quickly leads to the intricacies of electro-chemistry. But the principle may be likened to an electric battery. The cell has a surrounding membrane or coat which exhibits an electrical potential and maintains a small negative voltage difference between the inside of the cell and the outside. This is caused by differences in the ion composition of the fluids internal to the cell and surrounding it.

Under resting conditions, the inside of the cell is more negative than the outside. The mechanism underlying this phenomenon is not entirely known but is presumed due to the action of a so-called sodium pump that characterizes the membrane (Guyton 1979). Sodium ions, Na^+, and potassium ions, K^+, are among the ingredients that make up the chemical composition of the intracellular and extracellular fluids of the neuron. The effect of the pump is to drive the sodium out of the cell into the surrounding fluid. This leaves a void of positive ions inside the cell, creating a strongly negative electro-potential. Much of this potential is neutralized by the movement of potassium ions which flow into the cell inasmuch as they are diffusible through the membrane. The result is a high concentration of sodium in the extracellular fluid and a high concentration of potassium in the intracellular fluid. On balance the result is a more negative internal voltage. This condition is depicted in Figure 5.2 for an axon membrane.

<u>mEq = milliequivalent</u>

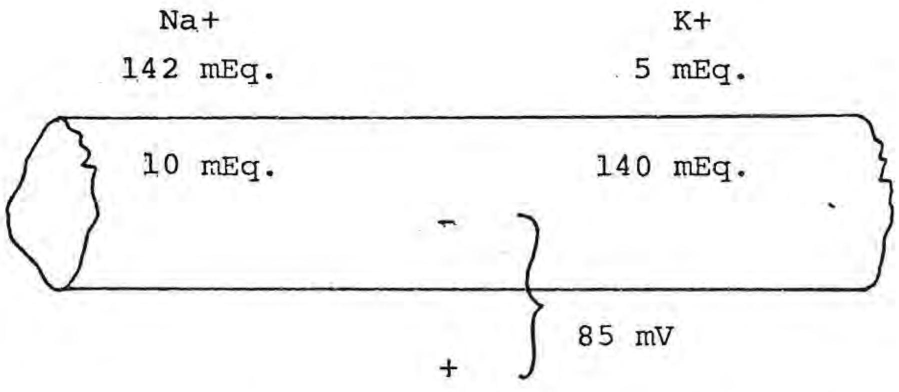


Figure 5.2. Concentration gradients for sodium and potassium for axon membrane at resting state (After Guyton 1979)

When the neuron is triggered, the membrane potential breaks down, and the voltage on the outside drops momentarily. The inner signal sends the membrane potential through a series of changes called the action potential (Guyton 1979). At first the membrane potential becomes positive, but a few ten-thousandths of a second later it returns to the very negative level, thereby forming a nerve impulse. It is this impulse (or action potential) that is transmitted along the nerve fiber, from one part of the body to another.

In the active nerve, the flow of sodium is inward, so the inside of the cell becomes relatively positive during the action potential, or depolarization, as it is sometimes characterized. The inward flow occurs because the membrane permeability to sodium increases. The more the membrane potential decreases, the more easily the sodium ions can pass through the membrane. Eventually this reaches a limit and the permeability to potassium increases until the neuron is restored to its resting conditions. Meanwhile, the chemical activity advances down the line, transmitting the action potential and producing the inward flow of sodium ions, much like an energy wave. When the nerve impulse passes, the sodium pump goes to work again and restores the negative electropotential inside the cell. The movement of the action potential is depicted in Figure 5.3.

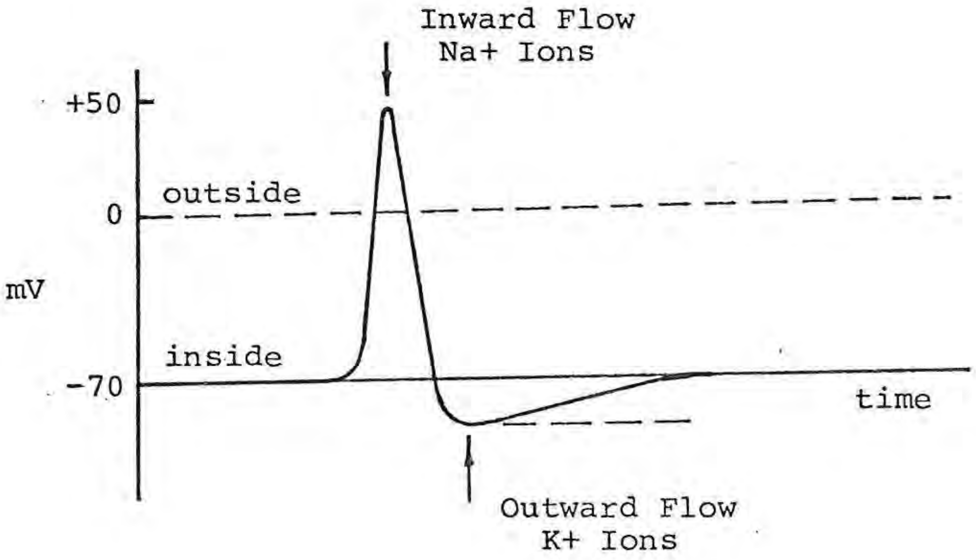


Figure 5.3. Movement of the action potential.
(From Easton 1974)

Neurons are still believed to be the prime movers in the affairs of the mind, but the class of glial cells, more abundant in the brain than neurons, may be contributors as well. They help to insulate the neurons from each other and service them with supplies from the blood. But they may also be active in the thinking process and in learning, though this is still a matter of conjecture and controversy.

SYNAPTIC JUNCTIONS

The synapse is the medium through which impulses are transmitted from one neuron to another; it is the junction between the terminal ends of an axon of one neuron and the dendrites or the cell body of another (Matzke 1972). A one-way street with traffic lights, it is capable of passing some impulses and stopping others.

Figure 5.4 shows the synaptic knob of a typical fiber from an axon making contact with a dendrite. The terminal has many small vesicals that contain transmitter substances. When a nerve impulse reaches the ending, momentary changes in its membrane structure allow a few of the vesicals to discharge the

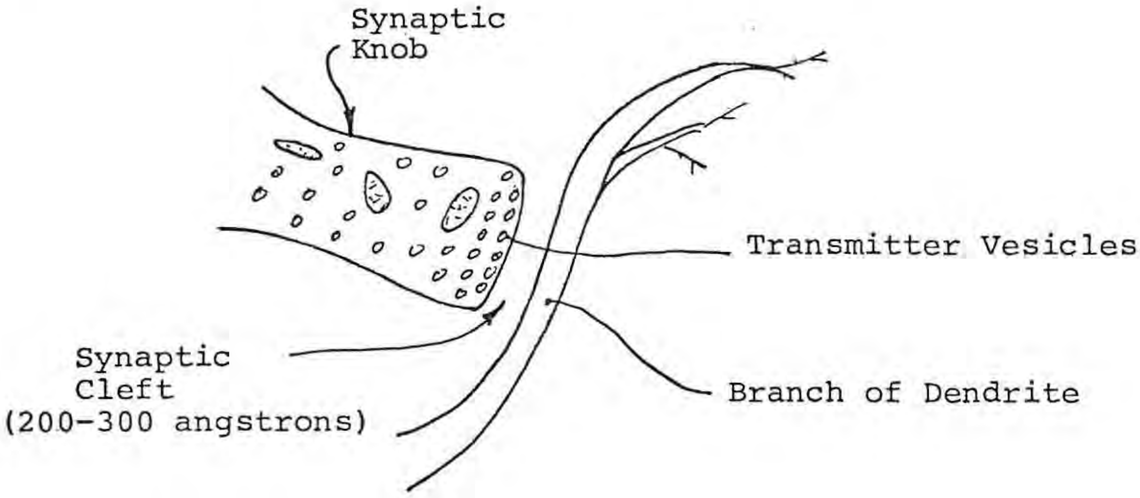


Figure 5.4. A typical synapse. (From Guyton 1979)

transmitter substance into the synaptic cleft -- the small gap between the knob and the dendrite (Guyton 1979).

Different kinds of transmitter substances are known to exist. Some of them, like acetylcholine or norepinephrine, are excitatory in nature, while others, such as glycine or gamma aminobutyric acid, are inhibitory. An excitatory transmitter tends to increase the permeability of the neuronal membrane to which the synaptic knob is attached. This allows sodium ions to flow to the inside of the cell, thereby increasing the positive charge inside the cell -- the post-synaptic potential. If this rise in potential is high enough, an action potential is initiated in the post-synaptic neuronal axon. An inhibitory substance, as one might suspect, tends to decrease the post-synaptic potential, making the neuron more resistant to the formation of an action potential.

A terminal can thus excite the neuron to which it is attached or can inhibit it, depending on the type of transmitter substance it releases. But all knobs derived from the same axon secrete the same type of transmitter substance. Therefore, neurons are either excitatory or inhibitory and cannot be both.

It is common for synaptic knobs from different neurons to be attached to the dendrite or body of a given neuron. Transmitter substances of different types might therefore act in concert on the neuron. In such a situation it is the resultant of the combination of excitatory and inhibitory effects that determines whether the neuron will fire or not. The neuron may thus be viewed as an integrator. If the sum of the influences on it is above a threshold of excitation, it fires; otherwise it does not.

The net excitation of a neuron may not be enough to initiate an action potential, but the neuron may still become facilitated; i.e., it may become more excitable to impulses from other synaptic knobs. When the excitation is above the threshold, the neuron will fire, and it will continue to fire so long as the potential remains above this threshold. Furthermore, the higher the positive potential, the more rapidly will the neuron fire.

Not all neurons exhibit the same action potential pattern. Some have different thresholds from others. Some have higher firing rates; some have lower rates. One cell may have an impulse rate of 25 per second; another may have a rate of 1000 per second. The transmission speeds may also be different; these may vary from 1 meter per second for the very tiny fibers to 100 meters per second for large fibers. In short, there are many different types of neurons with different response characteristics (Guyton 1979).

NEURAL NETS

The large number and many kinds of neurons make possible an extremely flexible albeit complex nervous system. They form myriad combinations, with thousands or millions tied together into neural nets or neuronal pools to perform one or another function. The nets may differ in any one of a number of ways. They may differ as to the number and type of input or output fibers, the types of neurons in the net, their threshold levels or firing rates, the manner in which synaptic knobs are supplied to other neurons, or in general their overall organization. It is the logic of these organizations with which we are concerned here.

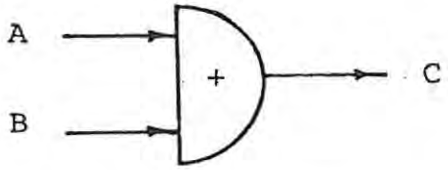
Neural nets may be compared with logical nets. To this end, take any two declarative sentences, A, B, and form the conjunction, A and B. We know that A can be true or false and that B can be true or false, though we can't tell which until we see the sentences. Since the conjunction, A and B, is itself a declarative sentence, it too must be true or false, and its truth value depends on the truth value of each one of its components. In fact, A and B is true only if A is true and if B is true. This logical situation can be summarized in a table of values, or truth table, as follows:

A	B	A & B
true	true	true
true	false	false
false	true	false
false	false	false

Generalizing the conjunction to the operator "+," letting A, B, ... etc., stand for elements of any appropriate set, and using 1 and 0 for the "truth" values, the table of values for the operator becomes:

A	B	A + B
1	1	1
1	0	0
0	1	0
0	0	0

The logic may now be interpreted in terms other than declarative sentences. Instead of the conjunctive arrangement of sentences, it may represent a summative electronic switching circuit, as shown in the following schematic diagram.



In this interpretation of the logic, the values 1 and 0 are read as ON and OFF, respectively, and the operator + identifies the type of circuit. The switch inputs, A, B, are then either ON or OFF, and the switch output, C = A + B, is either ON or OFF. For this circuit the switch is ON if both A and B are ON; otherwise it is OFF. The table of values for the switch summarizes this relationship.

A	B	C
ON	ON	ON
ON	OFF	OFF
OFF	ON	OFF
OFF	OFF	OFF

Might this logic be interpreted to represent a certain organization of neurons?

The conditions on the logic are clear: If the output is to be 1, A and B individually must have the value 1. But if either input is 0, the output is necessarily 0. There can be no deviation from these conditions. In this voting system the individual can exercise a veto.

In the voting system of the neuron, however, the individual does not have a formal veto right. He may exercise a great deal of lung power and thus strongly influence the election, but a simple negation may not be adequate. The activation of a neuron does not depend on the stimulus conditions of any single synaptic knob; it is a function of the aggregate stimulus. This does not mean that the majority rules. Most of the knobs as a group might present only a feeble voice, so a very vocal minority could control the response. All of the influences have to be taken together. If the stimulus on balance is excitatory and above the threshold, the neuron will fire, and it will fire with a particular pattern. Generally, the stronger the excitation, the greater the firing rate.

To see what we are up against in formulating the neural logic for our simulator, consider just the neural structure of the retina of the eye. The retina contains at least eight different types of neurons, though only three of them are generally called basic, in the sense that they are in the main stream of the visual circuit. The three basic types are rod and cone receptor cells, bipolar cells, and ganglion cells.

Modifications of the dendritic or receiving end of neurons, rods are slender, elongated formations. They are highly sensitive to light and pool their inputs in converging circuits so are useful receptors in dim light. Cones are another modification of dendrites; they are shorter and thicker, less sensitive, and are used for color vision and brightness descrimination.

A layer of pigmented cells covers the rods and cones. Light entering the eye causes these cells to stimulate the rods and cones chemically. The pigment migrates among the receptors in amount according to the degree of retinal illumination, increasing in brighter light.

Rod and cone cells attach to bipolar neurons; i.e., their axons synapse with the dendrites of the bipolar cells. The fovea, or central part of the retina, is populated solely by cones, and these cells synapse in a one-one relationship with the bipolar cells. Away from the center, however, there is a progressive convergence of rods and cones on single bipolar cells.

This synaptic relationship extends to the next layer of the retina, containing the ganglion cells. In the fovea there is a one-one relationship, and in the periphery a many-one relationship, between the bipolars and ganglions.

Figure 5.5(a) illustrates the network of neurons in the retina and suggests the complexity of the visual system. It shows nine receptor cells at the top connecting vertically with bipolar cells and those in turn connecting to the ganglion cells.

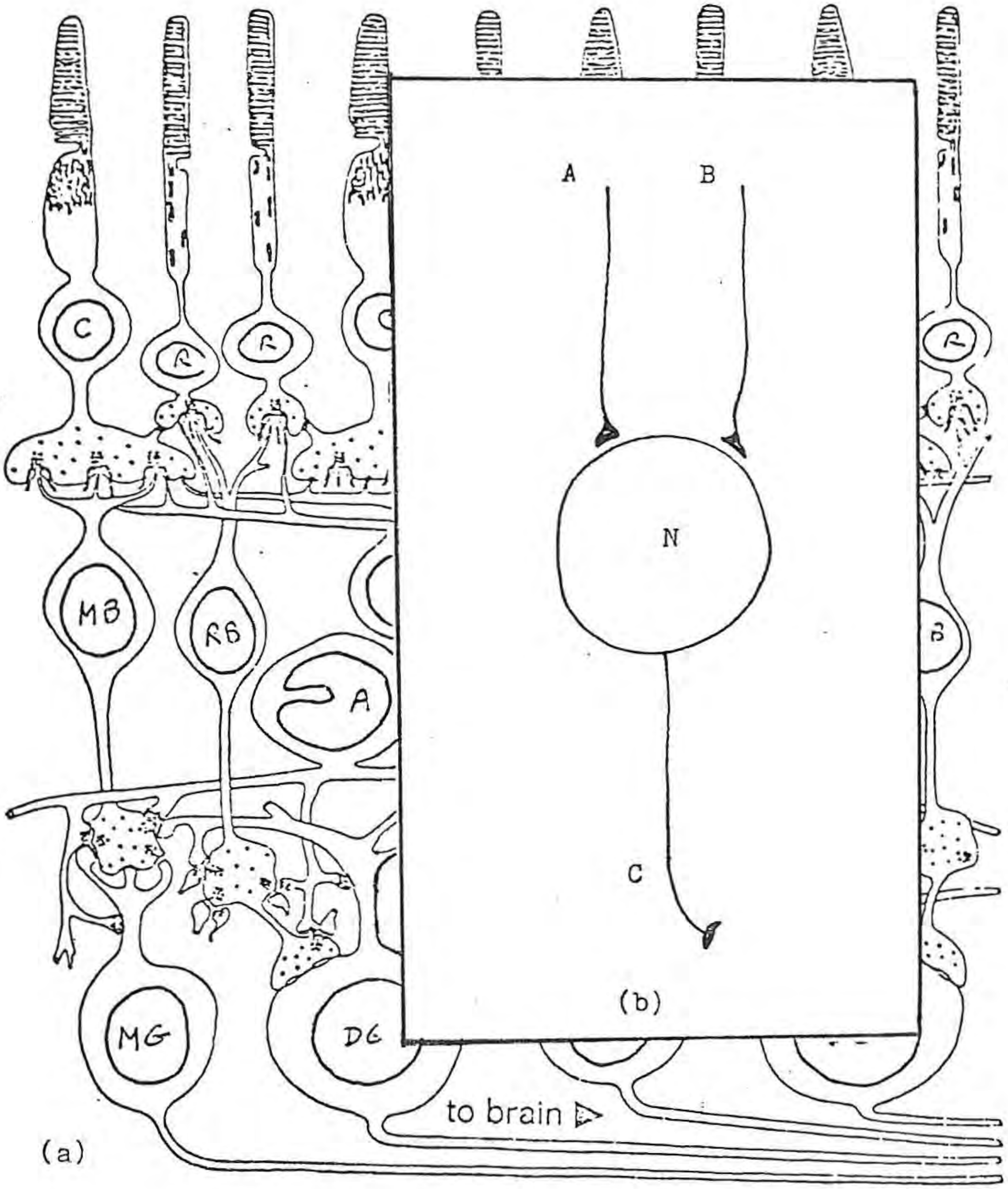


Figure 5.5. (a) Nine of the millions of receptor cells of the retina shown in schematic form to suggest the complexity of the eye. C, cone; R, rod; MB, midget bipolar; H, horizontal; MG, midget ganglion; DG, diffuse ganglion. (b) Schematic of a 2-signal input, 1-signal output system.

It also shows other neurons that are not part of the direct conduction path from the receptors. These include the amacrine and horizontal cells.

Horizontal cells are contained in the layer of cells made up of bipolar cells, and they connect the receptors with the amacrine cells. The amacrines modify the activity between the bipolars and the ganglion cells. They have no axons and they branch out among the bipolars and the ganglions. They may be concerned with reverberating circuits (Matzke 1972).

As a first formulation, consider the neural organization in which only two neurons, A and B, act on a given neuron, N, which has an action potential represented by C, as in the insert in Figure 5.5(b).

Suppose that both A and B are excitatory and that the threshold of excitation for N is E. Suppose further that each neuron has three action potential states: zero action, normal, and hyper. These firing rates can be represented as follows:

A: $0, a, a + \alpha$
B: $0, b, b + \beta$
C: $0, c, c + \gamma$

Presuming that two hyper stimuli are necessary to produce a hyper response, a table of values for the logic of this organization can be formed if the parameters are made to satisfy some set of conditions such as:

$$\alpha, \ \beta > 0, \ \alpha > \beta,$$
$$a + b = E,$$

and
$$a > b > \alpha > \beta.$$

As shown in Table 5.1, this neural organization has a complex, multi-valued logic, yet it is still vastly over-simplified. For one thing, a neuron usually has several, if not many, hyper states; indeed, the rate of firing may range over a continuum

A	B	C
$a + \alpha$	$b + \beta$	$c + \gamma$
$a + \alpha$	b	c
$a + \alpha$	0	0
a	$b + \beta$	c
a	b	c
a	0	0
0	$b + \beta$	0
0	b	0
0	0	0

TABLE 5.1 Logic values for a 2-signal input neural organization with 3 action states.

of values. Secondly, the neuron could be in a facilitated state of firing already, the result of prior stimulation. Again, the organization doesn't include inhibitory influences. And it doesn't have feedback connections -- synaptic knobs which reach back to fasten onto branches feeding the neuron, possibly producing repetitive or reverberating circuits.

The net is an example of a converging circuit (Guyton 1979). Here, a number of fibers from one or more source neurons converge on a single output neuron causing especially strong stimulation. This type of circuit is useful in that it allows impulses from different sources to produce the same effect, viz., the output of the neuron. It can also perform almost any kind of selective function by employing subcircuits which filter out unwanted conditions.

Another type of circuit is the diverging circuit. Instead of a number of fibers converging on a single fiber, it works the other way around -- one fiber feeds to several others. In this respect it is an amplifier, because a signal from a single nerve fiber causes an output in many different fibers (Guyton 1979). In the control of skeletal muscles, for instance, stimulation of a single motor cell in the brain under appropriate conditions sends a signal down to the spinal cord and then to the muscles to stimulate as many as 15,000 muscle fibers.

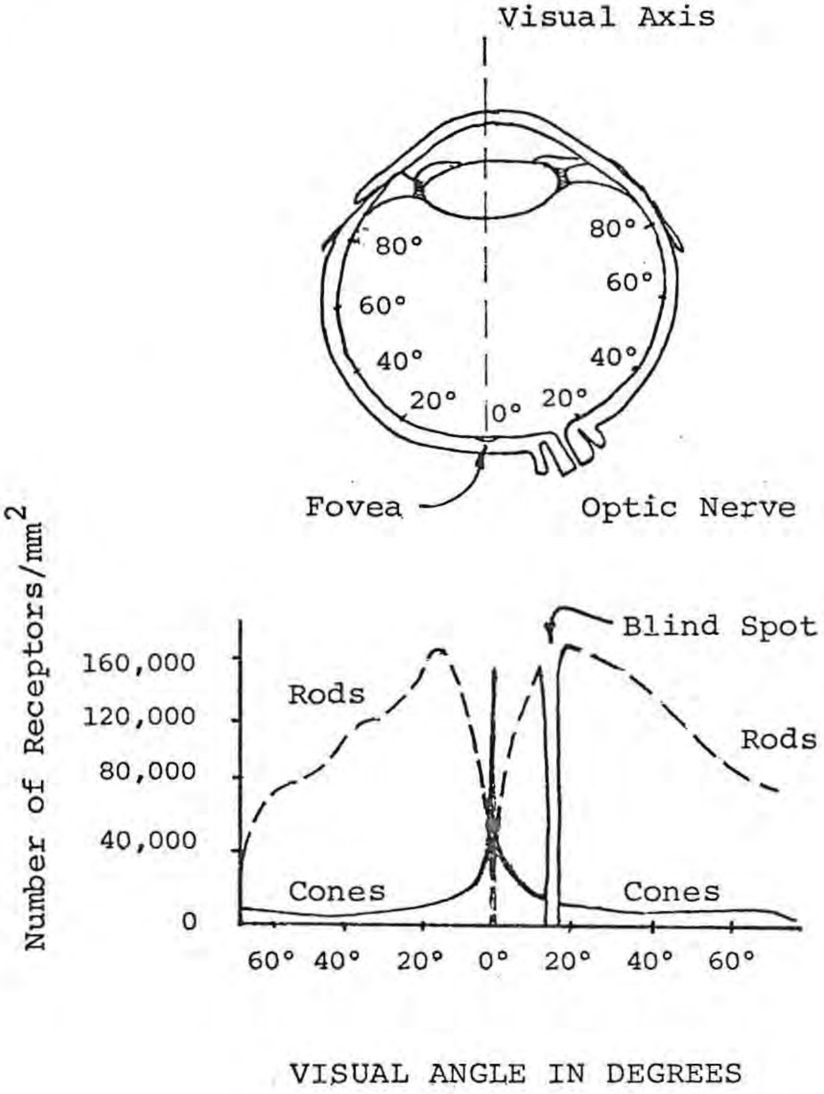
The diverging circuit is common in the sensory nervous system, too. By branching into several different directions at the same time, the same information is distributed to different places. When a limb moves, for instance, the sensory information from the joints and muscles caused by the movement is transmitted by such a circuit to the neural nets of the spinal cord, cerebellum, thalamus and cerebral cortex (Guyton 1979).

STRUCTURE OF THE VISUAL SYSTEM

The human eye, a globe approximately 25mm in diameter, consists essentially of three coats enclosing the transparent refractive media -- the cornea, lens and the fluid in the intervening spaces. The innermost layer is the retina and contains the neural elements responsible for sensing radiant stimuli -- about seven million cones and 120 million rods. An opening in the iris, which acts as a diaphram, allows varying amounts of light to pass into the chamber of the eye. Muscle fibers attached to the ciliary body of the middle coat contract and expand to increase and decrease the refractive power of the lens, a capability known as accommodation.

An image, commonly known as the proximal image, is formed on the retina, the more highly specialized portion of which is called the fovea. The center of the fovea, subtending an angle roughly 1 degree, or 400μ across, provides the highest degree of visual acutiy. (A micron, μ, is 10^{-6} meters.) Within a zone about 600μ across there are no rods and approximately 34,000 cones. Beyond this limit, rods begin to appear and their proportion to cones increases progressively. The total number of cones in the so-called "inner fovea" (an area about 1500μ across and subtending an angle about 5 degrees at the nodal point of the eye), amounts to 115,000. The diameter of the entire central area (including the parafovea and the perifovea) is roughly 5000μ to 6000μ (Davson 1972).

A simplified representation of the eye is given in Figure 5.6, showing projections of the density distribution of rods and cones.



<u>At 0°</u>:
Rods at minimum density, cones at maximum density.

Figure 5.6 Density distribution of rod and cone receptors across retinal surface. (From Haber 1969)

The eye is basically an outpost of the brain, a peripheral sensor connected to the cortex via the visual nervous system. The receptor cells of the retina connect synaptically to bipolar and then to ganglion cells in the retina, with horizontal and amacrine cells providing extensive lateral interconnections.

The ganglions are 3 to 4 inch long cells that lead outward through the optic nerve and tract to the lateral geniculate body (see Figures 5.5 and 5.7) (Kaufman 1974, p. 49).

As Figures 1.1 and 5.7 show, these fibers decussate (cross) in part, so that left and right half-fields receive exclusive right and left cerebral hemisphere representation. That is, the

> fibers from the nasal halves of the retinae decussate in the optic chiasma, so that each optic tract contains fibers from the temporal half of one retina and the nasal half of the other. A visual stimulus, arising from the right half of the field, is therefore conveyed exclusively along the left optic tract and thus to the left cerebral hemispheres ... (In primates) about equal numbers of fibers are crossed and uncrossed. (Davson 1972, p. 482)

Fibers in each optic nerve number about 1,000,000. After the two tracts partly cross at the optic chiasma, they tie to the lateral geniculate bodies, though some fibers go instead to the superior colliculus in the midbrain. Only a small portion of the optic tract fibers actually go to the superior colliculus, but it is enough to "suggest that visual responses to light would occur in the absence of an occipital cortex; in fact, however, only pupillary responses, which ... are mediated by fibers relaying in the pretectal nucleus, are obtained in the absence of a functioning cortex" (Davson 1972, p. 484). The fibers in the optic nerves represent 38% of the total sensory input.

The great preponderance of the optic tract fibers project on to the lateral geniculate bodies, the intermediate stations in the thalamus in the midst of the brain.

> (Each) neuron in the geniculate body predominantly represents a minute region of the retina . . . (This) nucleus is layered in such a manner as to keep the messages from right and left eye separated and to forward them independently upward in the optic radiation. Because the optic radiation fibers mostly connect the two eyes in a single cell in the cortex, the geniculate body is the last station in which the message

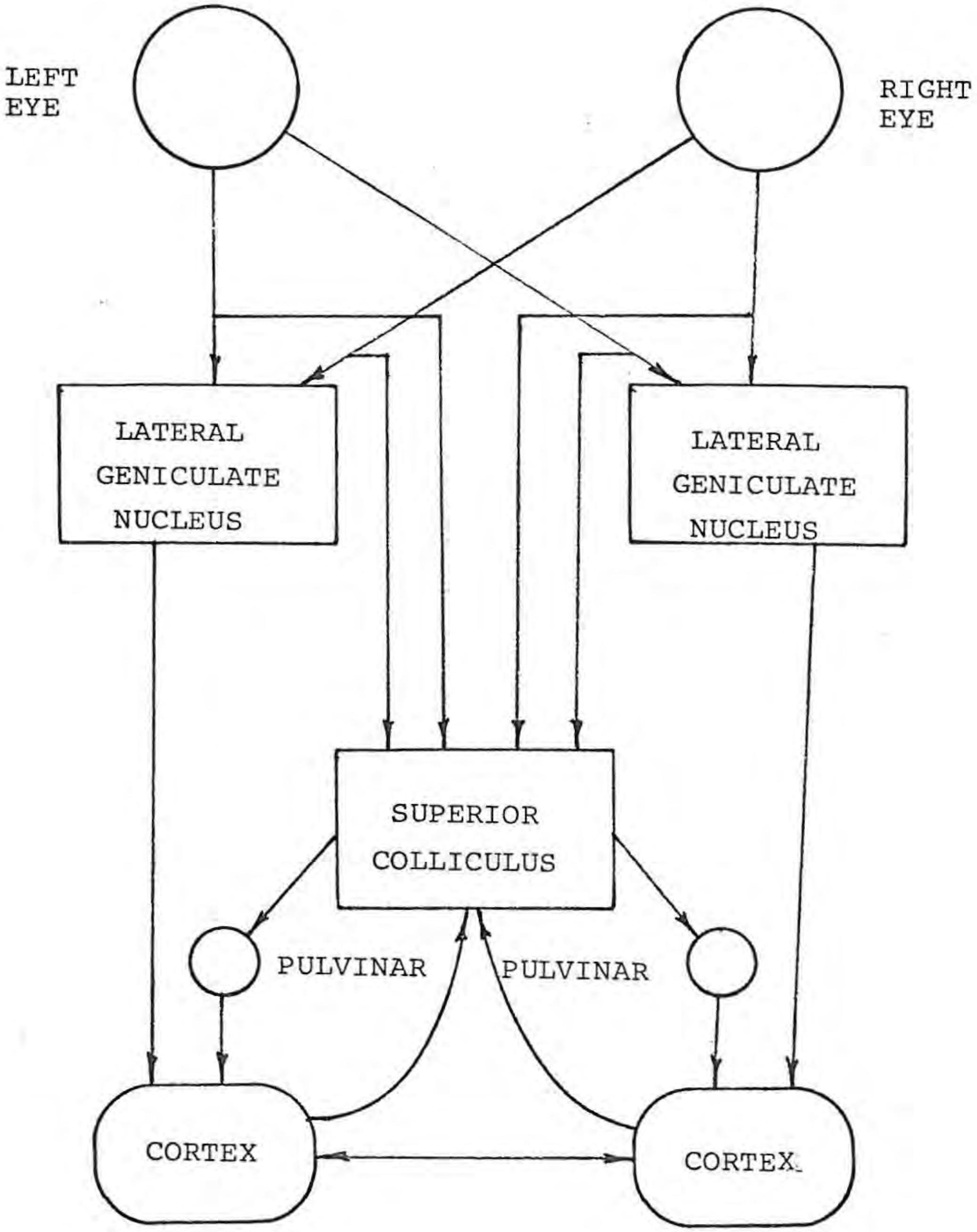


Figure 5.7. Interconnections among some of the more important portions of the visual system. (From Kaufman 1974)

> from each eye can still be individually influenced -- also by nonvisual inputs to it -- before binocular treatment of it sets in (Granit 1977, p. 105).

According to Davson as well, there seems to be a sufficient separation of the fibers from the two eyes that the fusion of the retinal images required by binocular vision cannot take place at this level. In this respect, then, the lateral geniculate body is regarded as a sorting center that rearranges the crossed and uncrossed fibers that had become quite mixed in the optic tract. Nevertheless, "there is some evidence that the message is modified, and this modification is effected not only by activity on the part of geniculate cells, but also by corticofugal fibers, i.e., by fibers originating in the occipital cortex, which, by either excitatory or inhibitory activity, modify the responses of the geniculate cells to the retinal impulses . . . By this feedback arrangement the cortex is able to modify and control the message it receives" (Davson 1972, p. 485).

Along the main path the fibers now number about six times that in the optic tract and proceed from the lateral geniculate bodies to the occipital portion of the brain. According to Granit, any single fiber from the geniculate body has terminals on 5,000 neurons in the primary visual area (Striate area or area 17) and each of these neurons is in contact with 4,000 other neurons (Granit 1977). Studies of the cortex have led to the representation of the projection of the retina on the visual cortex by a laying out of the retina on a point-to-point basis. However,

> from a strictly anatomical point of view this point-to-point projection, in the sense of a single cone being connected to a single bipolar cell, which is connected to a single ganglion cell, and so on, is not possible; in the retina the one-to-one relationship between cone and optic nerve fiber only holds good in the central fovea, and even here it is only a functional relationship since impulses from a single cone have subsidiary paths which permit a spread of their responses outwards to several ganglion cells. Similarly, as we have just seen, in the lateral geniculate body, although there are

> no internunciary neurones, each fiber of the tract ends on a number of geniculate cells, and a further dispersion is possible in the cortex by intracortical association cells. The point-to-point relationship is therefore a functional one, in that there is a preferential path from one cone, say, to one cortical cell. (Davson 1972, p. 490)

Even the smallest lesion in the visual cortex, leading to degeneration, always involves cells in all six layers of the geniculate body. This indicates that the conducting unit is six fibered and that therefore fusion of the temporal field of one eye with the nasal field in the other is possible in the visual cortex. Further, "complete destruction of one occipital lobe is followed by complete cellular atrophy of the homolateral geniculate body, hence the cells of this body project exclusively on to the occipital cortex of the same side" (Davson 1972, p. 491).

Sharply differentiated from, but closely related to the striate area are the neighboring areas 18 and 19, the parastriate and peristriate areas respectively. "Cells of Area 17 connect by short axons to Area 18, whilst from this area connections are made to Area 19 and back to the striate area" (Davson 1972, p. 491). Area 18 appears to be most closely concerned with integrating visual activity in the two hemispheres.

Since cortical visual impulses pass exclusively to the striate area, any higher visual functions involving complex associations, such as combining hearing with vision or the visual guiding of motor activity, must also involve the striate area. But learning involves areas 18 and 19 as well, for bilateral extirpation of these areas causes the irrecoverable loss of learned habits, although re-learning of the habits can occur. "If the temporal lobes were also removed, all possibility of learning, or re-learning, was lost although the removal of the temporal lobes alone was without influence either on the learned habit nor yet on the power of the animal to acquire it. Thus the temporal lobes, in some way, are able to act for the visual association areas in the learning of visual discriminations involving form ... Since the striate area is not directly connected with the temporal lobe, the learning in the absence of Areas 18 and 19 is presumably brought about by the mediation of subcortical links e.g., by way of corticofugal fibres from the striate area to the pulvinar of the thalamus, and thence from the pulvinar to the temporal cortex..." (Davson 1972, p.493-4).

Area 17 also has the characteristic, perhaps unique among symmetrical points on the cortex, that it does not respond one to the other when stimulated electrically, thus showing the probable absence of interhemispherical connections between the sides. The corpus callosum is the interhemispherical tract that provides such connections, but relative to Area 17 there appears to be no doubt that it is at the junction of Area 17 with Area 18 that the great majority of the posterior callosal fibers project, and it is here, too, that the vertical meridian projects. It would seem that "the representation of the visual world is on a continuum, the neurones associated with the vertical meridian and their callosal connections being the hyphen necessary to bring together the two half-fields" (Davson 1972, p.497). As the main bridge between the symmetrical halves of the brain, the corpus callosum, with its roughly $2x10^8$ nerve fibers, makes possible the functioning of the two hemispheres as one single brain.

As important as the striate cortex appears to be, it is still "merely one of the first brain sites where some reorganization of the sensory message takes place before it is delivered to other portions of the brain for an elaboration I will call perception" (Granit 1977, p.63). It, like the other primary sensory projections, does not represent sites of conscious perception.

According to Granit (1977):

> any portion of the cerebral cortex can be removed without causing loss of consciousness. It is, however, inevitably lost when the function of the higher portion of the brain stem is interrupted by injury, pressure, disease, or local epileptic discharge. (p. 76)

He adds further that

> (the) living brain responds with electrical signs of alertness (arousal) to electrical stimulation of the brainstem within a region whose role seems to be to collect branches from all incoming (afferent) fibers from the various sense organs and to make use of the information obtained through them to activate the cortex of the entire cerebrum (Magoun's reticular activating system). (p. 79)

According to Penfield, too, the stream of visual information comes to the higher brain-stem (optic thalamus) and detours out to the visual cortex, then it flows back to the higher brain-stem. The visual sensory cortex is a way station between the eye and the higher brain-stem (diencephalon). Each sensory input gives off collateral branches on its way to the thalamus. These collaterals feed into the reticular formation of the brain-stem. This may give the reticular formation a means of inhibiting or reinforcing incoming sensory messages in relation to the thalamic or cortical reception of those messages.

The centrencephalic system of functional integration, which involves the reticular formation of the brain-stem plus the collateral branches to the thalamus, the uppermost nucleus of the brain-stem, makes possible the sensory-motor reaction, as well as conscious reaction and planned action. The stream of nerve impulses (efferent) that control voluntary activity passes from the higher brain-stem outward, making a detour to the motor cortex, then goes to the lower brain-stem and spinal cord and to the muscles.

There is an enormous number of interconnected cells in the brain, and we have seen that activation of a very large number is required for perceptual awareness to occur. (There are, for example, 5×10^7 cells/cm^3 in the visual cortex alone. Many of these eventually tie to cells in the motor cortex, which contains 10^7 cells/cm^3. The cerebellum itself contains about 10^9 cells, and this is seemingly an ancillary portion of the brain.) The large requirement is demonstrated in experiments in which the exposed brain of surgical patients was stimulated with electrical probes. Whereas an individual shock elicited a virtually instantaneous evoked potential in a cell, "it required a whole series of shocks before the patient registered conscious awareness of the stimulus in the form of a percept. In fact, the interval or latent period was as long as half a second" (Granit 1977, p. 76).

> The latent period of the conscious response suggests that coengagement of the brain stem by a network of nervous loops is the most elementary assumption one can make to explain the onset and disappearance of awareness of an event that one has good reason for localizing to the cortical gray matter. It also means that when afferent nerve stimuli elicit fast movements, they are well underway before one becomes aware of them. This is true not only of reflexes but of acquired skillful responses as well. Such movements can now be traced at several sites by electrical recording within the brain, spinal cord, and muscles of monkeys. Formerly the experimenters were restricted to measuring the reaction time of human subjects, which implicitly was regarded as a conscious response indicated by the motor act of pressing a Morse key. Now it seems likely that this act, too, is completed long before it has reached the level of conscious awareness. Reaction times are of the order of 0.1 to 0.2 sec. If Libet and his coworkers are right about awareness requiring about half a second, then conscious recording of the act of pressing a key must succeed the motor response and turn up after the completion of the reaction time. (Granit 1977, p. 76-7)

It is commonly said in tennis circles that the player cannot actually see the ball bounce off his tennis racquet as he hits it, the argument being that the action is too fast to be observed. Putting the matter of visual resolution aside here, we can understand from the preceding evidence that the statement may be correct in one sense, but incorrect in another. It is true if it means that the player does not see the occurrence when it actually happens, i.e., coincidentally with the event, because the interval of occurrence is shorter than the latent period of consciousness. But the statement is not true if it means that the player has no conscious awareness of the happening at all. He does in fact see the ball bouncing off the racquet as his intuition leads him to believe. But the seeing is late; it occurs only after the ball has hit and moved away from the racquet.

The situation is analogous to our being able to see events in distant galaxies. We do indeed see stars explode. But because of the finite speed of light and the great distances to the galaxies, by the time we do see the displays the stars have already exploded and are long gone. In a similar way we do in fact see the ball hit the racquet, but because of the finite speeds of neural transmission (fibers in the visual system conducting at rates on the order of 20 to 40 meters per second and those in the motor system, being larger, taking 40 to 90 meters per second), the motor event does not reach awareness until after it has been completed.

Conscious awareness is an extremely valuable and very remarkable genetic adaptation, but because it requires a complex neural structure in order to be effective, it is slow. Perhaps for this reason humans are impatient to automatize their behavior and seem frustrated when they cannot do so.

RECEPTIVE FIELDS

Interaction among neurons may be in the form of enhancement or suppression; i.e., the synaptic connections between neurons can be either excitatory or inhibitory. Thus, for instance, a pooling of excitatory synapses on a bipolar cell in the retina would increase the likihood that it would become active. This kind of interaction (lateral summation) is useful in maximizing responses to low energy levels of light. If inhibitory synapses were attached as well, then lateral inhibition would occur, the extent of the inhibition depending on the logical structure of the interconnection and the input intensities. Lateral inhibition is useful to provide more complex coding when light levels are high. Figure 5.8 gives a schematic of the neural logic found in the horseshoe crab and believed to exist in man as well (Haber 1969, p. 41).

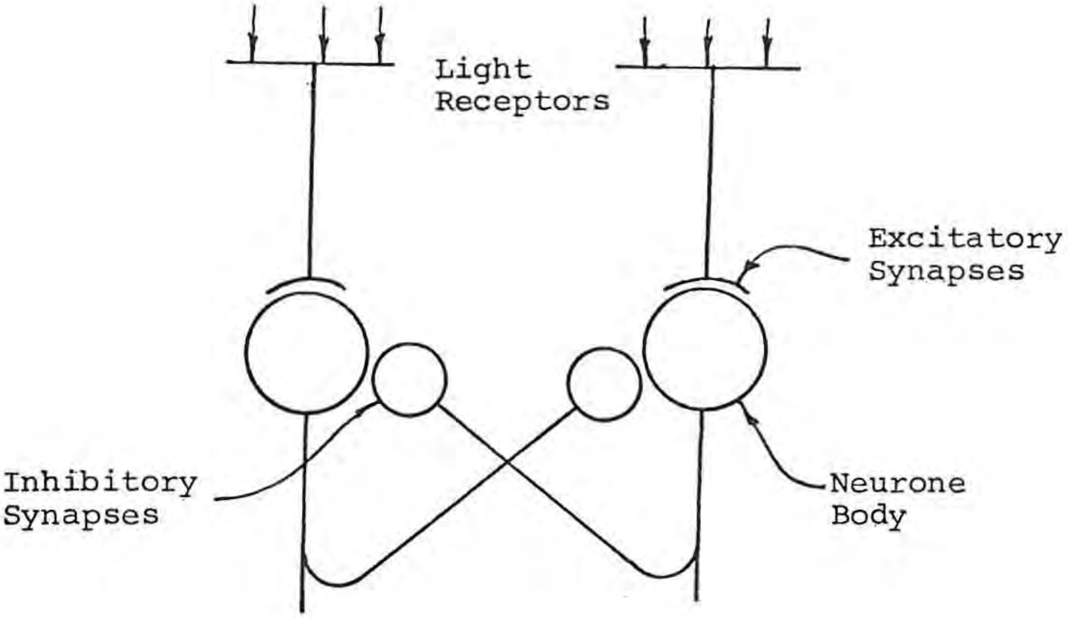


Figure 5.8 Diagram representing excitatory synapses between two pairs of receptors and ganglion cells and mutual inhibitory synapses between the two ganglion cells. (From Haber 1969)

The effect of the lateral inhibition is to reduce steady-state excitation, for if light falls uniformly on both of the receptors in the figure the inhibitory circuits are activated, suppressing the output from each ganglion cell. However, if light is absorbed by only one of the receptors, the ganglion cell to which the other one is attached will give no output and will thus not activate its inhibitory circuit; the ganglions will act as isolated cells.

In general, the receptors do not tie one-to-one to the ganglion cells. Adding to the complexity are the horizontal and amacrine cells, which affect the signal flow through the system, so that it is possible for many paths to be initiated from the receptor cells to particular cells downstream, such as the ganglion level, in the lateral geniculate body, in the visual cortex, etc. When the cluster of starting points is mapped out for a given downstream cell, the result is a receptive field for that cell. These receptive fields usually have well defined structures, as noted above. One such structure is the on-center, off-surround concentric field, shown in Figure 5.9.

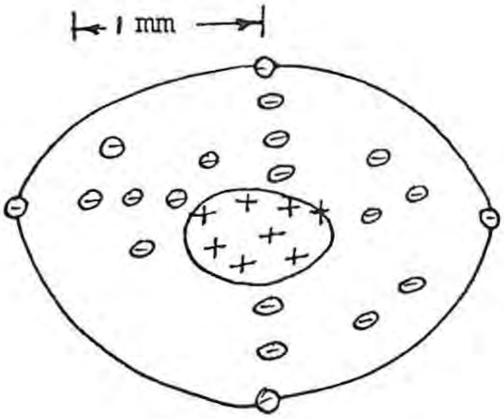


Figure 5.9 Schematic of the on-center, off-surround concentric receptive field at the ganglion level. Plus signs indicate an increase and minus signs as a decrease in activity for light on the receptors. (From Haber 1909, p. 43)

Another variety of receptive field is the off-center, on-surround. In this type the surrounding part of the receptive field signals the onset of light. In both types, however, large stimuli would tend to produce no response, since the light would fall on both parts and they would mutually inhibit one another. In general, relatively few receptive fields continue to signal the presence of unchanging light. While each receptor may continue to fire, the effect at the ganglion level will depend on the pattern of light and the shape of the receptive field.

> There are three important characteristics of the on-off inhibitory mechanisms as found at this level of the visual system. The first is that when light falls only on the on-center, it tends to increase the level of activity in the ganglion cell above its spontaneous firing rate. When light falls only on the off-surround area it tends to depress the level of activity of the ganglion cell below its spontaneous firing rate. Thus, the center is an excitatory area and the surround is an inhibitory area.

> Second, when light falls primarily on the on-center there is an increase in the activity level of the ganglion cell at the time of the onset of the light. The ganglion then returns rather rapidly to its spontaneous level, even if the light is left on. When the light is turned off, there is no further change in activity. If the light falls primarily in the off-surround area, there will be no change in the resting level of the ganglion cell when the light is turned on. When the light is turned off, however, there will be a rapid depression in activity which again will rather quickly return to baseline level, even if the light is left off. In this sense, then, the two parts of the receptive field are sensitive to the leading and trailing edges of stimulation over time, rather than to steady-state levels.
>
> Third, there is a mutually inhibitory characteristic to the two parts of the receptive field. Thus, light falling on the on-center area will tend to inhibit responses to light falling on the off-surround area and conversely. This effect does not show strikingly until light falls on both areas simultaneously, in which case we find a canceling effect being roughly proportional to the relative amounts of stimulation falling in both areas. In this sense, then, the on-center, off-surround receptive field is designed to be mutually inhibitory for large uniform illumination. It serves as an ideal mechanism by which the visual system can ignore spatial redundancy. Symmetric receptive fields of this kind will only be active when there is some spatial discontinuity in the stimulation falling on that part of the retina. (Haber 1969, p. 44-6)

By virtue of these properties, a graphical representation for which is given in Figure 5.10, if two adjacent areas of luminance, one more intense than the other with a fairly sharp edge formed by the luminance difference, is presented to the retina, the visual result is a brighter band on the bright side of the edge and a darker band on the dark side, thus enhancing the edge. This is the so-called Mach band (See Figure 5.10.a and 5.10.b).

Edge enhancement from the on-off type of receptive field organization also results from physiological drifts, tremors, and microsaccades that shift the receptors of the eye relative to the retinal projections every 10 to 100 milliseconds. At the edge of the light source a shift will activate a previously unstimulated receptor and deactivate a previously stimulated one, the former on one side of the light spot, the latter on

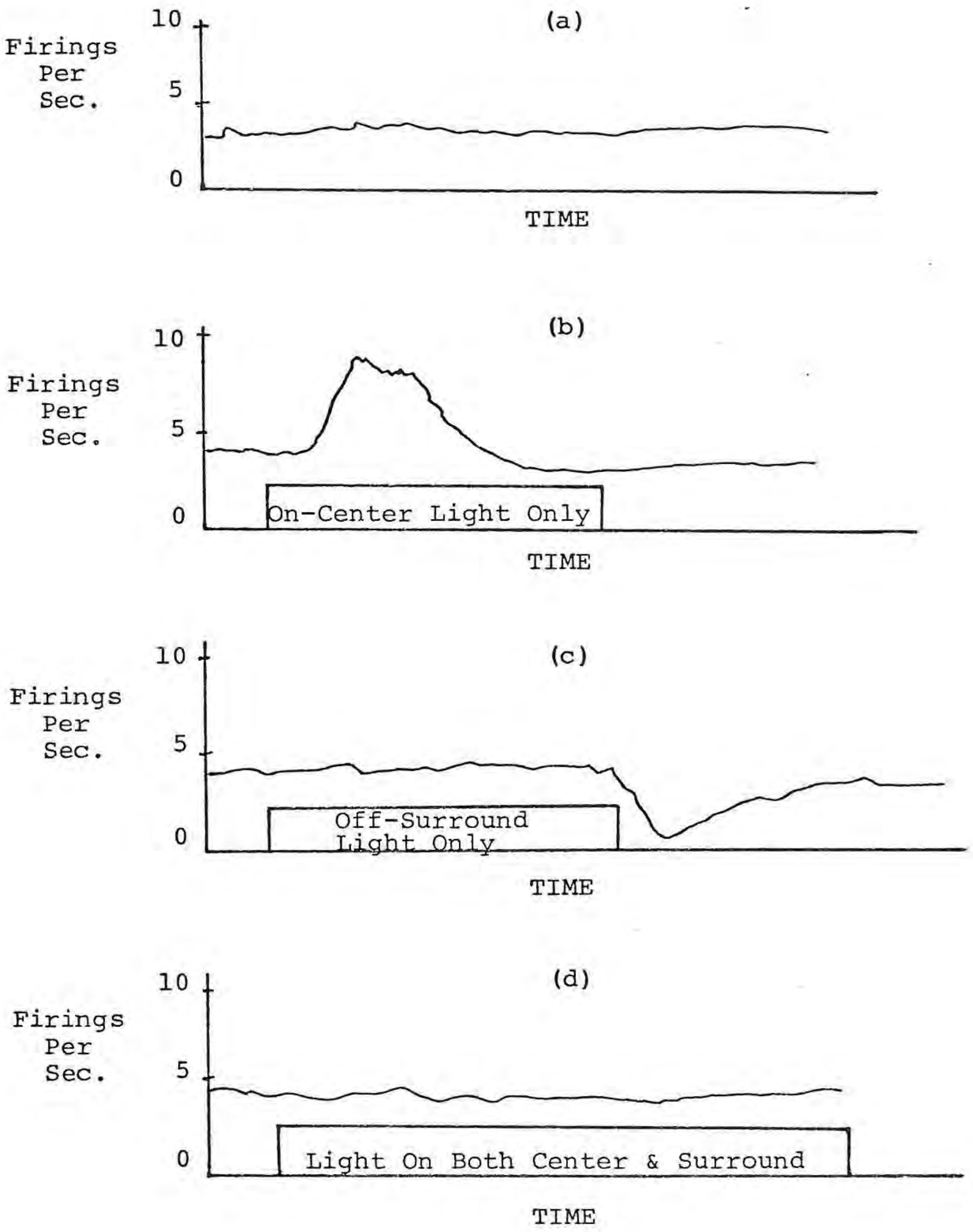


Figure 5.10. Functions showing changes in activity in ganglion cell for a) no light, b) light only on on-center, c) light only on off-surround, d) light on entire receptive field uniformly. (From Haber 1969, p. 45)

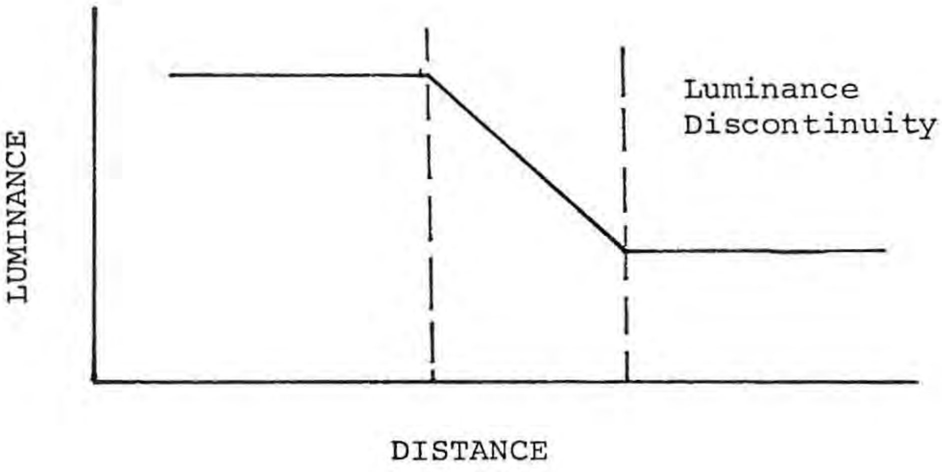


Figure 5.10.a. Schematic of luminance distribution across boundaries.

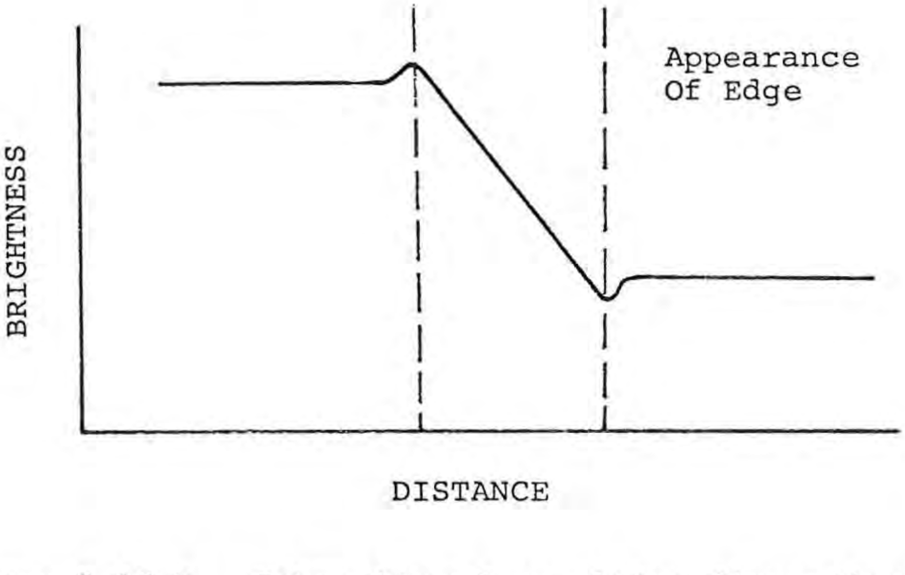


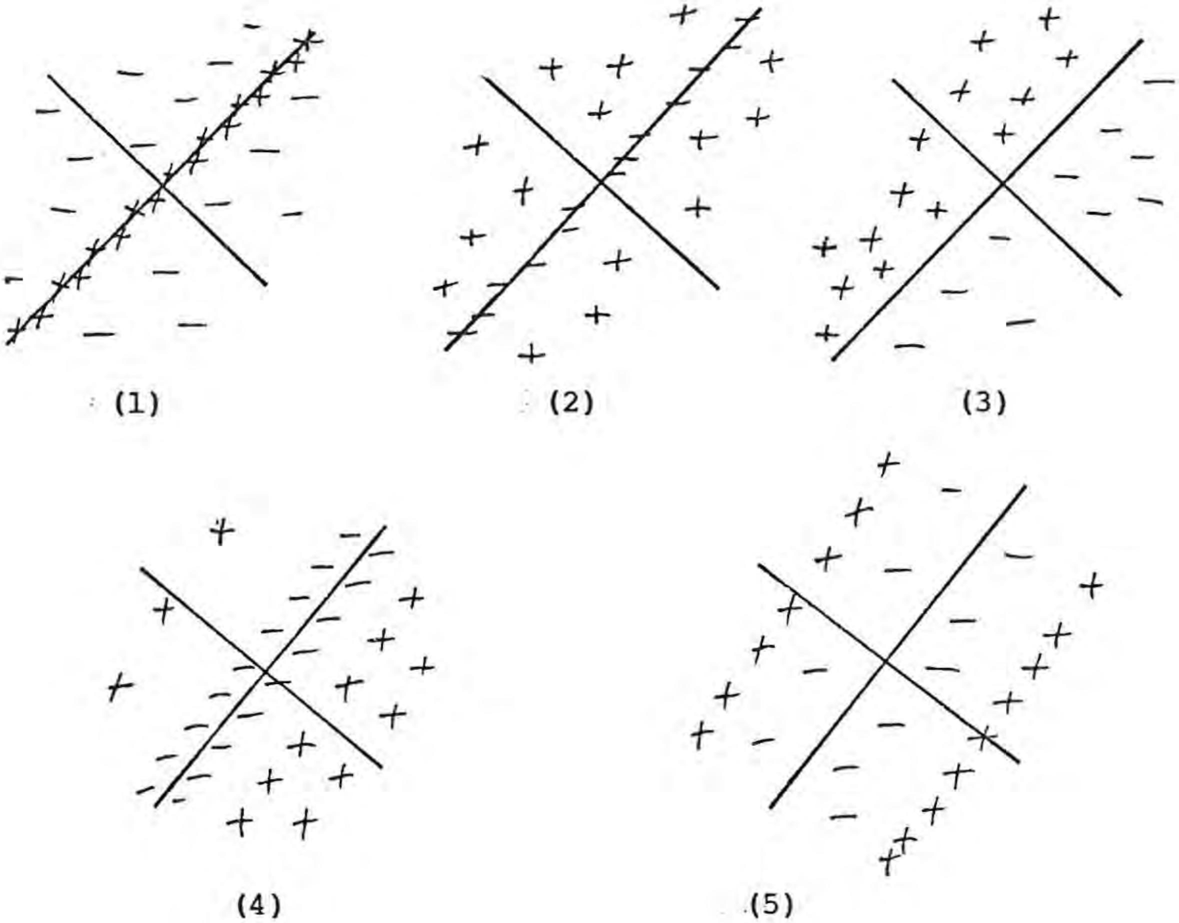
Figure 5.10.b. Schematic of resulting discontinuity in brightness at the boundaries of the surfaces of different luminances.

the other side. Small eye movements of this sort back and forth over the light source will signal the presence of an edge.

Receptive fields that have been mapped for cells in the geniculate body have shapes and properties essentially the same as those for ganglion cells. For either group, an optimal response

> usually depends only on the size, intensity, and location of a spot of light on the retina. If the spot is too large, the threshold for a response increases, but even diffuse light will produce some response if the light is intense enough. This latter property is found less at the geniculate level, where the penalty for exceeding the critical size is more severe. But at both of these levels, no shapes other than circular ones seem relevant, and no direction of movement seems better than any other. Thus, the specificity of coding at these levels is not too great. (Haber 1969, p. 53)

The receptive fields of cortical cells, however, are quite different, and have been described as simple, complex, and hyper-complex. Simple fields have antagonistic regions as do ganglion and geniculate ones, but they are most responsive to elongated stimuli oriented in parallel with the axis of the field. In Figure 5.11, for instance, the maximal response occurs to a narrow lighted bar for sample 1, to a dark bar on a lighted background for 2, and to an edge separating two stimuli of unequal intensity in 3, all oriented at 45 degrees.


(1) (2) (3)

(4) (5)

Figure 5.11 Schematics of sample receptive fields of simple cortical cells for diagonal orientations. All other orientations have been discovered. (From Haber 1969, p. 54)

So far as the detection of movement is concerned,

> All simple cortical cells will respond to a moving stimulus, but the orientation of the direction of movement is critical and specific to the orientation of the receptive field. In most cases the direction of movement did not matter, except for a few fields which had some asymmetry in the flanking regions. (Haber 1969, p. 53)

A field with asymmetry in the flanking regions is shown in Figure 5.11, sample 4. One having sensitivity with respect to rate of movement is shown in sample 5, which responds more vigorously to a relatively rapid movement because the transitions from + to - and from - to + would be close together in time only with rapid movements.

It is apparent that these simple cortical fields are edge and line detectors. "They are sensitive to lines of specified widths and orientations and edges of specified orientations. For most, the orientation and rate of movement is also specified. The sizes of these simple fields are relatively small, averaging about two degrees, with many as small as 15 minutes. They are found over most areas of the retina. Each field is specific to stimulation in its area -- hence these can provide information about where on the retina a pattern is located." (Haber 1969, p. 54)

Complex cortical receptive fields are different from simple cells in two important ways. They are larger, averaging 5 to 10 degrees, and often are as large as 20 to 30 degrees. Also, while they are generally sensitive to the same kinds of features, the location of the features in the field does not matter.

Hypercomplex cortical fields behave as if they were a combination of complex fields. Some respond to angles, for example. (These are most likely to be found in Area 17.) Others respond only when the patterns falling on the receptors of both eyes are not in perfect alignment. "This is most likely to occur when both eyes are focused on a nearby object. Because the eyes are separated by about two inches in our heads, slightly different retinal projections will fall onto the two retinas. A cell responding to the retinal disparity could provide coding for binocular stereoscopic depth." (Haber 1969, p. 55)

Thus the activity of a single cortical cell represents the changing activity of millions of retinal cells sampled over a long time. The arrangement of these cells in the cortex seems to hold a pattern across its layers and columns. If, for instance, a cell in a position in one layer responds to lines of a given orientation, a cell one layer down, i.e., down a column, will respond to a line of the same orientation but in a new location on the retina. The columns thus form a functional unit even across the eyes, since they tend to map onto both eyes.

We thus find several functions performed by receptive fields. There are edge detectors that locate discontinuities in luminance and may also respond specifically to orientation. There are line detectors for various orientations and widths. There are movement detectors for both edges and lines for given paths, velocities and even accelerations. And there are detectors for binocular disparity. Unfortunately, however, there is no evidence as yet that receptive fields exist for curved lines or for simple shapes like circles, which would be useful in tracking a tennis ball. Such shapes might be detected by a combination of cortical cells, or by more complex organizations --a likely prospect, according to Haber and Hershenson (1973, p. 369-70).

Another type of receptive field of special importance in visual tracking is one that could detect the scale of space, built up primarily from information about the textural changes in the retinal projection. In this field, the texture itself would be the visual feature to be detected. Given such fields, higher-order texture gradient detectors to signal changes in texture from one part of the field to another should be a natural outcome.

In the process of growing, one of the major developments that may be taking place is the acquisition of a metric for the scale of space which infants already possess. This would explain

> the infant's ability to respond to the constancy of objects and would still leave room for the integration of information available to the infant only as a consequence of his own movements. The relational information provided by the retinal projection alone could be sufficient to produce perceptual constancy but it may not be sufficient to produce the exceptionally fine acts of perceptual-motor coordination of adults. Certainly the pinpoint accuracy in motor skills achieved by athletes in many sports -- shooting in basketball and hockey, pitching in baseball, passing in football -- requires more than the maturation of fine muscle control. The visual space we perceive must have a very precise metric and that metric must be related to the size of our body and its parts.
>
> A system which responded to relational information as a consequence of its structure, and to metric information

> as a consequence of development (learning, adaptation, or differentiation), would be precisely suitable to an organism gradually maturing and growing over a number of years. The basic spatial information -- the ground with objects having constancy of size, shape and position spaced out on it -- would be available immediately and would provide a foundation for later development since it is based on those qualities of space which are permanent. The metric of this space would be changeable and could be continually modified as the organism's body size changes with age. Thus at every age, the organism would supply his own metric to the relational qualities of the scale of space depending on his size within that space. In this sense then, the perception of space is both innate and acquired. (Haber and Hershenson 1973, p. 369-70)

But what is this texture, upon which the scale of space might be based? In order to know what logic could be involved in the detection of texture and its gradients, we must know what kinds of properties it possesses. One possibility, as yet unproved, is that edges and contours are detected in response to spatial frequencies, into which the intensity discontinuities that make up the edges and contours can be analyzed.

> There is rather clear evidence that the visual system detects bars of specific widths and orientations, and also that it detects grating patterns of specific spatial frequencies. It is possible that these are quite independent properties of patterns that the visual system is tuned to detect, but parsimony would suggest some relationship should be found between them. (Haber 1969, p. 57)

Such a relationship can be established with a cell that responds to a <u>cluster</u> of the center-surround receptive fields aligned so that their centers are a certain distance apart, the distance corresponding to a desired spatial frequency. For the detection of surface texture, the fields would have to be finely tuned, since this texture is primarily of high spatial frequency (Haber 1969, p. 58).

There is, in fact, some indication that such groupings do exist. For instance, some ganglion cells have been shown to be maximally responsive to given spatial frequencies, while cortical cells have shown similar responsiveness but only when the orientation was properly aligned. Nevertheless, this is still a matter of speculation, requiring experimental verification.

Furthermore, since any portion of the retina might, at one time or another, be the recipient of stimuli characteristic of any one value of texture density, that portion must contain all of the receptive field clusters necessary to permit the full range of perceivable densities. If, for example, perception of the full range of textures required ten groupings of receptive fields (in the form of a cascade of simple to complex to hypercomplex receptive fields, say), then each receptor must be part of each of ten groupings. That is, it must be connected to each of ten cascade cells. Otherwise, that receptor would be unable to contribute to the perception of some one or more texture densities. If no receptor in a given area of the retina connected to a cascade cell defined for some density, then that area would be blind to the density. There would then appear to be a discontinuity in the scale of space.

Also, a certain minimum number of cascade detectors would be required, inasmuch as the texture density of perceptual space is a smoothly varying phenomenon, near to far. That is, there are no apparent discontinuities in the scale of space as it is normally perceived. Changes in the density of any segment of surface in space occur in strict accordance with the scale of space, the correlate of which is given in the governing rules of perspective on the space. There must be enough detectors to create this smoothly changing scale.

CRITICISM OF FEATURE DETECTORS

Distinguishing sharply between feature detection and feature identification -- a necessary condition in pattern recognition --, Pribram feels that feature detectors, while certainly not unimportant, play a somewhat limited role in perception:

> Feature detectors are, of necessity, built into the neural apparatus and, of necessity, they cannot be radically modified by experience if they are to do the job of detection. Feature detectors are therefore stable, "wired-in," native elements of the input systems which preprocess signals before further operations on them are performed. On the other hand, the mechanism of identification upon which recognition is based needs to be flexible and modifiable by experience. Because of the immediacy of recognition, however, identification must, at any given moment, share preprocessing with detectors. It is this sharing which has led to confusion about the two mechanisms and the feeling that features do the whole job. (1971, p. 324)

The detection apparatus must, however, be such as to allow for the paradoxical situation in which, on the one hand, a topological correspondence between receptor surface and the cerebral cortex is preserved and, on the other hand, the sensory system can, mysteriously, still function with very high efficiency even when it becomes damaged, through disease or surgery, and only the smallest part of it remains intact. According to Pribram, an animal in whom 80 to 90 percent of the input mechanism has been removed or interrupted is able to solve problems requiring discriminations of patterns differing only in detail (p. 122). Since it doesn't seem to matter which part of the input system is destroyed, the stored information has to be reduplicated over many locations. How is this possible?

How, too, do objects appear sufficiently consistent that we can recognize them as the same, independent of our angle of view or their distance from us? How do we recognize an object regardless of the part of the retina, and therefore of the brain, which is directly excited by the light coming from that object? The capacity for such size and object constancy is already developed in the human infant only a few weeks of age, so any easy explanation of the constancy phenomenon in terms of learning is brought into question, in Pribram's view. But what sort of mechanism would be required? What mechanism would simultaneously allow for the flexibility of perception and the constancy of recognition once distribution has taken place?

In response to these questions, Pribram describes a modified version of a process suggested by Gerhard Werner for somesthetic feature analysis:

> (A) cortical column is conceived to consist of input and operator neurons, and of interneurons and test cells. An input to a neural unit of the column that displays a receptive field is distributed to interneurons which in turn connect to an operator neuron. The interneurons are tunable -- i.e., they adapt and habituate, they have memory. Each interneuron thus acts as does a bin in a computer that averages the patterns of input to which it is exposed. Only when a pattern is repeated does structured summation occur -- nonrepetitive patterns simply raise the baseline and average out. Thus the operator neuron, sensitive solely to patterns of excitation is activated only when input patterns are repeated. The entire process is sharpened by feeding the output from the operator neuron back onto the input cell via a test neuron that compares the pattern of neural activity in the input and operator neurons. When match is adequate, the test cell produces an exit signal, otherwise the tuning process continues. Thus each cortical column comes to constitute an engram by virtue of its specific sensitivity to one pattern of neural activity, a "list" of interresponse times of a firing neuron or the wave form that describes the envelope of the firing pattern.
>
> Each cortical column is conceived as being connected with others by horizontal cells and their basal dendrites, which are responsible for inhibitory interactions. Whenever these horizontal cells are activated unsymmetrically, as they are by directional sensitive inputs, a temporary structure constructed of several columns is put together. These extended structures, dependent on hyperpolarization rather than on nerve impulse transmission, are composed therefore by the action of the junctional microstructure and constitute temporary neural states.
>
> We now have good evidence that the so-called association areas of the cerebral cortex exert a type of control over the input systems which is in many respects similar to that exercised when a zoom lens is extended and retracted. This function would have the effect of changing the number (and perhaps the complexity) of cortical columns that can be contained in such a temporary structure.
>
> The logic of the input systems can thus be conceived to constitute a filter on input, a screen that is being continually tuned by that input. One of the characteristics of the filter is that it constitutes a self-adapting system whose parameters of adaptation are controlled by its own past history and by the operations performed on it by other neural mechanisms. (1971, p. 130-1)

The current neurological state is thus seen as a summation of the events that have transpired for the individual to date -- the totality of historical forces which, together with current inputs, determine the manner in which patterned responses are produced. Put in this context, it is no wonder that a feature detection view of perception is sorely inadequate. But more specifically, what is wrong with the detection view is:

> First, the features analyzed are not the distinct features they appear to be. Second, the richness of the phenomena of perception is unaccounted for by the feature detectors so far discovered. And third, manipulations of sensory input during development have decoupled the effect produced on feature detectors as studied with microelectrodes from that produced on feature analysis as studied by behavioral discrimination. (Pribram 1972, p. 132)

THE INPUT PROCESSOR AS A PATTERN RECOGNIZER

Feature detectors, as such, are only a part of the complex fabric of the input systems. Along with other mechanisms, they are thought to provide the essential reference, the backdrop against which other more changeable configurations of neural events take place.

> They are the wired-in parts of the screen, the warp across which the woof of experientially sensitive neural microstructure is woven. At any given moment the fabric of the screen processes the neural events impinging on it -- preprocesses them on the way to subsequent cell stations. The warp of the screen is unaffected by the processing, but a residue is left on the woof, another thread has been woven into the fabric. (Pribram 1971, p. 325)

Identification is a necessary adjunct to detection and intimately related to it, involving a neural mechanism which, according to Pribram, incorporates the logic elements of the screen. Ordinarily, these logic elements -- the columns of cortical cells -- are more or less connected to each other by their directionally sensitive elements. The directional sensitivity of the receptive fields of cortical cells provides pointers to adjacent cells, thus turning a cortical column into a data structure, a list.

> Lateral inhibition, by separating logic elements from one another, structures the list. Each logic module, each list, can be thought of as a dipole which becomes polarized by the input signals . . . The electrical dipole could become constituted of the changes in molecular conformation . . . Conformational modifications can be measured by nuclear magnetic resonance spectroscopy and X-ray diffraction studies since each distinct conformation resonates at a different natural frequency. Large molecules, such as the lypoprotiens and glucoids which make up the synaptic and dendritic membranes in the brain's microstructure, are known to be liable to conformational change. Whenever a neural signal traverses such a membrane, conformational changes would tend to become stabilized, aligning molecular structures for the duration of the signal and for some limited time after. These temporarily stabilized conformations, if sufficiently extensive, would, in effect, produce electrical polarization of the microstructure. This polarization would be enhanced when the influence of each dipole on its neighbor was minimized through lateral inhibition. Without such inhibitory interactions, the alignment of dipoles would tend to weaken much as like poles of magnets aligned in parallel tend to disturb the alignment. The alignment of dipoles by input is therefore enhanced by the effects of temporal cortex stimulation on lateral inhibition,. . . an enhancement which provides constancy to the relationship between input and logic elements. This constancy also cuts the cortical system into smaller functioning units, allowing readier adaptation of each unit to its input. (Pribram 1971, p. 325-6)

In this system, preprocessing and modification brought about by experience are, in effect, interleaved in such a manner that some parts of the preprocessor are changed by the processing itself, making the neural mechanism self-organizing. The mechanism of detection, to work effectively, cannot be modified radically by experience. But the mechanism of identification, which needs to be flexible due to the variety of objects to be identified, and which, because of the immediacy of recognition, must share preprocessing with detection, might be altered in the course of time to "resonate" rather specifically to a certain configuration of the neural microstructure.

The pattern recognition process, or discrimination, i.e., the perception of meaning in the world, is clearly a very active process. The perceiver is also highly selective, seeing this or that, choosing one aspect of his experience or another, much as if he were performing normal motor skills. In fact, evidence shows that control over the perceptual response "involves pathways through brain structures usually considered to be motor in function," in a manner analogous to that in which behavior is effected largely through control over peripheral receptors (Pribram 1971, p. 312).

According to Pribram, a large number of experiments have been done, by him and others, which show that the organism's input channels and even the sensory receptors themselves, are subject to efferent control by the central nervous system. One result showed that stimulation of the infero-temporal area of the cortex reduces redundancy, while stimulation of the frontal lobe enhances redundancy in the visual system.

> These opposing effects operate essentially either to "open" the organism to his environment, allowing the processing of a greater number of different signals, a greater amount of information to go on at any moment, or, conversely, to "close down" the input channels so as to restrict processing to a more limited number of different signals, a more limited amount of information. (1971, p. 211)

ADAPTATION

A process intimately related to contrast enhancement, and possibly reciprocal to it, is identified as adaptation, or habituation. In the visual system, this is the process where the eye adapts to a stabilized image configuration with the effect that the pattern ceases to be observed -- it simply disappears. This is observed most vividly in an experiment in which an image is projected on the retina using mirrors and lenses in such a way that the image doesn't move. After only a very short time, fading occurs in chunks and the pattern is soon gone.

Pribram cites several investigators who suggest that this neuronal adaptation "results from the operation of a feedback mechanism in which the signal at one stage feeds back onto a previous stage and thus reduces its sensitivity or gain" (p. 59). In particular, he says that Dowling and Boycott (1965) have shown with the electron microscope that the bi-polar, amacrine, and ganglion cell contacts can function in just this fashion. The inference is that this feedback, from the amacrine to the bi-polar cell, is negative; but this conclusion remains to be established more directly.

In a wider sense, adaptation is also related to awareness with respect to instrumental behavior, i.e., habit. In this respect it can be said that the more reflexive the act, the less does mind accompany it.

> The reciprocal relationship between awareness and behavior is perhaps best illustrated by the psychological processes of habit and habituation. If an organism is repeatedly exposed to the same situation, is placed in an invarient environment, two things happen. If he consistently has to perform a similar task in that environment, the task becomes fairly automatic, i.e., he becomes more efficient. The organism has learned to perform the task; he has formed <u>habits</u> regarding it. At the same time, the subject <u>habituates</u>; he no longer produces an orienting reaction; he no longer notices the events constant to this particular task in this environment . . . As noted, however, habituation is not an indication of some loss of sensitivity on the part of the nervous system but rather the development of a neural model of the environment, a representation, an expectancy, a type of memory mechanism against which inputs are constantly matched. The nervous system is thus continually tuned <u>by</u> inputs to process further inputs. (Pribram 1971, P. 104-5)

On the tennis court, the relationship between awareness and habituated movement is reflected in the player's ability to perform integrated actions while attending to something else, such as the moving ball. The less attention he has to pay to the more detailed aspects of the game, the more he is able to concentrate on the mental aspects of the game, such as proper positioning, tactics and shot selection. A player who is unsure of his strokes, for example, is less likely to be attentive to the other things; he is too busy with detailed body movements.

To characterize this relationship physiologically, Pribram points out that nerve impulses and slow potentials are two kinds of processes that could function reciprocally.

> A simple hypothesis would state that the more efficient the processing of arrival patterns into departure patterns, the shorter the duration of the design formed by the slow potential junctional microstructure. Once habit and habituation have occurred behavior becomes "reflex" -- meanwhile the more or less persistent designs of slow potential patterns are coordinate with awareness. Thus, even the production of speech is "unconscious" at the moment the words are spoken. My hypothesis, therefore, is an old-fashioned one: we experience in awareness some of the events going on in the brain, but not all of them.
>
> In short, nerve impulses arriving at junctions generate a slow potential microstructure. The design of this microstructure interacts with that already present by virtue of the spontaneous activity of the nervous system and its previous "experience." The interaction is enhanced by inhibitory processes and the whole procedure produces effects akin to the interference patterns resulting from the interaction of simultaneously occurring wave fronts. The slow potential microstructures act thus as analogue cross-correlation devices to produce new figures from which the patterns of departure of nerve impulses are initiated. The rapidly paced changes in awareness could well reflect the duration of the correlation process. (1971, p. 105)

CHAPTER 6

THE MOTOR SYSTEM

In the previous chapter we examined the input side of the human organism, concentrating attention on visual information, i.e., on afferent signals initiated at the receptors in the eyes. We now consider the output side of the organism and look at the innervation of skeletal muscles, i.e., at efferent signals generated by mechanisms in the nervous system which stimulate contraction of muscle tissue to cause movement. These mechanisms are the motor functions and reside at all levels of the nervous system. The innervations are transmitted over motor neurons, and it is these neurons that we consider first for simulation.

MOTOR NEURONS AND MOTOR END PLATES

A motor neuron is like other neurons in that it has a soma or cell body containing a nucleus and cytoplasm, and it has dendrites and an axon. Like other cells it also has a cell membrane which is metabolically very active and capable of producing action potentials. The principal difference is that its function is to transmit impulses to muscle fibers and for this reason it has specially constructed axon terminals.

As the axon approaches the muscle fibers, it branches to contact the diverse muscle cells it is to innervate. The motor neuron may have as few as 10 to 20 attaching branches, for small muscles used for fine movement, or as many as 100 or more, for large muscles used for coarse movements. The group of muscle fibers innervated by branches of one nerve fiber is called a motor unit (Figure 6.1). An entire muscle involves many motor units (Easton 1974).

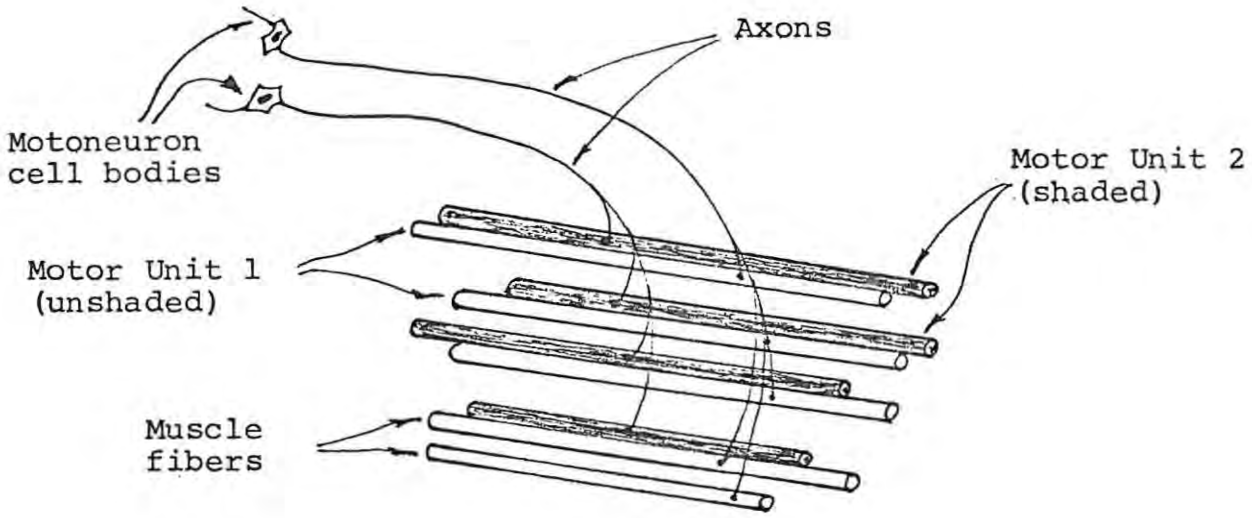


Figure 6.1. The motor unit. Two motor units are demonstrated, one shaded, one unshaded. (From Easton 1974)

The branches of a motor neuron contact the muscle fibers at motor end plates (Figure 6.2). The synaptic knobs containing vesicles of acetylcholine fit into the depression on the muscle sarcoplasm called synaptic clefts. It should be noted that motor neurons are only excitatory, not inhibitory. When impulses arrive at the end plate, the vesicles release the acetylcholine and depolarization of the membrane occurs. Another chemical, cholinesterase, is then released to inactivate the acetylcholine so that the membrane can repolarize again.

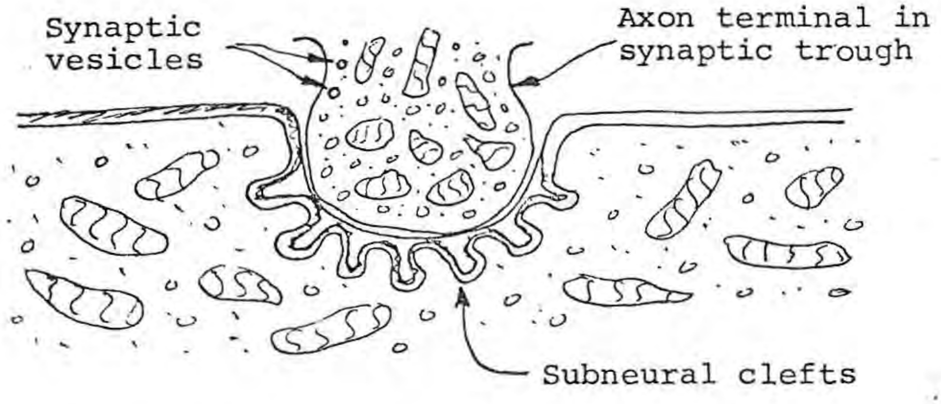


Figure 6.2. Schematic showing the axon terminal of a motor neuron seen in an electron micrograph. (After Jenson and Fisher 1975)

CONTRACTION OF MUSCLE

The physiological basis for muscle contraction is not well known. Skeletal muscles are made up of thousands of muscle fibers, which extend the length of the muscle and attach to muscle tendons, which attach to bones. When the fibers are stimulated, they contract, and the force of contraction is transmitted through the tendons to the bones.

Each fiber contains several hundred to several thousand myofybrils, and each myofibril has lying beside it about 1500 myosin filaments and about 3000 actine filaments. (See, for example, Guyton 1979, for details.) The myosin and actin filaments interdigitate and somehow interact when the muscle is stimulated, possibly somewhat like the oars of a canoe interacting with the water.

The fibers of a given motor unit are typically distributed somewhat randomly over the muscle and, being innervated by the same nerve fiber, are excited simultaneously and therefore contract in unison. Because of the distribution, stimulation of a motor unit causes a weak contraction in a broad area of the muscle rather than a strong contraction at a specific point.

To increase the strength of muscle contraction, it is necessary to innervate more of the incoming nerve fibers at the same time; and to sustain contraction of the muscle, trains of impulses are needed. When several impulses come in quick succession, the muscle does not have time to relax from one contraction before it must start another. As long as the impulses continue to arrive, muscle force may be sustained (Easton 1974).

The summation of contractions in individual muscle fibers may be of little importance, because the normal impulse rate may be only 10 to 20 impulses per second, whereas contraction times can be on the order of 1/100 second (for ocular muscles) or 3/100 seconds (for a gastrocnemius muscle) (Guyton 1979). Muscles of this type will already have relaxed when the next pulse arrives. However, each contracting fiber pulls on the tendon of the entire muscle, and contractions in several motor units add together to produce a contraction force in the whole muscle. If the contractions in the various motor units were in phase, twitches at 10 to 20 per second would be sensed as definite vibrations. But this seldom occurs, because the motor units do not contract synchronously but are out of step with one another (Easton 1974).

Two kinds of contraction summation may therefore be distinguished. For a given number of active motor units, wave summation characterizes the kind of summation of contraction in which the overall force on the muscle attachments is smoothly maintained by asynchronous motor unit activity. At any moment in the interval of activity, some fibers are likely being contracted, so tension is smoothly maintained for the most part.

Wave summation is to be distinguished from quantal summation, which refers to the increase in force of contraction due to the increase in the number of motor units activated. With the addition of each active motor unit, contraction of the associated fibers contributes a discrete additional force to the muscle attachments. For this reason the summation is called quantal.

Other factors which affect strength of muscle contraction are: size of the muscle, number of fibers in the muscle, and the extent to which the muscle has already been contracted. The strength of muscle contraction is not uniform over the stretching range. That is, the force that the muscle can exert against its attachments varies with the extension of the muscle. Consider a flexor in the forearm, for example. When the arm is fully extended at the elbow or fully contracted, the force it can apply is less than that capable of being produced when the arm is only moderately flexed, or more nearly in its normal stretched state. This is shown in Figure 6.3. The normal length of a muscle is almost exactly optimal for maximal strength of contraction.

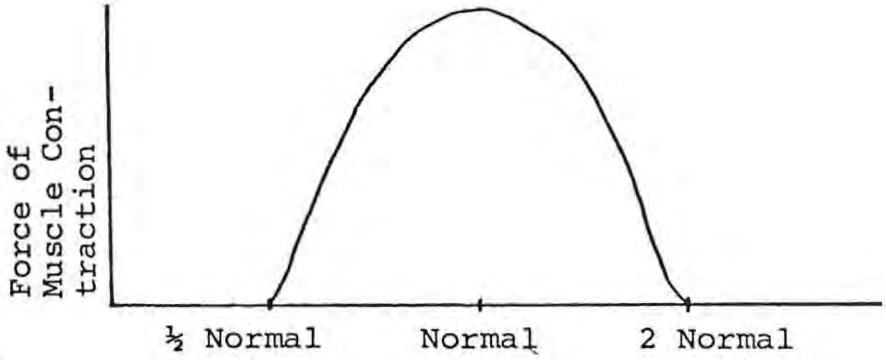


Figure 6.3. Effect of the initial length of a muscle on the contractile force developed following muscle excitation. (After Guyton 1979)

Independently of the length to which muscle is stretched, strength of contraction increases both with the number of fibers it contains and with its physical enlargement. Large muscles with many fibers are able to exert more force than small muscles with few fibers. But from one person to another, differences in muscle strength are due mainly to the size of its fibers, which can be enlarged with appropriate resistive or isometric exercises.

Growth of muscle, or hypertrophy, is the result of an increase in diameter of the individual fibers. Associated with hypertrophy is usually an increase in the efficiency of muscular contraction, for the hypertrophied muscle stores increased quantities of glycogen, fatty substances, and other nutrients, and the number of contractile myofibrils also increases. All these cause the efficiency of the contractile process to increase so that the percentage of energy lost as heat becomes considerably less in the athlete than in the nonathlete (Guyton 1979).

CONTROL OF MOTOR FUNCTIONS

To control motor activities, the appropriate muscles have to be innervated at the correct time with the proper pulse rates. The operational structure, as we saw above, is the motor unit -- a group of muscle fibers innervated by a motor neuron arising out of the spinal cord. The unit either acts or it doesn't.

To act, i.e., to contract its muscle fibers, it must be activated by an action potential. And in this deceptively simple mechanism are hidden the variety, versatility and complexity of motor control.

In the first place, there are many motor units, and they operate independently of one another. Any number and combination of the units may be activated at any given moment. To activate these units, it is necessary to transmit a complex pattern of neural impulses to them. Good practice may require long hours of trial, error and correction and a great deal of skill.

There is also the possibility of graded contraction of motor units, a function of the frequency with which motor impulses are transmitted to the muscle fibers. Within limits, the higher the frequency of the impulses, the greater the contraction of the muscle and hence the greater the force applied to its attachments.

Beyond this is the organization of groups of muscle fibers into separate muscles, with tendons arranged variously so as to produce different joint actions. This leads to a variety of combinations in which different muscles can be activated to produce desired movements, such as those in the game of tennis.

Complicating the control problem is the fact that an individual muscle may act in one or more of several ways, depending on the circumstances. We know that when a fiber is stimulated, it contracts. But this is not to say that it shortens. It only develops tension within itself, and while it may therefore have a tendency to shorten, it does so only if other factors permit it. For instance, the tension has to exceed internal or external resistance. Other muscles may be pulling against it. Or its mechanical leverage may be poor, as we will see in the next chapter.

The muscle tends to shorten, and it tends to do all its possible actions. However, there is nothing in the muscle itself, no mechanism as such, to determine which of the various possible movements or joint actions will occur. The muscle can only exert a pull, and this pull applies to all the possible movements. But outside forces may prevent the muscle from doing anything. This complicates the simulation even more.

In isometric contraction, for instance, tension is developed in the related muscles, yet the corresponding body parts do not move and the length of muscle does not change. And in isotonic contraction, if a muscle develops sufficient tension to overcome a resistance, it will shorten. However, it may actually lengthen if the resistance overcomes the tension. In lowering a weight, for example, contracted biceps may actually be lengthening, whereas in first lifting the weight, the biceps had shortened.

Since a muscle can only exert a pull, control of movement depends entirely upon the selective activation of the individual motor units in various combinations. Of course, if a muscle is too weak from lack of training or from a debilitating disease or is too fatigued, no amount of stimulation will be effective. But in that event, no control is possible at all. Otherwise, desired movements require organized patterns of neural impulses.

There are several sources for such innervation patterns, but spinal reflexes are deemed to be fundamental for all patterns (Rasch and Burke 1978). Supporting this, Guyton says:

> Though most of us have an inherent belief that it is only the conscious portion of the brain that causes muscle movements and other motor activities, this is farthest from the truth, for perhaps the greatest proportion of our motor activities is actually controlled by lower regions of the central nervous system, specifically the spinal cord and lower brain stem, which operate primarily at a subconscious level. (1979, p. 301)

Reflexes are reproducible patterns of movement that result from particular kinds of peripheral stimulation entering the nervous system. Common examples are: sudden withdrawal of the hand from a hot object, lifting a foot away from a sharp stone, and the stretch reflex of the knee tendon. (When a muscle is suddenly elongated, by a sudden blow, e.g., the middle of its spindle is stretched, as we will see below. This sends a signal to the spinal cord which excites the motor neurons controlling muscle fibers surrounding the muscle spindle, causing them to contract and thereby damp the stretching action by opposing it.)

These movements are called reflexes because the effect of a stimulus seems to travel into the central nervous system and be reflected back to the muscles. The pathway includes the receptors, afferent fibers carrying impulses from the sensors into the central nervous system, central connections, and efferent fibers carrying messages out to the muscles. This pathway is a reflex arc. (Easton 1974)

In coarse outline, the arrangement of the path is as follows. Afferent fibers travel from the various sensors of the body to the spinal cord and up the back (dorsal) of the central canal in sensory or ascending tracts to the brain. Efferent fibers from the brain come down the front (ventral) of the central canal in motor or descending tracts. In reflex arcs, involvement of the brain is minimal.

Some muscles are arranged in antagonist pairs, and impulses that reflexly cause an excitation in the motoneurons to one of the pair (the agonist) also cause a reflex inhibition in the motoneuron of its antagonist muscle. For example, at the same time that tension in the quadriceps (four-headed muscle in the thigh) increases, hamstring tension decreases, otherwise the leg wouldn't bend. Such muscles are said to be reciprocally innervated.

As long as peripheral connections are intact, reflexes involving the spinal cord can proceed without the presence of the brain though not without certain local controlling neuronal mechanisms of the cord. One reflex of the spinal cord is the extensor thrust mechanism, which allows stiffening of the extensor muscles of the legs when pressure is applied to the pads of the feet. This reflex, together with impulses from the bulboreticular formation or reticular activating system of the brain stem needed to stiffen the trunk and limbs, make it possible to stand erect, i.e., to support one's self against gravity. The spinal cord also provides the rythmic to-and-fro movements of the legs used in walking.

The bulboreticular system also draws information from the vestibular apparatuses of the ears to maintain equilibrium of the body by adjusting the tone of the various muscles. The bulboreticular system is actually an integrating center. It receives incoming fibers from many sources, including the spinal cord, the equilibrium apparatus of the ear, the motor portion of the cortex, and the basal ganglia. Thus it combines and coordinates sensory information from the body, motor information from the motor cortex, equilibrium from the ears, and proprioceptor information about body movements from the cerebellum. With this information it controls many of the involuntary muscular activities.

> Once the body is supported against gravity and maintained in a state of equilibrium, locomotion then depends on rhythmic motion of the limbs. Rhythmic circuits in the spinal cord are capable of providing the to-and-fro movements of the limbs, and the movements of the opposing limbs are kept in opposite phase with each other by the reciprocal inhibition mechanism of the cord. Thus, most of the functions of locomotion can be provided by the cord and brain stem, but the cerebral cortex must control these functions in accord with the desires of the individual. When he wishes to move forward, to stop, or to turn to one side, his motor cortex and basal ganglia simply initiate the action, stop it, or change it by sending command signals. The cord and brain stem provide the stereotyped actions required to perform the actual movements. In this way, the energy of the brain is conserved to perform other mental feats. (Guyton 1979, p. 312)

THE GAMMA SYSTEM

The reflex theory postulated by Sherrington (1947) made explicit the notion that all afferents are sensory (i.e., that they are connected to sensory receptors) and all efferents are motor (i.e., that they are connected to contractile muscles). But Pribram (1971 , p. 85-6) pointed out that there is data to show that the organism's input mechanisms are directly controlled by the central nervous system. For one thing, one-third of the fibers of the ventral root are small-diameter fibers (called gamma fibers) and end not in contractile muscle tissue per se but in specialized receptors called muscle spindles that are embedded in the contractile muscles.

Experiments performed on these fibers show that they have no direct effect on muscle contraction. That is, the γ fibers (gamma fibers) are <u>efferents whose function is not motor</u>. Further, the γ system effects a negative feedback on input derived from the muscle spindles (afferent activity of the dorsal root), such as do the mechanisms of adaptation and habituation discussed in Chapter 5. In addition, stimulation of the spinal cord, the brain stem, cerebellum, and even the motor cortex influences the activity of the muscle spindle afferents (dorsal root), so the feedback is very extensive (Granit 1944, p. 103-18).

Experiments by Pribram yielded similar results for the visual system:

> Nonvisual inputs (clicks and taps to the paw) evoked responses in the optic nerve of cats (whose muscles, including those of the pupil, had been immobilized). Further, the electrical activity of the retina (measured by electroretinogram) and of afferents originating in the retina was altered by such nonvisual stimulation . . . Finally, as in the case of other sensory modalities, stimulation of the appropriate part of the cerebral cortex resulted in changes in the receptivity (e.g., size of the receptive field) of the retinal ganglion cells . . . The results of these experiments strengthen the belief that the organization of the visual mechanism resembles the other sensory systems in that central control of the input does exist. (1971, p. 87)

Thus there are two separate nerve-muscle systems, innervated, respectively, by large and small neurons. The relationship is shown in Figure 6.4. In this figure, the large neurons, or alpha (α) fibers, are represented by the line drawn from the ventral root of the spinal column to the tension or extrafusal fibers of the motor end plate. The gamma fibers are represented by the line from the ventral root to the <u>intrafusal</u> or sensory fibers of the end plate. The gamma fibers regulate the organism's receptors and therefore sensory functions.

Afferents from the muscle spindles are shown leading to the dorsal root of the spinal column. These spindles sense the amount of tension in the muscle fibers among which they are located. Muscle spindle afferents are muscle receptor neurons whose job it is to sense when a muscle is stretched. Integral to the control of motor activity, the muscle spindle consists of a connective tissue sheath containing several intrafusal fibers which lie parallel to and alongside the regular muscle fibers or extrafusal fibers. The fibers in the sheath have a central heavy nucleated area called the muscular bag, which stretches when the muscle is stretched. This excites nerve endings (the annulospiral endings) which are entwined around the nuclear center.

Tendon stretch receptors are similar to the muscle stretch receptors, except that they sense when the <u>tendon</u> is stretched. The two types of receptors are not necessarily stimulated together. They act together for the most part when a muscle is stretched under a load, i.e., under isotonic stretching. But under isotonic <u>contraction</u> the tendon is still pulled slightly by the load, whereas the muscle itself is contracted. Under isometric contraction the tendons are <u>strongly</u> stretched (Easton 1973; Jenson and Fisher 1975).

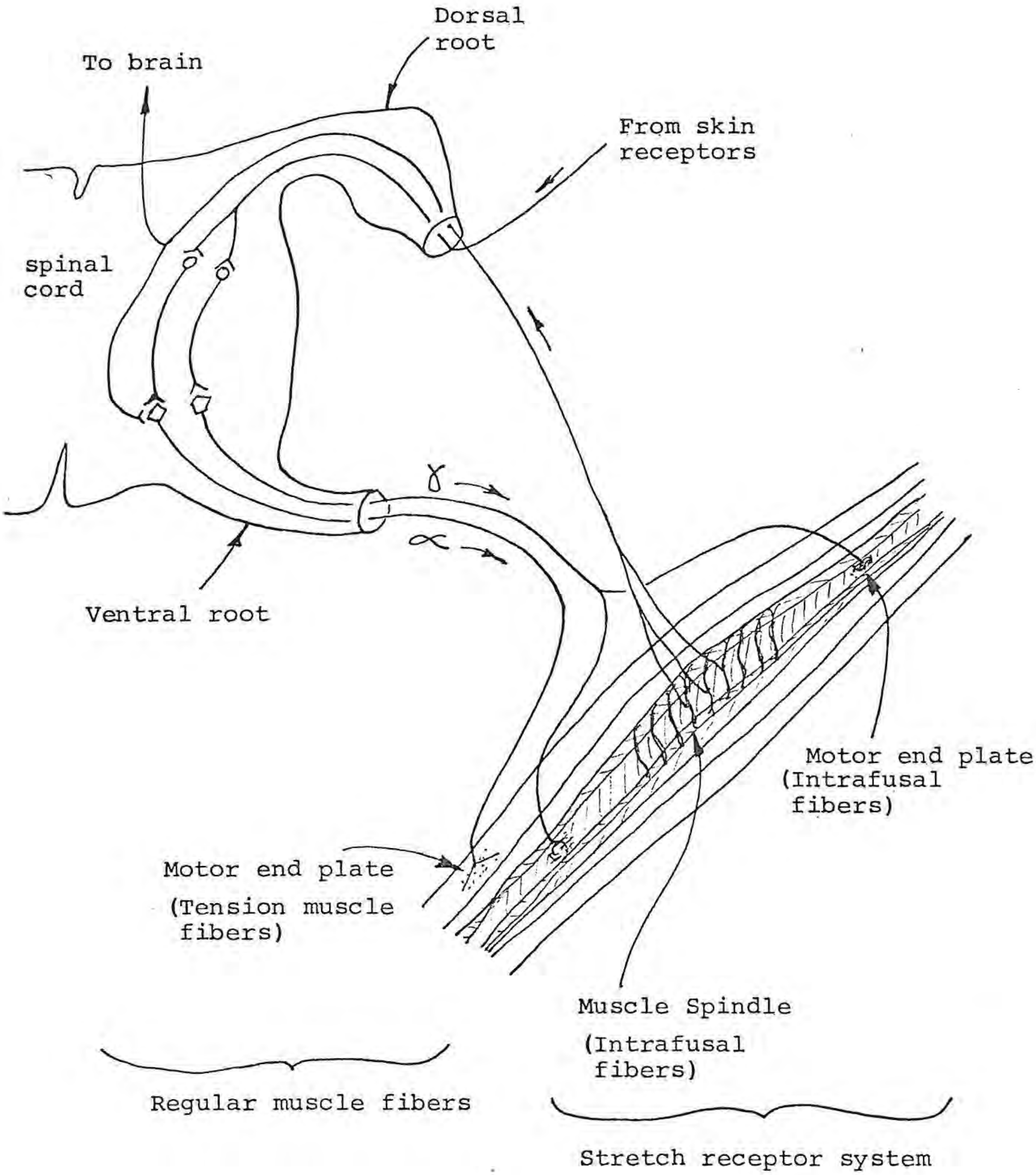


Figure 6.4. Schematic of gamma (γ) motor neuron system. (From Pribram 1971)

By central control, the sensitivity of the muscle spindle can be set at various levels or positions, somewhat like a thermostat, or steering wheel in power steering. These settings can be predictive; the settings can be made to anticipate a sensory need. The setting depends on the gamma motor neurons, whose impulses result in contractile shortening of the spindle, itself, without any detectable influence on the strength or shortening of the whole muscle (Rasch and Burke 1978). It appears that there follows a non-conscious response, a reflex arc which operates through higher brain centers but is not conscious, that powers the extrafusal muscles. That is, afferent signals from the activated spindle reach the brain and trigger α motor neuron messages to the extrafusal muscles, contracting them.

When a muscle is made to contract under the influence of the α motor neurons, the muscle spindles are slackened. The result is a cessation of γ afferent discharge from the spindle. However, as the spindles become slack, gamma motor impulses can be increased, thereby restoring tension within the spindles and re-setting the sensitivity of the sensory mechanism. Similarly, when the muscle slackens due to muscular relaxation, the spindles may be stretched so that afferent discharge increases. But then gamma motor impulses may be decreased, again restoring the reduced state of tension and re-setting the sensitivity of the sensory mechanism to a lower level.

> The gamma neurons and the intrafusal muscle fibers thus appear to be a servomechanism for controlling afferent discharge. In the spinal cord, the gamma motor neurons are under the integrated control of several efferent tracts originating in both the subconscious and the volitional centers of the brain. These higher centers can "decide" in advance what level of reflex sensitivity will be required and set the tension within the spindle accordingly. Technically, this might be called a "follow-up length servo." (Rasch and Burke 1978, p. 88)

HIGHER CENTERS OF MUSCLE CONTROL

Highly coordinated functioning of the neuro-muscular system is the key to movement skill. In a skillful act, each movement occurs in the correct sequence and timing and with the right amount of force; the act appears smooth and rhythmical. This means that neural impulses reach the proper muscles with just the right intensity at the correct time. To occur precisely on time and in the proper way, knowledge of the external environment and the condition of the internal environment is essential; sensory information is needed. Hence, the key to movement skill is the coordinated action of the sensory-motor processes.

We have seen that reflexes are basic to these processes and that the bulboreticular formation of the brain stem is instrumental in maintaining posture, equilibrium and the rhythmic movement of the limbs. But without control from higher centers of the central nervous system, the movements are mechanical, uncoordinated, jerky and undirected or unconscious. Intricate tasks such as talking, writing, playing musical instruments, games like basketball and tennis, and the like, involve major degrees of control by the brain.

Besides the buloreticular formation, discussed above, there are three other major muscle control centers in the brain. These are: the motor cortex, the basal ganglia, and the cerebellum. They are shown in the schematic drawing in Figure 6.5.

Motor innervations are transmitted from the motor cortex to the spinal cord along one or the other of two separate pathways. The more direct of the two is called the corticospinal tract (from the cortex to the spine), which passes without synapses to the cord. These fibers actually occur in pairs and cross from one side to the other, so the motor cortex in the left hemisphere of the brain controls muscles on the right side of the body, and that in the right hemisphere controls the left side of the body.

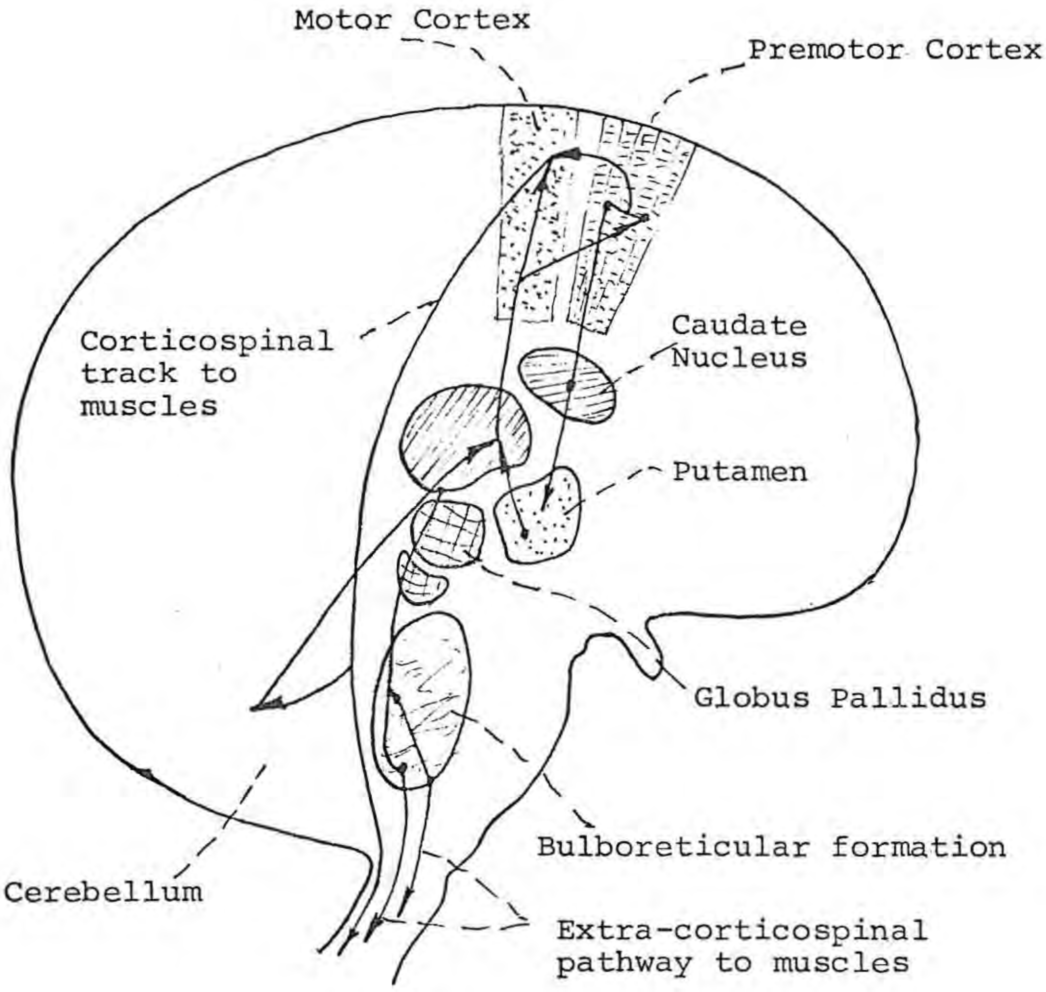


Figure 6.5. Control of muscle activity by the motor cortex, basal ganglia, and cerebellum. (From Guyton 1979)

The less direct route is over the extracorticospinal pathway, which consists of several fiber tracts. These are the other paths, or those not within the scope of the corticospinal tract. They originate mainly in the basal ganglia and the bulboreticular system, as indicated in Figure 6.5, and are involved in the control of most of the stereotyped and non-conscious body movements.

Nerve fibers of both the corticospinal and the extracorticospinal pathways terminate in a special neuronal network of the spinal cord. It is this network that sends direct signals to the muscles. Signals that come from the brain combine with those from the sensory nerves entering each spinal segment and are used by the neuronal network of the cord to control muscle activity (Guyton1979). The neural network is schematized in Figure 6.6.

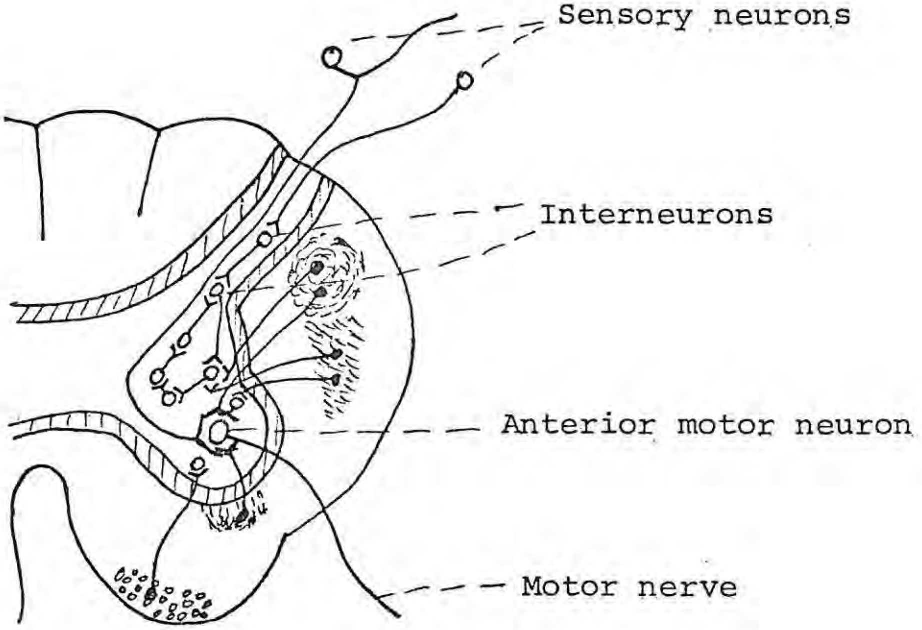


Figure 6.6. Convergence of different motor pathways on the anterior motor neuron. (After Guyton 1979)

Located in the anterior portion of the spinal cord (Figure 6.6) are many very large neurons called anterior motor neurons. They send large axons out from the spinal cord into the motor nerves (the nerves that supply the muscles). It should be recalled that motor nerves are only excitatory; they either excite muscle into contraction or they do not, but they do not inhibit. Thus, if inhibitory control of muscle is to occur, it must take place upstream of the motor nerves. Indeed, this is the case. The anterior motor neurons take inputs from many sources, some of which are excitatory while others are inhibitory. Muscle control is therefore more complex than simply transmitting muscle contraction signals (Guyton 1979).

Many patterns of muscle contraction are determined in a large group of smaller neurons (interneurons) contained in central portions of the spinal cord gray matter. For example, patterns of the flexor reflex of the knee and the extensor and walking reflexes are determined there. These interneurons receive signals from incoming sensory nerves, from the corticospinal tract and from the extracorticospinal pathway and in turn transmit signals to the anterior neurons.

The brain may "command" the neuronal network to perform a certain task, such as walking or running. In response, the interneuronal mechanism to do the task is set into motion, causing the discrete muscle contractions that are required. But no single message to the interneurons necessarily causes a muscle contraction. The contraction occurs only if a preponderance of information favors it. Other excitatory or inhibitory influences may block the action (Guyton 1979).

MOTOR CENTERS IN THE BASAL GANGLIA

The basal ganglia are large paired masses of neurons embedded deep in the white matter of the cerebral hemispheres, above the midbrain. The most important of them appear to be the caudate nucleus, the putamen and the globus pallidus, and are arranged somewhat as given in Figure 6.5. Neuronal connections with other portions of the motor control system are shown in Figure 6.7.

While not much is known about the detailed functioning of the basal ganglia, it seems clear that the caudate nucleus controls those gross intentional movements of the body (either conscious or sub-conscious) which aid in the overall control of body movements. The putamen operates in conjunction with the caudate nucleus to control gross intentional movements. Both work with the motor cortex in organizing the various movement patterns. Damage to these elements can lead to uncontrolled sequences of different unrelated motions.

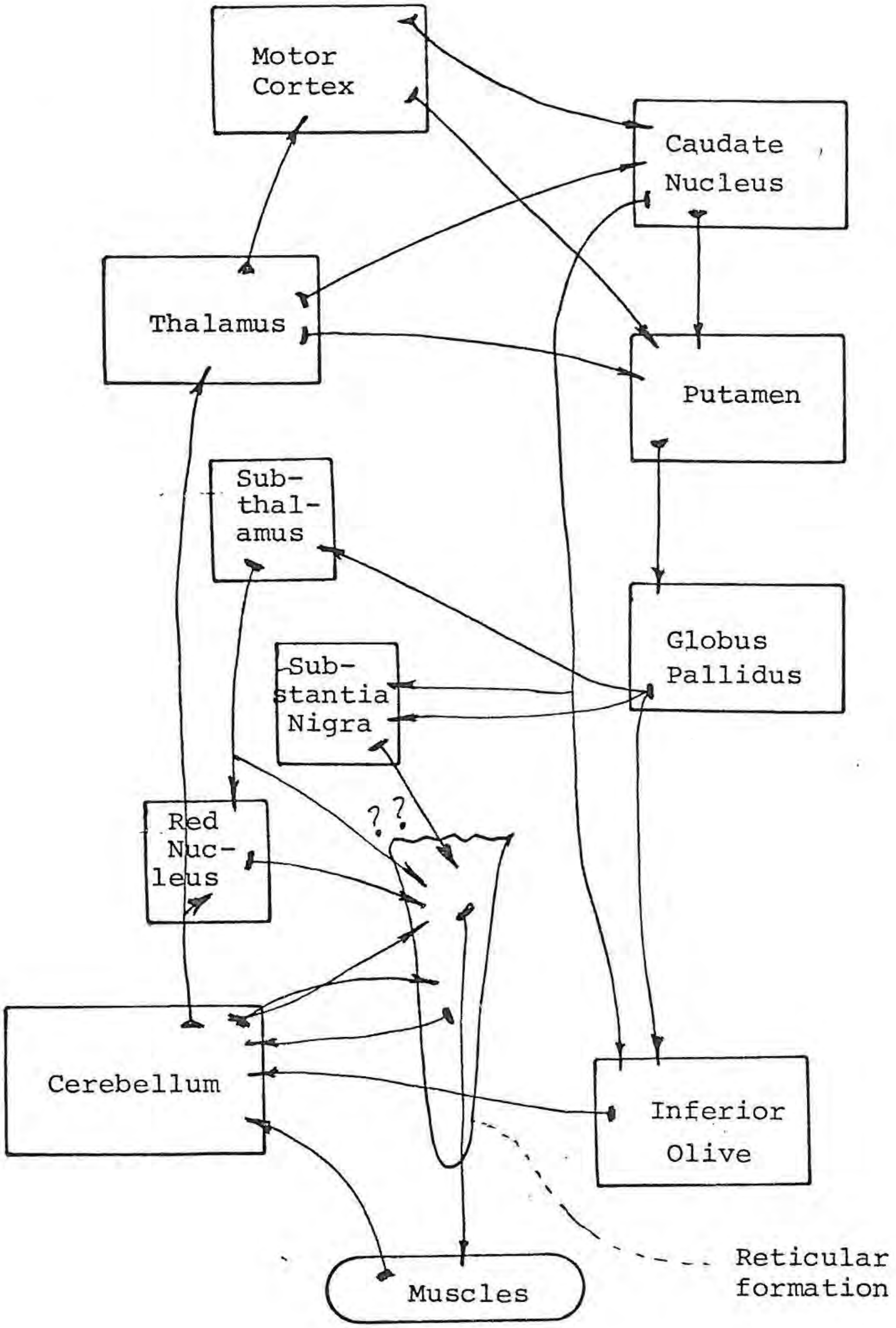


Figure 6.7. Interconnections of the basal ganglia with other parts of the motor system. (After Guyton 1979)

The globus pallidus possibly directs the positioning of the gross parts of the body, more or less the posture, when a person begins to perform a complex movement pattern. Say when a tennis player gets set to take a particular shot, such as a volley at the net, he first positions his body in a semi-crouch and tenses the muscles of his upper arm. These are mainly globus pallidus functions.

MOTOR CENTERS IN THE CORTEX

The cerebral cortex, or simply cortex (Figure 6. 8), the largest and phylogenetically the newest portion of the brain, is definitely involved in voluntary movement, but the precise nature of the involvement is not yet known.

The motor cortex is the area of the cortex which seems to be the most directly concerned with muscle control. It is located immediately anterior to the central sulcus (fissure) of the brain and is divided functionally so that the points for control of muscles in the lower part of the body are near the mid-line, while those for control of the upper body are located far laterally. There is a point-to-point communication between the motor cortex and specific muscles everywhere in the body, so that signals from discrete parts of the motor cortex activate discrete muscle movements, sometimes involving only a single muscle.

However, body parts are not uniformly represented in the cortex. The hands and face, for instance, have very detailed representation, while a large area of back muscles has very limited representation. By comparison, the degree of representation of muscles of the thumb and fingers and also of the mouth and throat is as much as 100 times that for the trunk muscles (Guyton 1979).

Another important, though less well defined, area of the cortex is the premotor cortex. The storehouse of "patterns" of motor

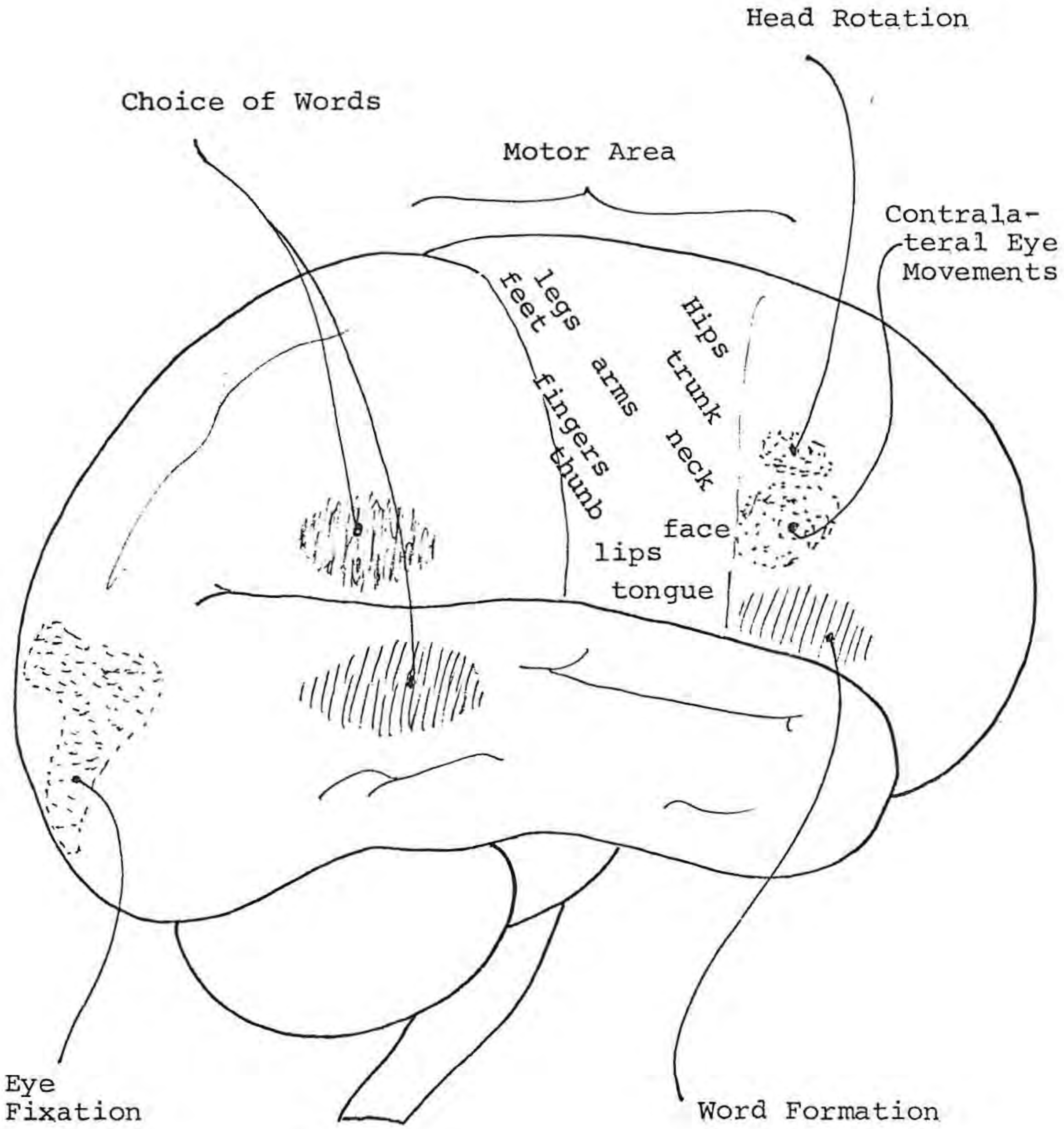


Figure 6.8. Representation of the different muscles of the body in the motor cortex, and location of other area of responsibility for certain types of motor movement. (After Guyton 1979)

activity that can be called forth by the thinking part of the brain, it is intimately concerned with the orderly sequence and timing of complex movement patterns.

> The precise part of the brain that is utilized for storing the skilled patterns of activity is not known. It probably partly involves the motor cortex itself, and also some of the sensory areas,some of the areas of the frontal lobes immediately in front of the motor cortex, and some of the deeper centers for motor control as well, such as the basal ganglia. Of special interest is the area 1 to 3 cm. wide that lies immediately anterior to the motor cortex in the frontal lobes. Electrical stimulation of discrete points in this area frequently elicit skilled patterns of movement, especially skilled movements of the hands. Also located in this area are centers for control of eye movements and for formation of words during speech. (Guyton 1979, p. 320)

While the motor cortex is pre-eminently involved in early phases of skill learning, in which conscious attention is given to each action, the premotor cortex seems to take over the functions as they are learned. Motor learning is usually a slow and almost painful process which finds the sensory nervous system constantly checking for success. Visual, auditory, somesthetic and all other types of information that might be useful in the estimation are involved. But as the movements become engrained, as the need for feedback is reduced, and particularly as speed of performance is increased to the point where the time taken to perform the act is less than the time required for information to feedback to the brain, the premotor cortex apparently takes control.

The extent to which such control takeover occurs is not clear, though certain sensory considerations appear to restrict it to relatively simple actions. Relatively more complex skills cannot be performed satisfactorily in the absence of the sensory system. These skills require a sequence of patterns of movement and the sequences are stored intact in the memory bank of the sensory system. Conscious attention is thus required and it would seem that control must then revert to the motor cortex, if it had ever been taken over by the premotor cortex at all. Even so, the precise point at which this might occur is not established.

MOTOR CENTERS IN THE CEREBELLUM

The cerebellum, the smaller part of the brain (sometimes called the hind brain), is an oval shaped miniature of the cerebral cortex. It is located posteriorly and inferiorly in the brain; that is, it sits in back of and below the cerebral cortex, behind the brain stem. It is actually out of the main stream of neural links with the spinal cord. Its function is to remove the rough edges from movement; it modifies motor signals and contributes to the refinement of desired movements. Communicating with the other motor areas of the brain through several large neuronal trunks, it helps both the motor cortex and the basal ganglia perform their functions, making the movements smooth rather than jerky.

The cerebellum thus plays an important role in predictive control, which involves both feedback and feedforward. It acts as a feedback mechanism to help control muscle movements initiated by the motor cortex and basal ganglia, and it is closely allied to the damping function in its ability to predict the position of different parts of the body. Anticipating movements from the present state of the muscles and joints, it can distribute signals which prevent errors in the movement patterns. Though not directly responsible for muscle control, the cerebellum helps to make groups of muscles operate together in a coordinate manner so that very accurate and very fine degrees of muscle control can be achieved.

> Movements of parts of the body are affected greatly by their inertia and momentum. That is, a limb requires a certain force to start it moving, but once started, it keeps on moving until an opposing force stops the motion. Neither the cerebral cortex nor the basal ganglia are organized to take these physical factors into consideration. Instead, the cerebellum makes the automatic adjustments that keep these factors from distorting the patterns of activity . . . It receives signals from the proprioceptive receptors located in all joints, in all muscles, in the pressure areas of the body, and anywhere else that signals informing of the physical state of the body can be obtained. Signals are transmitted into the cerebellum, too, from the equilibrium apparatus of the ear, and even from the eyes to depict the visual

> relationship of the body to its surroundings. Finally, the cerebellum receives information directly from the motor cortex as well as from the basal ganglia of all motor signals that are being sent to the muscles. In summary, the cerebellum is a collecting house for all possible information on the instantaneous physical status of the body. (Guyton 1979, p. 320-1)

Comparing information about the present condition of the parts of the body with information from the cortex of the muscular movement that it intends to perform, the cerebellum obtains feedback information which it sends back to the motor cortex and basal ganglia to initiate appropriate corrective action.

But the cerebellum doesn't work simply with data on the current status of muscles. Operating in conjunction with the somesthetic cortex, it predicts the state of the muscles to the next instant, perhaps 30 milliseconds into the future. For example, in running after a tennis ball, the cerebellum will predict where the legs will be a moment from now. This information is used by the runner to make the appropriate anticipatory responses on the basis of what he expects to be the case. He thus uses both feedback and feedforward computations in his predictive control loop.

INTEGRATED CONTROL OF MOVEMENT

It was believed at one time that the center of control of the motor processes resided in the motor cortex. However, development of the microelectrode and its application to the study of the cerebral processes in motor control in laboratory animals indicate that the motor cortex is actually functionally nearer to muscle movement than are control zones deep within the brain. The motor cortex is also more directly connected to spinal cord motor neurons than either the cerebellum or basal ganglia. It now appears that inputs to the cerebellum and basal ganglia are more abstractly coded and complex than those to the motor cortex. The primary function of the cerebral motor cortex may therefore be the <u>refined</u> control of motor activity rather than the source of volition (Evarts 1973).

All three major motor areas become electrochemically active prior to the onset of movement, though, as indicated above, each zone involves a different aspect of control. Contrariwise, the sensory cortex, which is adjacent to the motor cortex and receives inputs from receptors in the skin and joints, appears not to become active until after the initial muscular contraction. This indicates that these cells are not in the circuit that initiates the first muscular contraction, although they may play a part in guiding movements through feedback mechanism (Evarts 1973).

The entire cerebral cortex sends fibers to both the basal ganglia and the cerebellum, and these centers send many fibers back to the motor cortex, by way of the thalamus. This means that the basal ganglia and the cerebellum receive data from the somatosensory, visual and auditory regions of the cerebral cortex, that they transform the data and send a new pattern of messages to the motor cortex, and that messages are then sent to the muscles via the spinal cord from the motor cortex.

> (This) does not mean that there is a one-to-one relation between the motor cortex nerve cells and the spinal-cord motor nerve cells. On the contrary, there are a number of differences between the pattern of activity of nerve cells in the motor cortex and the activity of motor nerve cells in the spinal cord. It may be that the relation of the motor cortex nerve cells to the spinal-cord motor nerve cells is similar to the relation between the cells in the lateral geniculate nucleus . . . and the cells in the visual region of the cortex. Cells in both the lateral geniculate nucleus and the cortex respond to the location of the stimulus on the retina, but if there is a pattern in the stimulus, it will be processed by the visual cortex. In much the same way it appears that the activity of nerve cells in the motor cortex may be related to certain patterns of activity within a group of muscles, whereas the activity of a spinal-cord motor nerve cell is related only to a single set of fibers in one muscle. (Evarts 1973)

The messages to the spinal cord appear to be related to the amount and pattern of muscular contraction rather than to the displacement that the contraction produces. This is in line with a view expressed by J. A. V. Bates of the National Hospital for Nervous Disorders in London that force is the basic output of the body. We have seen, too, that acceleration (or force, when mass is present) may be considered to be the fundamental concept of mechanics. (Velocity and displacement are then derived quantities, obtained, respectively, by first and second integration of force.)

The significance of this idea can be grasped by comparing the force of muscle contraction that would be required, in turn, to swing a tennis ball and steel ball of comparable size through a given distance with a given speed. While the overt motions appear to be the same, the muscle forces are quite different in the two cases, and the pattern of activity in the motor cortex would also be different.

Another characteristic that shifts the locus of central control away from the motor cortex is that the activity in the nerve cells in the motor cortex is more likely related to what the muscles actually do rather than to the circumstances in which they do it. For example, the same set of nerve cells in the motor cortex are found to control the contraction of arm muscles regardless of the circumstances of the movement. However, in other areas, such as in the cerebellum or basal ganglia, cells are differentially active depending on the type of movement rather than on the muscle activity (Evarts 1973). This implies that different types of movement involve different neural mechanisms, even though the same muscles may be involved in the different movement types: for example, fast saccadic or slow pursuit movements.

Indeed, it has been suggested that the major role of the cerebellum is to preprogram and initiate rapid saccades or ballistic movements, while that of the basal ganglia is to generate slow or pursuit movements. The motor cortex, on the other hand, is involved with both slow or fast movements.

CHAPTER 7

MOVEMENT OF THE BODY

In Chapter 6 we looked at the micro-structure of the human organism's muscular system, noting in particular the manner in which muscles contract and how such contraction is controlled. Now we examine the macro-structure, or the musculo-skeletal system of the organism as a whole. This approach presumes the occurrence of muscular innervation and control and considers the various kinds of movements that are possible with the given anatomical structure. These movements involve muscular forces and we analyze the movements by viewing the body as a system of levers by means of which the muscular forces are applied.

THE MUSCULO-SKELETAL FRAMEWORK

For muscles to be effective they must work against other muscles or ultimately against an external agency, such as the ground or water, according to the medium of the action. When no such agency exists, as in free fall (from a diving board, airplane, and the like), movement of one part of the body will produce a comparable movement in another part of the body in reaction to it. In other words, movements have to satisfy what is known in physics as the principle of linear or angular momentum (See Chapter 2).

Behavior of the individual body parts under muscle contraction cannot, therefore, be determined in isolation; the whole system has to be considered. In a tennis forehand stroke, for instance, the muscles of the hitting arm provide the torque which drives the racquet head against the ball. But the drive depends for its force on the strength of the torso, which braces the hitting arm, and on the stability of the legs, which power the torso. If muscles in the legs or back should "break" at the moment of impact with the ball, or if the court surface is slippery, power will be lost.

As we saw in Chapter 1, the adult human body contains more than 200 bones and over 430 skeletal muscles. Programmed innervations of these muscles by the central control system produce patterned contractions which lead to coordinated movements of the skeleton and thus a movement of different parts of the body, or to the body as a whole acting against an external resistance. So the arrangement, or organization, of bones and the way in which they are held together with muscles, is especially important in the production of movement. Differences in the structure create differences in the forces that are produced. Some structures are therefore better than others for certain activities.

The skeleton may be partitioned conveniently into two groups of bone structures (Easton 1974). The skull and vertebral column, together with the ribs and the sternum, is the axial skeleton. The pectoral and pelvic girdles and the appendages (or limbs), which attach to them, make up the appendicular skeleton.

The human skeleton contains a variety of long, short and flat bones. Long bones, such as the humerus and femur, of the upper arm and upper leg, respectively, are found in the limbs, while short bones are mostly in the hands and the feet -- in the carpal and tarsal bones. Flat bones, such as the sternum, ribs and scapula, provide extensive area for the attachment of muscle and ligament.

The vertebrae are special bones joined together by means of strong ligaments to form a sufficiently stiff column to prevent excessive twisting of the spinal cord but one with enough flexibility to allow some movement of the individual vertebrae with respect to one another.

The ribs, while providing protection for the heart and lungs, combine with the diaphram muscles to make efficient breathing possible. They are moved by intercostal muscles.

The links between the limbs and the axial skeleton are the pelvic and the pectoral girdles. The pectoral girdle forms a joint with the axial skeleton on the front side only and is anchored to the ribs by strong ligaments as well as by the muscles that attach it. The pelvic girdle attaches at the sacrum. The arms and legs articulate (join with) their respective girdle by way of a ball-and-socket joint: the head of the humerus of the upper arm in the glenoid fossa (cavity) of the scapula, and the head of the femur of the thigh in the acetabulum (cup) (Easton 1974).

The humerus, in turn, forms a hinge joint with the ulna, one of two bones of the lower arm. And the femur forms a hinge joint with the tibia, one of two bones of the lower leg. Associated with the ulna and the tibia, are, respectively, the radius of the arm and the fibula of the leg. The tarsals and metatarsals of the hands and the carpals and metacarpals of the feet round out the main structure of the appendicular skeleton.

The bones of the skeletal system are made to move by the contraction of muscles whose ends attach to the bones. As we saw in Chapter 6, when a muscle contracts it tends to pull its ends toward the center of the muscle. Therefore, bones which are attached to the ends of the muscle tend to be pulled toward each other. The skeletal muscles are the machines which produce this mechanical action. In order to simulate the action realistically, an accurate machine model is needed for each muscle. This calls for a detailed study of the pertinent muscle groupings.

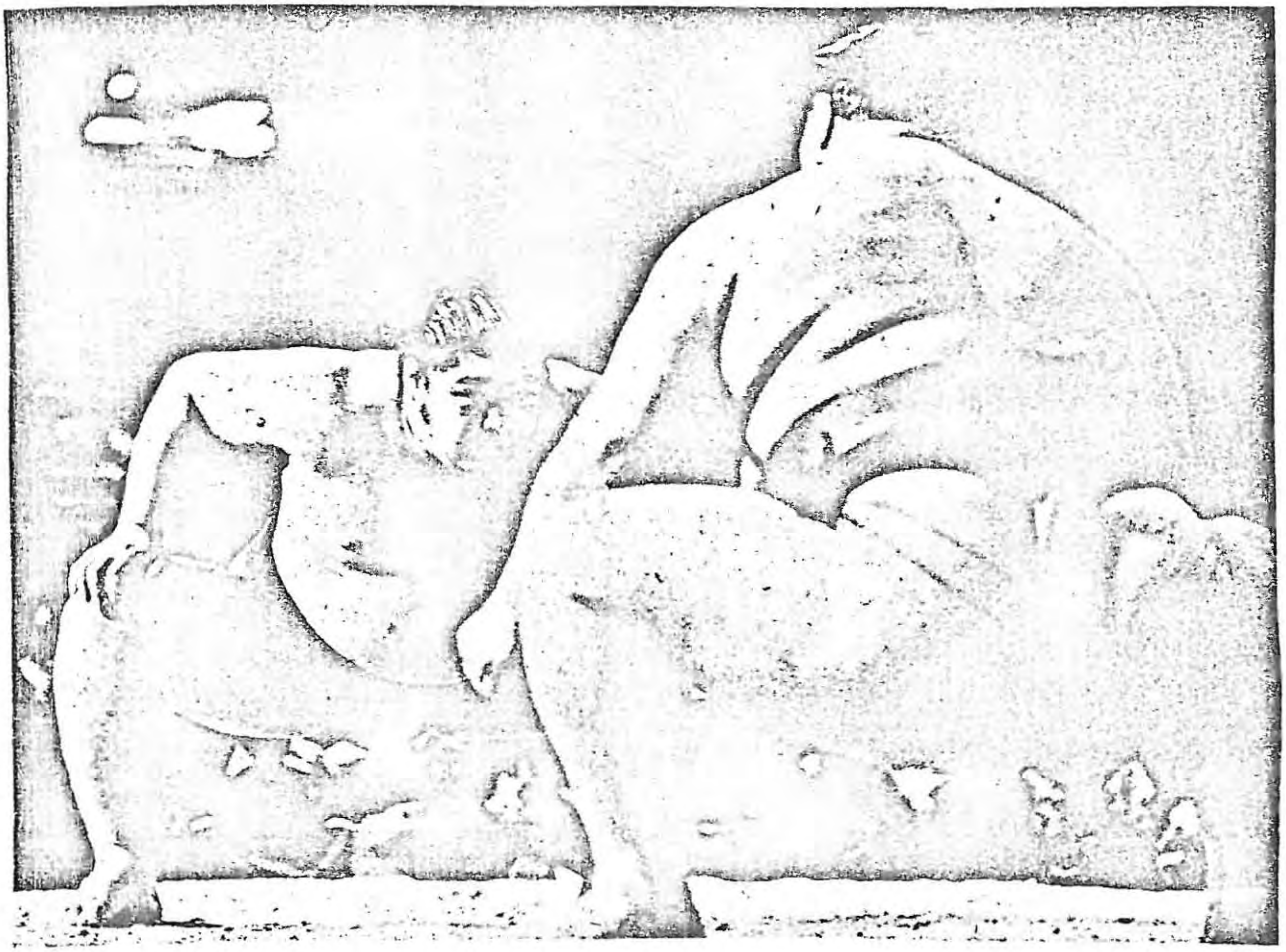
The nature of the applied force of a muscle varies according to the arrangement of the muscle's fibers, i.e., according to its shape. There are two main types of such structure: the longitudinal, or fusiform, and the pennyform (Rasch and Burke 1978). Within these types the fibers are arranged in many ways with respect to one another and to the tendons.

The simpler of the two forms is the fusiform, whose fibers run parallel to the length of the muscle. Most of the muscles of the limbs, especially those attached to the bones of the hands and feet, are fusiform; they are long, thin, and pointed at both ends; that is, they are cigar shaped.

Generally, muscles which are long and slender are weak but can shorten through a relatively large distance. Contrariwise, muscles which are short and broad have great strength but can only exert the strength through a proportionately short distance. Muscles of this type are called penniform. They are shaped more like a feather, having a tendon for the shaft and muscle fibers for the barbs. Since the fibers are arranged diagonally to the direction of pull, more of them can be brought into play, but the range of motion is reduced.

LEVERS, TORQUES AND MOMENTS

Suppose you are standing at attention with your hands to your sides. Now imagine a point at which all of your weight might reasonably be concentrated so as to maintain the standing balance of the body parts. Would this point lie above the head, say, or to the side of the body somewhere? Or is it more likely to be inside the abdomen, possibly around the stomach? As an intuitive representation of the body weight in space, the latter point is more meaningful -- it is called the center of gravity (c.g.). (See Picture 7.1 for a good example of a <u>low</u> c.g.)



Picture 7.1. Grand Sumo wrestlers showing low center of gravity. (Photo by Hughe Robinson)

We saw in Chapter 2 that gravitational forces act on material objects. For any given object, this pull of gravity may be considered to be a composite of a large number of little pulls on tiny parts of the object. It may also be visualized as a resultant of all of the little pulls, originating at the center of gravity. If the object could be supported at the c.g., with no other contact on the object being made, it would balance exactly.

Balancing an object on a knife edge or on a needle point can be a useful trial and error method of finding the center of gravity, but it is coarse at best and has serious limitations when the object is irregular. A more sophisticated technique makes use of the concept of a lever, and employs torques and other moments to compute the c.g.

While the formal or mathematical notion of a lever may not normally be understood by the average individual, the intuitive feeling is experienced even by the typical child, who applies torques in one form or another dozens of times a day. For example, the child may, on charging into the house, push against the center of the door to open it wider. Possibly finding too much resistance, he may slide unconsciously toward the door knob, where it can be opened more easily. Or he may experience difficulty turning the lid on a jar of peanut butter and run to his mother for assistance. These and many other examples demonstrate the normal, every day application of torques and levers. An application of torque in arm wrestling is shown in Picture 7.2.

People frequently use screwdrivers, crowbars, and other such devices as aids to pry open paint cans, lift heavy objects, and the like. This shows a practical, if not a formal, understanding of the lever principle which says that increasing the length of the lever arm increases the advantage of the lever. Without changing the applied force, an advantage can be gained by increasing the distance to the fulcrum. That is, more torque can be exerted, and therefore more weight can be lifted or a greater force can be applied to the object of interest.

Picture 7.2 Virgil Arciero applies torque to win an arm wrestling match. (Photo by Jack Lardomita)

Without changing the distance of the lever arm to the fulcrum (which is actually called the moment arm), and without increasing the magnitude of the force, the torque can be increased still more if that force can be directed more nearly perpendicular to the lever.

Referring to Figure 7.1, a precise meaning of torque can now be formulated. If F is a force acting at right angles to a weightless moment arm at a distance, d, from the fulcrum, or pivot point, then the torque, T, is defined as the product

$$T = Fd.$$

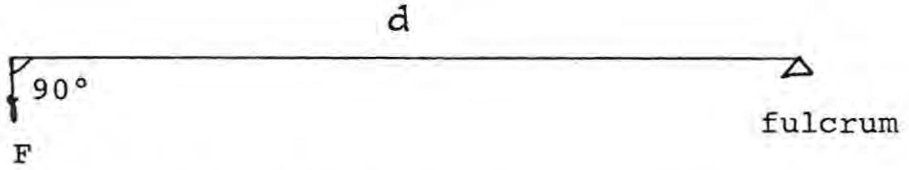


Figure 7.1. Formula for torque, or moment of force.

By definition, a unit of torque is a unit of force-distance. Since force is normally expressed in pounds (the English system) or in dynes (the metric system), and distance in corresponding feet or centimeters, torque is given in pound-feet or in dyne-centimeters. The torque may be positive, or negative, according to the direction it tends to rotate the lever around the pivot point. For convenience, it is deemed positive if the action is clockwise from the viewer's point of view; otherwise it is negative.

STABILITY OF A BODY

The plumb-line technique points up the importance of the location of the center of gravity of a body to its stability, a condition of prime significance to all individuals, but especially to the athlete.

Picture 7.3. Stephen Morimoto attempts to overturn his opponent. (Photo by Michael Edwards)

Generally speaking, a body can be said to be stable if its center of gravity is within its support structure; otherwise it is unstable. Consider the rectangular block of Figure 7.2., for example. The block resting on its base (Figure 7.2 (a)) is in stable equilibrium; the sum of its torques is zero. A body is in stable equilibrium if it can be jostled slightly without tipping over. If it is kicked no farther than shown in (b), for instance, it will return to its original position. Otherwise, as in (c), it will continue to roll and fall to another base. Picture 7.3 shows a young wrestler trying to de-stabilize his opponent.

The reason for the instability in position (c) is that the center of gravity of the block has passed to the outside of the support structure of the block. A vertical line drawn from the c.g. lies to the right of the base, thus creating an unbalanced torque which continues unopposed to twist the block clockwise.

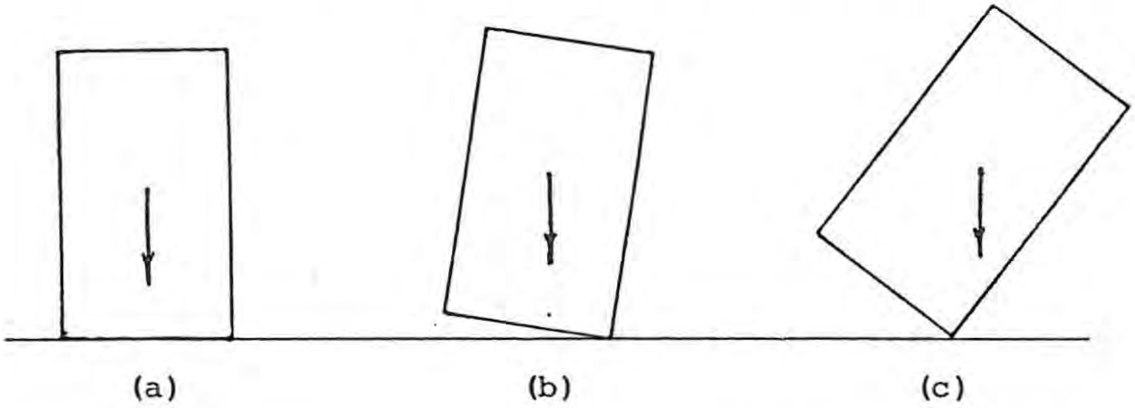


Figure 7.2. Stability conditions of a rectangular block. (a) and (b) stable, (c) unstable.

This block is presumed to be rigid; therefore its c.g. cannot be changed. However, if it were deformable, one might reshape it to produce a more stable structure. This can be done by shortening the object and widening its base. It is clear that merely widening the base is not enough, because the object might at the same time be made very tall; a tall, inverted T is not very stable. Just shortening the object is not adequate, either, because it could become very top heavy, like an inverted, truncated pyramid. But the effect of the joint deformation is to lower the center of gravity. Since the weight is unaffected, this means that a greater force for the same torque has to be applied to overturn the object.

For the human body, say in a standing position, increased lateral stability is gained by spreading the feet apart and bending the knees, i.e., by lowering the buttocks and getting into a crouching position (see Picture 7.1). By doing this the effective height shortens; the bulk is lowered. Thus the c.g. is lowered and greater force has to be applied to overturn or destabilize the person.

This practice is especially important for certain athletic events, such as defensive wrestling, in which the athlete strives to keep from being thrown to the mat. In tennis, too, it provides strong support for ground strokes, where power is generated off the legs. In this respect, off-balance shots are generally ineffective. But this is not to say that all actions are to be taken with the center of gravity safely nestled within the bounds of the support base. On the contrary, the center of gravity frequently shifts beyond the base of support, and rightly so , a fact to be kept in mind for simulation.

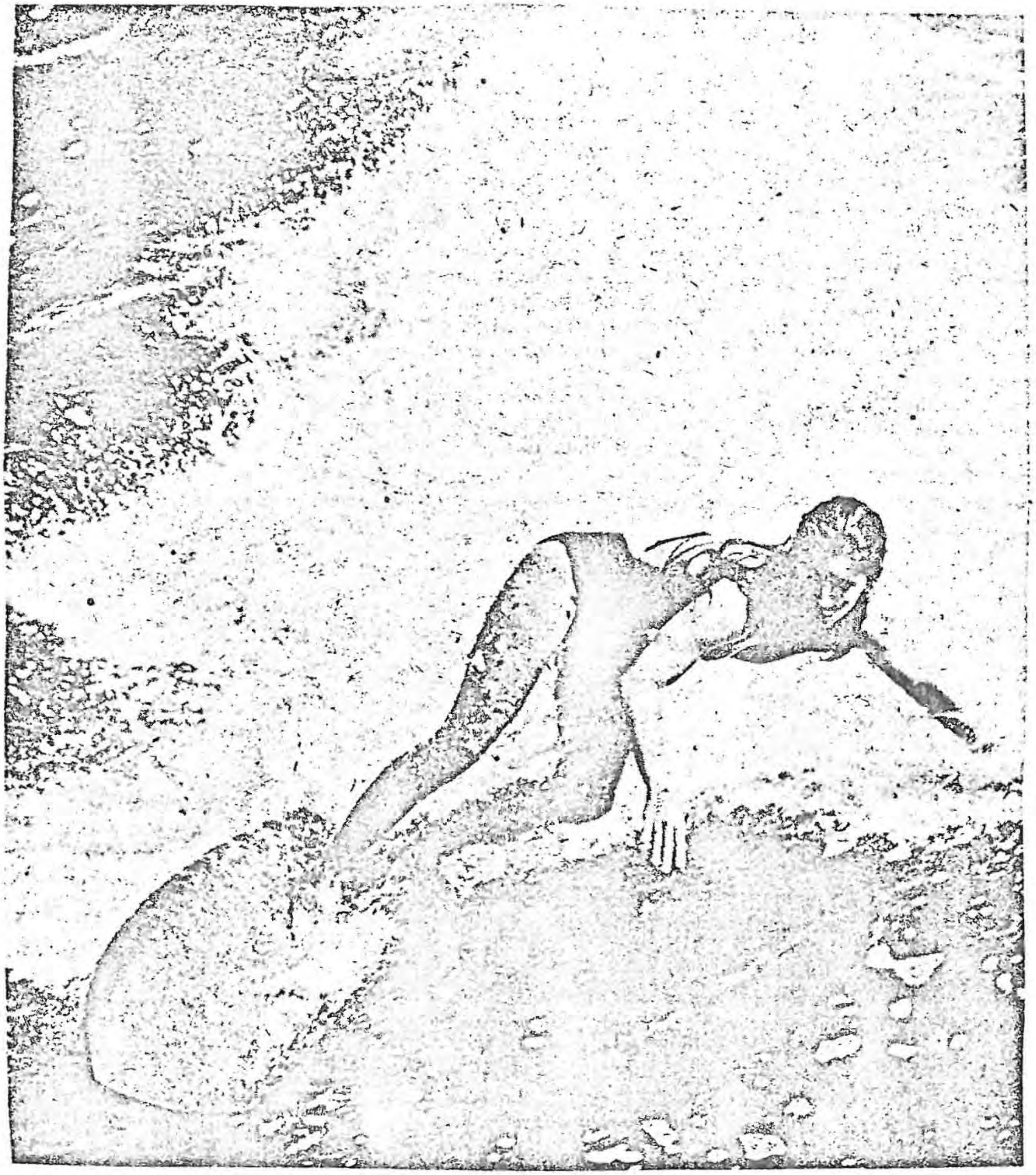
While it may be best in static events to keep the c.g. well contained -- in lifting weights, for instance, the body has to shift in such a way as to keep the gravity line from slipping beyond the support base --, there are many dynamic situations where this would be highly ineffective. For example, the simple acts of walking or running are almost literally acts of falling. In this behavior the area of support regularly reduces to just the area of the ball of the foot before the other leg is brought forward, and at this moment the center of gravity is moving well to the front of the support as the other leg is being brought into place.

This illustrates <u>dynamic</u> equilibrium. It is to be distinguished from <u>stable</u> equilibrium in that the situation is constantly changing. The parts of the skeletal structure are shifting with respect to each other, and the center of gravity is shifting (see picture 7.4). Indeed, this is the more normal condition in human movement, generally, and in athletics, specifically. Most action shots taken of athletes show that the players are statically unstable -- if placed in those positions they would fall --; yet they are not out of control dynamically, but are in dynamic equilibrium. Picture 7.5 is a good example.

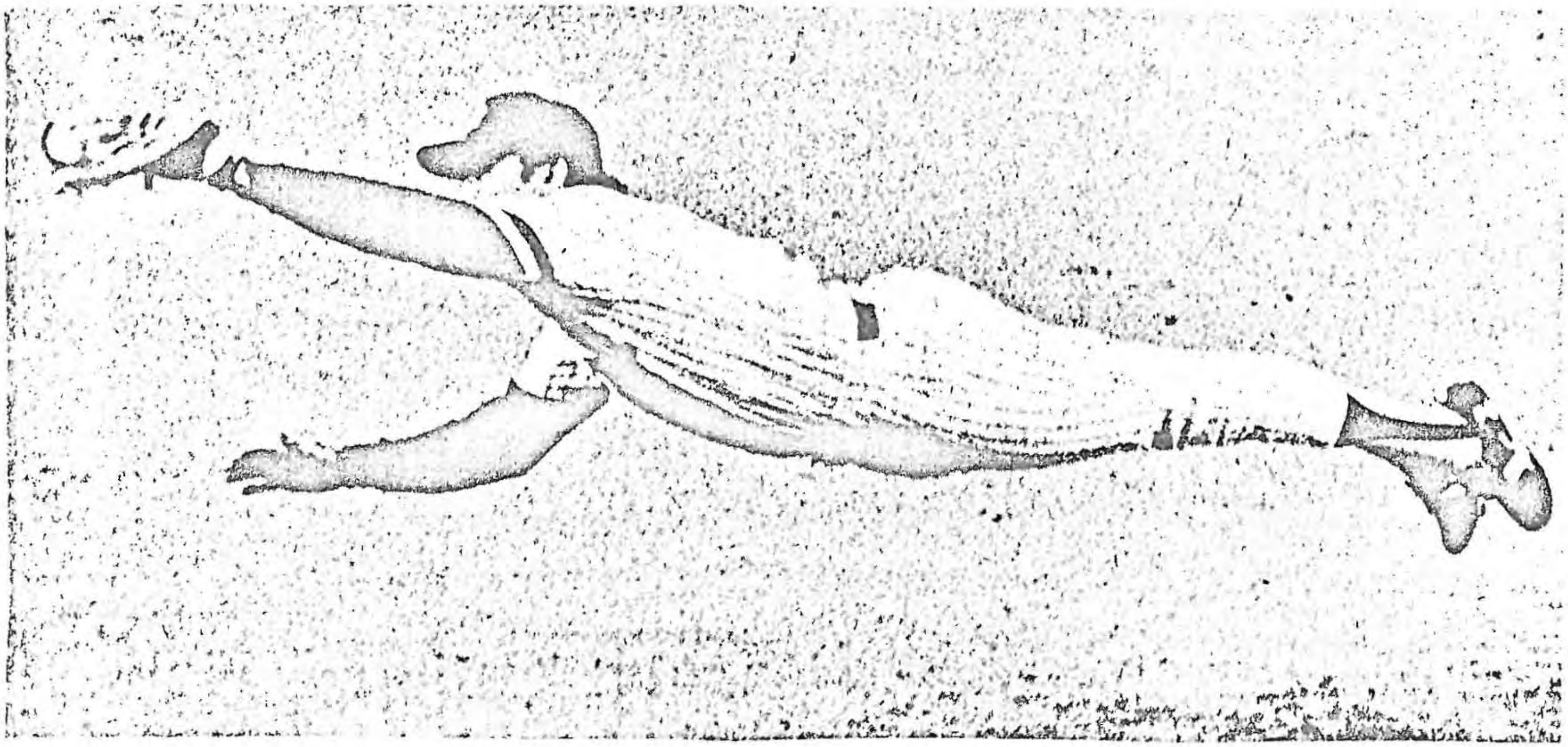
THE BODY AS A SYSTEM OF LEVERS

As stated above, the body moves as a consequence of the orderly, organized spatio-temporal patterns of innervations and contractions of muscles. Neural impulses innervate and muscle contracts and tends to pull its attachments toward the middle; the stronger the contraction, the greater the tendency to pull. The muscles pull against bones, which act as levers. For example, the coracobrachialis attaches to the scapula and humerus and tends to lift (flex) the arm, and the teres major tends to extend the arm. Similarly, the gluteus medius attaches to the ilium of the pelvic girdle and to the femur and tends to lift the leg out to the side (abduct the leg), while the adductor brevis, with others, tends to adduct, or draw the leg in. These and the other striate muscles act in a system in which bones move as moment arms or weight arms around appropriate joints. In other words, they can be said to form different kinds of levers.

We have seen that a lever is an application of torque, which is a moment of force, i.e., a force which acts normal to (at right angles to) the lever arm and at some distance from a fulcrum or pivot point. The force tends to rotate the lever arm about the fulcrum, so a lever is the application of a rotatory force. The lever arm, reckoned from the fulcrum to the point of application of the force is normally called the moment arm, or force arm.



Picture 7.4. Candy Woodward with a beautiful demonstration of dynamic equilibrium. (Photo by Daily Breeze)



Picture 7.5. Graig Nettles defys gravity grabbing a hot liner. (Photo by Associated Press)

This rotatory force is directed against some resistant element, such as a heavy weight, with the intention of lifting that weight, or moving it, or otherwise doing some useful work. The weight is the reason for using the lever. The lever arm, measured from the fulcrum to this weight, is called the weight arm. An analysis of levers therefore involves the analysis of forces applied to a moment arm and forces working on the weight arm.

The weight and the applied force need not be on the same side of the fulcrum, as the previous examples indicated. But it is the arrangement of these different forces on the lever that determines the kind of lever being used. Accordingly, there are first, second, and third class levers.

In a first class lever the weight and force are on opposite sides of the fulcrum, as shown in Figure 7.3. A lever is intended to be used to advantage. In this kind of lever a small force can be used to advantage over a heavy weight if a sufficiently large force arm can be employed. The trick is to counterbalance one torque with another one of opposite sign. Since a torque is a product of force and distance, a large distance can produce a large torque. This distance, d, must be such that F x d is at least as large as W x r, where F is the applied force, W is the weight against which the force is working, and r is the weight arm. That is, d must at least satisfy the equation.

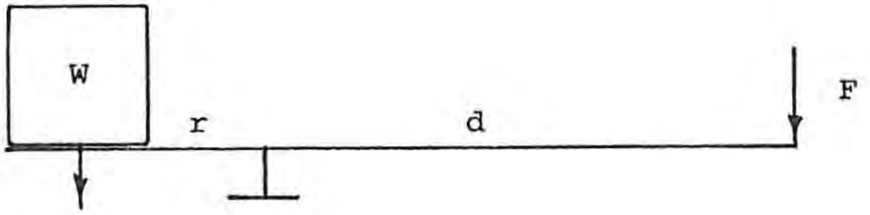


Figure 7.3. First class lever.

$$F \times d = W \times r.$$

Levers of this class include such items as scissors, crowbars, and teeter-totters. While there are not many of these levers in the human body, one example is the triceps, which attaches to the infraglenoid tuberosity at the shoulder end of the humerus and at the olecranon process of the ulna at the elbow (Figure 7.4).

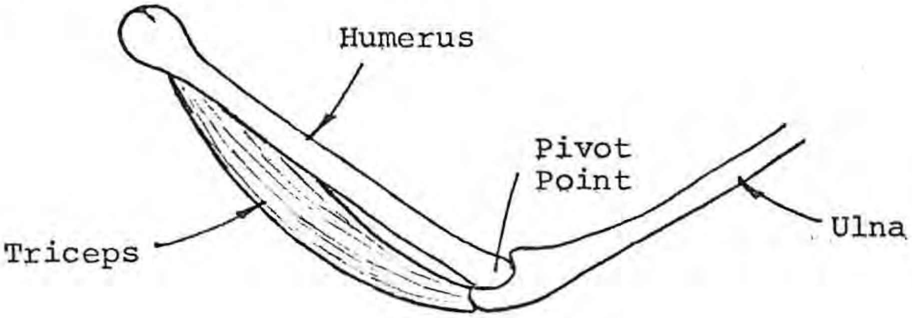


Figure 7.4. First class lever at the elbow.

In a second class lever, the weight and force are on the same side of the fulcrum but the weight is between the force and the fulcrum, as shown in Figure 7. 5. This lever is seldom found in the body.

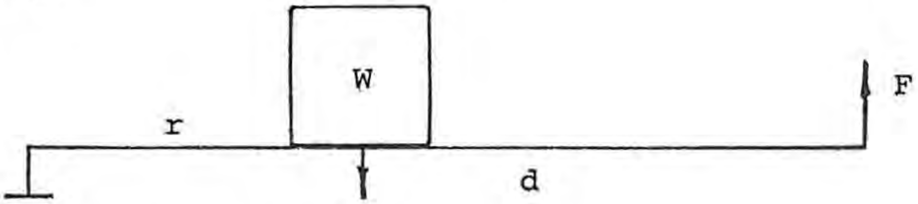


Figure 7. 5. Second class lever.

In the third class lever, both weight and force are on the same side, but the force is applied between the fulcrum and the weight, as in Figure 7..6. In this and in the second class lever, the torque equation to be satisfied is the same as

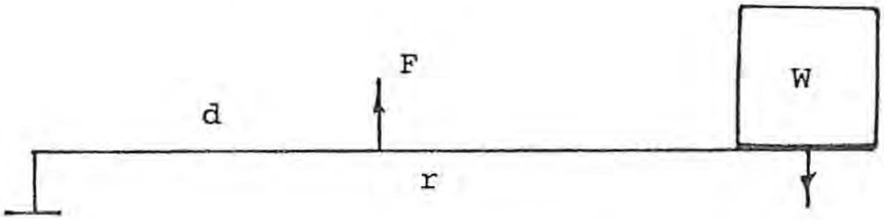


Figure 7. 6. Third class lever.

that for the first class lever, namely,

$$F \times d = W \times r.$$

Examples of this lever class are to be found in the inside door handle of a car, the spring pulling on the screen door, tweezers, finger-nail clippers, and the like. This is the type most common in the body. A typical example is the biceps brachii, which flexes the arm (Figure 7. 7).

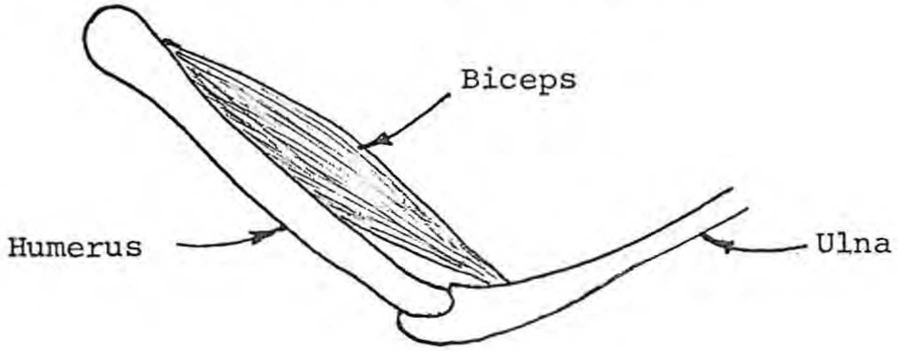


Figure 7. 7. The biceps brachii as a third class lever.

It should be clear that in this type of lever there is no force advantage. Since the force arm is shorter than the weight arm, the force to be applied must actually be greater than the weight itself if the torques are to balance. There is then a force disadvantage. That is, the mechanical advantage -- the ratio of weight to force -- is less than unity.

What then is the value, or advantage, of having third class levers in the body? The value lies in the gain in the speed of movement. In a dynamic situation the levers (bones) are in motion. They rotate about their joints. For these levers the weight end, or the end of the weight arm, being farther from the fulcrum than the end of the force arm, moves through a greater distance than the force end, so it moves with greater speed. Speed advantage is gained at the loss of force advantage.

Even greater advantage is attained if the angle of pull is smaller, and this implies an even greater sacrifice of force.

The smaller the angle of pull, the farther and faster a given amount of muscular contraction moves the bone.

From the point of view of force alone, the optimum angle for pull is 90°. At this angle no component of force acts along the length of bone. All of the pull tends to rotate the bone and the force arm actually equals the distance to the point of muscle attachment. At smaller angles, some part of the muscle tension tends to pull the bone into its joint, whereas at larger angles some component tends to pull the bone away from its joint. In either case, there is a loss of efficiency; power is reduced. Hence, the greater speeds at the lower angles is achieved only at the expense of a considerable loss of power.

When a weight or resistance of some kind is engaged by muscle action, not only the angle of pull but also the angle of resistance, changes with time. This is illustrated in Figure 7.8. where the applied force and the weight are at angles to the lever different from 90°. Since the torque equation applies only when forces are at right angles to the lever arm, the appropriate conversion of values is required. This involves trigonometric formulas.

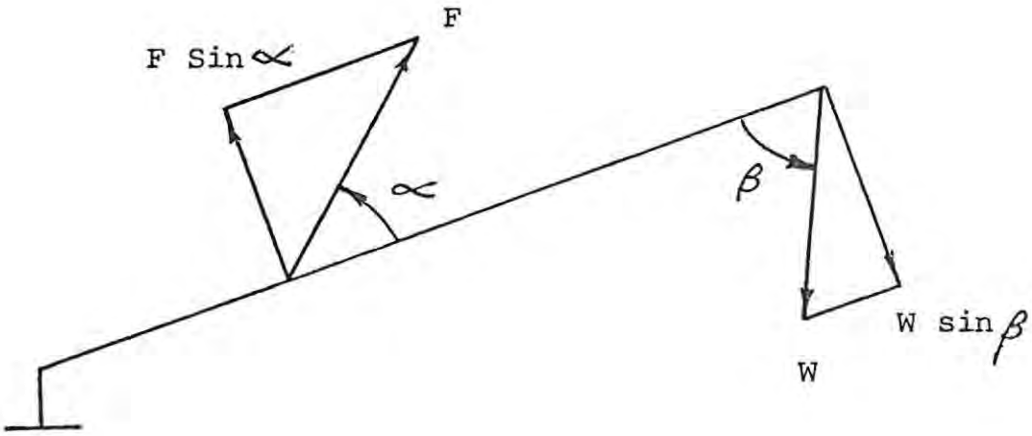


Figure 7.8 . Trigonometric conversion of forces.

The weight, W, acts on the lever arm with two components of force, one along the length of the arm and the other normal to it. The normal component is the effective weight producing a torque about the pivot point. This has the value $W\sin\beta$.

Similarly, the force, F, acts with its two components, one along the length of the arm and the other tending to counteract the action due to the weight. The normal component has the value $F\sin\alpha$.

In computing the dynamic characteristics of the torques acting to produce movement, it is necessary to consider the changes in angle that take place on these forces. This can be a formidable task. It is the more difficult because of the many other variables that have to be considered.

The human organism is seldom static. Even when at attention there is a normal, continuous adjustment of muscle tension to maintain equilibrium. Muscles fatigue and rejuvinate, resistances change, the flow of innervations is fluid, mechanical leverage varies with angular position of the bones, tension depends on muscle length, and the amount of work that can be accomplished depends on the tension. Somewhat like a battery, muscle appears to contain resistance, which consumes part of the energy.

There is the additional complexity due to the ability of muscles to contract finely between the very weak and very strong, depending on the number of motor units stimulated, the frequency of the stimuli and their timing to various motor units. The central nervous system is able, in effect, to recruit any number of the available motor units and stimulate them even to a point of great synchronicity for Herculean strength.

Finally, these problems have to be considered in the light of irregular, external forces impinging on the organism. For the fast-moving tennis player, this means reacting to the ball and to the opponent. The physical situation has to be summed up quickly. Estimates are required. Relationships have to be perceived. Anticipations calculated. And movements effected. This creates a complex system of lever dynamics.

ROTATIONAL DYNAMICS

In Chapter 2 we dealt with inertia and acceleration, i.e., with the quality of a body that resists change in its state of rest or uniform motion and with the forces causing changes in the state of rest or motion. This yielded the Newtonian expression $F = ma$.

A similar expression can be written for moments of force relating to moments of inertia. In this rotational form of Newton's equation, the moment of force, M, is equal to the moment of inertia, I, of the body times the body's *angular* acceleration $\ddot{\theta}$. That is, $M = I\ddot{\theta}$

The *moment* of inertia is the quality of a body that resists changes in its *rotational* movement. It thus depends on mass, as in linear mechanics. But now the organization of that mass is a most important factor. This means that objects with the same mass but different structure will have different moments of inertia. It is this dependence on structure that permits the figure skater to accelerate or decelerate a pirouette, for by bringing his feet together and pressing his arms to the side he actually lowers his moment of inertia and increases his angular velocity, and by stretching out the arms again he raises his moment of inertia and decreases angular velocity.

Computation of the moment of inertia is not always an easy task. However, for an idealized point mass at a distance, r, from the pivot point, it is given as $I = mr^2$, a formula that can be used as a computational starting point for any real object. This is done effectively by treating the object as a collection of "point" masses and summing up their respective moments of inertia. When the mass distribution and boundaries of the object can be stated mathematically, the integral calculus can be used to advantage. The moments of inertia for such objects as spheres and cylinders can readily be obtained if their mass distribution can be stated, for instance if they are homogeneous. Thus the moment of inertia of a cylinder rotating about its longitudinal axis is $\frac{1}{2}mr^2$, where r is the radius of the cylinder and m is its mass, the cylinder being homogeneous.

In the human organism, such computations are particularly difficult because the body segments are not homogeneous and the centers of mass cannot be given exactly. Values for the moments of inertia of the segments are therefore only approximate as well. So the dynamics accuracy must suffer.

Some approximations to local moments of inertia for various body segments are to be found in the U.S. Air Force report number AMRL-TOR-63-18. For this analysis, the body was segmented into 14 idealized masses, as shown in Figure 7.9. The model was developed to approximate the mass distribution, center of mass, moments of inertia, and degrees of freedom of the body. The analysis revealed that the segment moments of inertia about the mass centers of the hands, feet, and forearms are negligible when compared to the total body moments of inertia.

Insofar as this model is used to predict man's mechanical behavior, it is of interest here. But it has limited value in that the results apply specifically to conditions of weightlessness. The important gravitational force for earthbound creatures was ignored. While its absence poses interesting dynamics problems, its presence poses even more interesting problems for our tennis player. In either situation, however, there are certain common dynamics problems. On the earth or in free space, the biomechanical properties of the body change when its shape changes. If a man moves his arms or legs, his center of mass and moments of inertia change. The human body is complex and flexible. It is variable in shape, non-symmetrical, and non-homogeneous. In short, man is a highly resistive, deformable creature. Therefore his mechanical responses will be complex and varied.

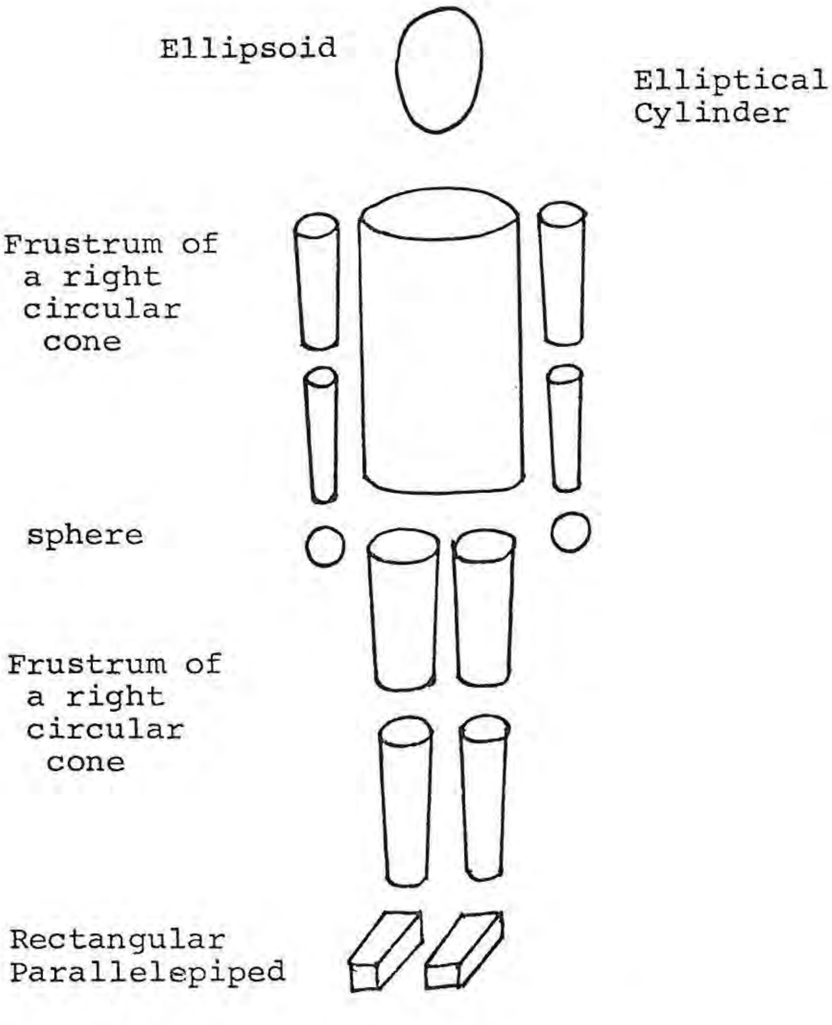


Figure 7. 9. Segemented model.

BASIC MOVEMENTS

In any mathematical formulation of the motion of physical objects, great care is taken to isolate components of motion which are independent of one another and by means of which composite motions can be determined. To this end, orthogonal coordinates are used. The basic components of motion are thus reduced to at most three, each one represented as 90° from the others in the coordinate system.

In order to construct a dynamics of the human organism, it is reasonable to follow this approach to attempt to establish basic movements out of which composite movements can be defined. Since the ground of human movement is muscle tension acting on bones, the basic elements must derive from this source.

We have seen that when a muscle contracts, it tends to pull against the bones to which it is attached. Apparently, muscles only exert a pull; they don't seem in any way to dictate what movement will actually occur. The best that can be said is that they tend to do what is in their capability to do -- whatever that might be, considering that such capability is not entirely visible! In any case, for any one of several reasons already mentioned, a muscle doesn't always fulfill its tendencies.

To account for these occurrences or non-occurrences, we need a science of human movement, one which is ultimately able to predict the "good feeling" the individual has when he performs a highly skilled action well. Such a science requires a detailed development of basic movements as a foundation on which to build a theory.

As MacConaill and Basmajian point out (1969), it is necessary to study the means by which movements are brought about or restrained, including gravity, the skeletal muscles and the mechanics of the joints. With this in mind they make use of the geometry and algebra of articular kinematics and the general statics of antigravity musculature. Since muscles pull on bones, and bones join at articular surfaces, the structure of those surfaces and the manner in which the muscles are attached to the bones should determine the mechanical action of the musculo-skeletal system.

According to MacConaill and Basmajian there are only two basic ways in which a bone can move, namely, by spinning and by swinging, movements which occur around some mechanical axis. By spin is meant any movement in which an arbitrary point on the bone rotates around the axis. A swing is then any movement that is not a spin, and a pure swing is a swing with no spin component.

It is important to note that, although translatory movement is a common occurrence in our lives, it is not a basic movement. Rather, it is a composite movement, stemming from the spins and swings produced by muscle tension. By virtue of this fact, it follows that any point of a bone moving at a joint moves in a curved line. This is obvious for spins, but it is no less true for swings, though the curvature may be slight, as in the case of the larger bones.

> In a pure swing this point moves from its initial to its final position in space along the shortest possible curved line. This line corresponds to the meridian of longitude on a sphere, and to a straight line on a flat surface. In an impure swing the movement is always along some curved line other than the shortest. This corresponds to an arc between two points on a flat surface, the line of pure swing corresponding to the chord between the same points. For this reason an impure swing is called an arcuate swing. A pure swing is called a cardinal swing. (MacConaill & Basmajian 1969, p. 15-6)

Movement of bones at joints is not the simple action found in a carpenter's hinge, where the pivotal axis is fixed and there is a single degree of freedom of movement. In the first place we are dealing with contacting or articulating surfaces. Secondly, the surfaces are not planar; they may be ovoid, for instance, or saddle shape. And finally, one surface may rock, slide, roll or spin over the other, depending on the kind of joint.

Ovoid surfaces are surfaces like egg shells, which are convex on one side and concave on the other and are such that the curvature varies from point to point. Saddle surfaces, on the other hand, are concave on one cross section and convex on the cross section 90° to the first. The two surfaces are illustrated in Figure 7.10. A chordal triangle is drawn on each surface to show the variation in curvature.

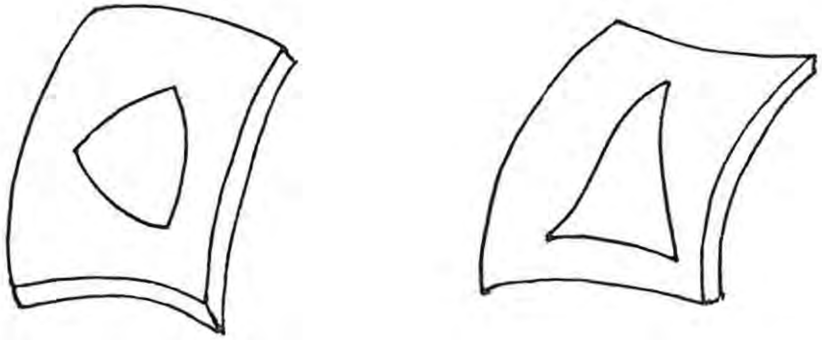
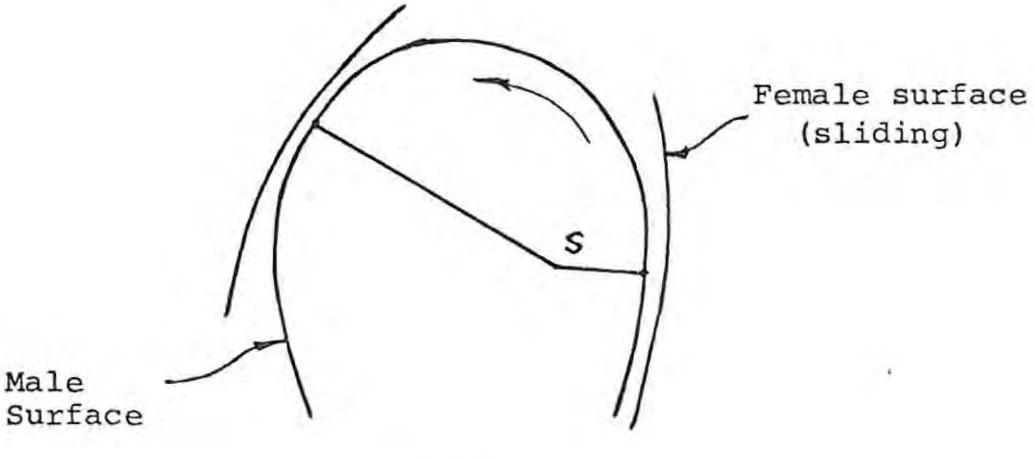


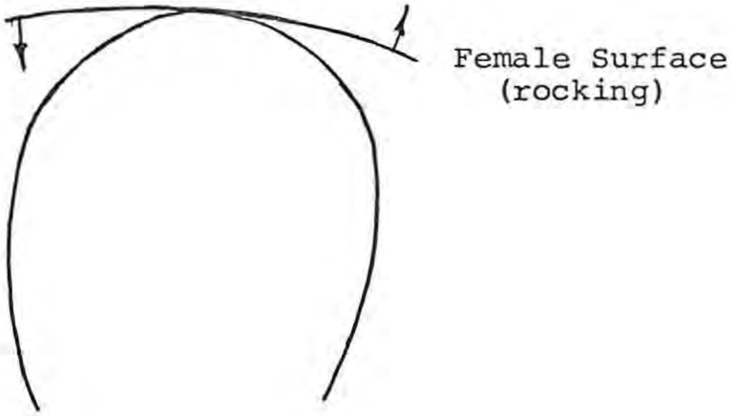
Figure 7.10. Ovoid surface (a) and saddle surface (b). (After MacConaill and Basmajian 1969)

In synovial joints, so-called because of the viscous lubricating fluid in the joints, there is at least one mating pair of articular surfaces, each in the pair being ovoid or each being saddle shape. In the ovoid pair the concave is called female; the convex, male. In the saddle shape pair the smaller is called female, the larger the male.

Considering the movements of ovoid pairs, for example, movement of the female surface on the male is to be distinguished from that of the male on the female. As shown in Figure 7.11, a female surface can both spin and slide on the male surface. Also, the female surface can rock to a small extent. The rocking occurs during sliding and works in the same direction, so that during a sliding movement the female surface constantly approaches the male in the direction of motion.



(a)



(b)

Figure 7.11. Female surface sliding over male surface through angle, s, (a) and female surface rocking on male surface (b). (From MacConaill and Basmajian 1969)

As a result of this rocking and sliding, the mechanical axis of the moving bone is swung through space, the total angle in an amount equal to the sum of the two components. As Figure 7.12 shows, this displacement of the axis is

$$a = r + s,$$

where r and s are the angular displacements due to sliding and to rocking, respectively.

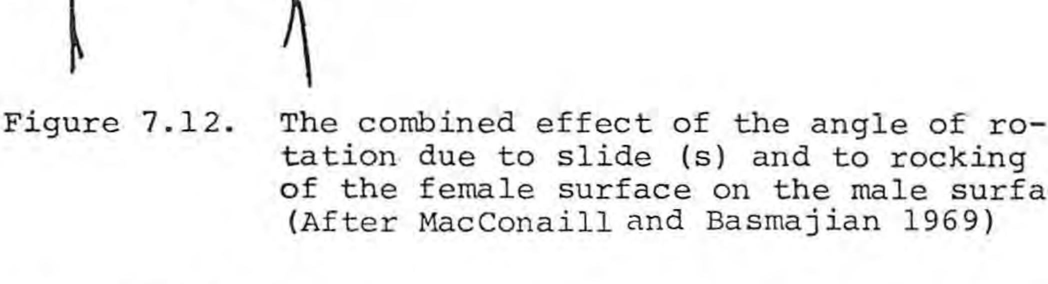


Figure 7.12. The combined effect of the angle of rotation due to slide (s) and to rocking (r) of the female surface on the male surface. (After MacConaill and Basmajian 1969)

Similarly, male surfaces both slide and spin, but they also roll on the female surface. Rolling and spinning are the principle movements of a male surface. Sliding normally accompanies rolling and its direction is opposite to that of the roll.

The mechanical axis of the moving bone is swung through space mainly by the rolling component of movement of the male surface, the effect of the sliding movement being to supplement that of the roll, just as the rolling movement supplements the effect of the slide in the moving female surface. And the same equation results, namely,

$$a = r + s.$$

This is illustrated in Figure 7.13.

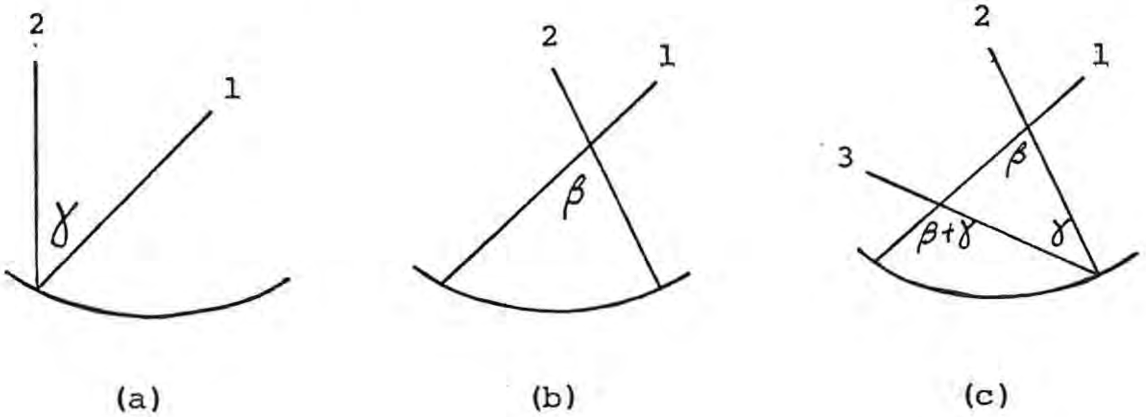


Figure 7.13. The effect of rolling (a) at angle γ, sliding (b) at angle β, and combined rolling and sliding (c) at angle $\gamma + \beta$.

If we now consider the action of muscles on bones, we see that the force of the pull which is exerted can be resolved into three components. One force, T, may be transmitted along the length, or axis, of the bone. Another, A, may work directly across the axis. And the third, R, is such as to rotate the bone around its axis. Thus, R is a spin component, T acts toward the joint, and A is the swing component, which itself can be resolved into one V, acting in the vertical plane and one, H, acting in the horizontal plane, as in Figure 7.14.

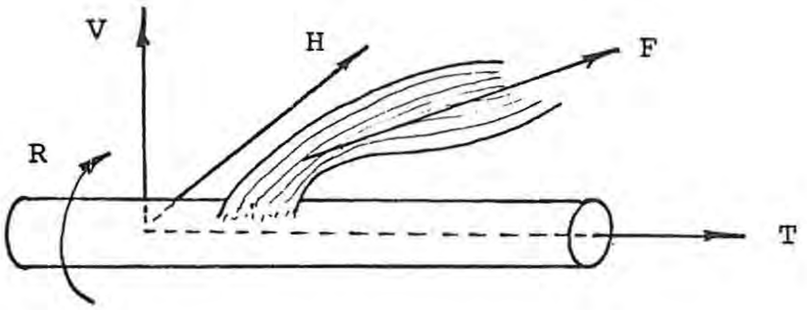


Figure 7.14. Four components of a force, F, of a muscle acting on a bone. (After MacConaill and Basmajian 1969)

COMPOUND MOVEMENTS

Given the basic movements, compound movements can be defined in terms of them (MacConaill and Basmajian 1969). Thus, for instance, a <u>composite</u> movement may be defined as any single movement which can be decomposed into two or more basic movements, typically swing and spin. Even the most common simple movements are of this type. All hinge joints have some degree of rotation combined with extension or flexion. For example, at the elbow the ulna is pronated (medially or inwardly rotated) in full extension and supinated (laterally or outwardly rotated) in flexion. Similarly, when the index finger and thumb are brought into a good posture for grasping, the terminal phalanx of the finger is supinated and the thumb is pronated.

When successive distinct movements are strung together in such a way that each makes an angle with its predecessor greater than 0° and less than 180°, a <u>diadochal</u> movement results. For example, humeral forward flexion followed by horizontal extension is a diadochal movement having two parts. If an adduction is added, a three-part diadochal movement is formed.

Other classifications are possible as well (Rasch and Burke 1978) Thus for instance, sustained force movements are movements in which a sustained force is applied against a resistance by contracting mover, or agonist, muscles, while their antagonists are relaxed. Examples include the armstroke in swimming, the leg thrust in a racing start, or the forehand ground stroke in tennis.

MOVEMENTS IN TENNIS

The compound movements normally exhibited in the game of tennis may conveniently be categorized into those motivated by the need to acquire information about the state of the ball and the players and those seemingly more productive acts aimed at reaching the ball and striking it. The former involves eye movements predominantly, though head and body movements are at times necessary concommitants. Discussion of possible eye movements will be left for the next chapter. In this section we shall summarize briefly those actions whose objective is to return the ball to the opposing player's court.

Movements of the body may be divided generally into two groups: movements at the ball and movements away from the ball. Movements at the ball are those more frequently dealt with in books of instruction and refer to the variety of striking actions with the racquet. Movements away from the ball, on the other hand, relate to the actions of a player in anticipation of ball placement by the opposition. It is evident that the selection and execution of shots is critical for effective performance on the courts, but proper positioning certainly improves the player's offensive and defensive capability.

Different game situations certainly call for individual tactical maneuvers, and a great deal can be said about offensive and defensive strategy. But here we are not concerned with functional or purposive aspects of movement but rather with its dynamic structure. In this respect the number of possibilities is considerably reduced.

Movements away from the ball are either shifting movements, intended to gain a better defensive or attack position, or intercept movements, designed to put the player in a position from which he is able to hit the ball. They can be subtle, barely noticable events, or explosive, wide-ranging actions. For example, a player might simply take a short step forward or backward, perhaps to adjust to his opponent's effective serve. Or he could back-peddle quickly as he sees his opponent rushing forward to attack a short lob. At the net he might suddenly bolt laterally, hoping to cut off a drive down the line, or race to the baseline to retrieve a lob.

During furious doubles action, all four players could be in continuous motion, possibly running backwards or forwards, net to baseline and back, taking overhead smashes, switching positions with partner, covering for partner's poaches, etc. In singles action in order to intercept the ball, a player might have to run all out from one side line to the other, charge to the net, make a diving stab at the ball, or scramble from a net position to deep behind his baseline. Movements away from the ball can thus range from gently walking, side-stepping or back-peddling movements, to aggressive running or jumping movements.

Having maneuvered to intercept the ball, our player is now in a position to take striking action, which he does with one or another of a standard variety of strokes with the racquet. These strokes are usually categorized as serves, overhead smashes, forehand and backhand ground strokes, and volleys at the net, each category allowing for a wide range of structural variation.

The strokes can be compared with the throwing motion. For instance, Broer (1973) differentiates among overhead, sidearm and underhand throws and shows the similarity in movement between the overhead throw of a baseball and the service motion or overhead smash. (The service motion is also frequently compared to the throw of a hatchet.) The forehand shot may be either an underhand movement, when the oncoming ball is low enough, or a sidearm action when the ball is higher. The backhand stroke is less well characterized in this fashion, and the net volley is more like a catching motion.

As in throwing, striking action with the racquet may involve all or only some of the lever components of a full stroke. The serve, for example, utilizes leg and body motion to propel the service shoulder upward and forward. From this accelerating power base, the shoulder muscles add to racquet head speed by contracting. Almost immediately thereafter, elbow muscles extend the lower arm to propel the racquet head even faster, until at near maximum speed the wrist muscles provide the last impulse of force. This is a rapid sequence of basic movements, not all of which need be used. Thus the first step might be neglected, with consequent loss of power, but possibly with increased control.

Striking movements also have a beginning, middle and an end, and the player is well advised generally to maintain a degree of symmetry over the stroke. That is, it takes time and motion to build up the speed, and therefore the power, of a stroke; for a given muscle contraction rate, a longer back swing is needed to generate greater racquet speed through the ball. Similarly, it takes time and motion to bring the racquet to a stop after the ball is hit; the higher the speed, the longer the follow through that is required. Roughly speaking, then, the extent of the follow through should be comparable to that of the back swing. Shortening the follow through can weaken the shot by biting into the last phase of the acceleration of the racquet.

CHAPTER 8

MOVEMENT OF THE EYES

Visual perception involves neuro-motor processes in an essential way. Attention is directed and the eyes are oriented to some selected component of the environment using the oculomotor system. On the tennis court the player transmits neural signals to the muscles of his eyes to guide them along the path of the ball. Activated in some complex way, the muscles contract and relax appropriately and the eyes and body move in some manner or other. Hochberg summarizes these movements briefly as follows:

> The observer's body is in almost constant motion in the world, his head is in motion on his trunk, and his eyes are in motion in his head. Two kinds of eye movements are essential for the perception of moving objects by moving observers in a three-dimensional world. Compensatory movements permit the eye to fix on some target while the body moves, . . . and pursuit movements swing the eye smoothly to obtain clear foveal images from moving objects. Further, accommodation and convergence bring the object to which we are attending into clear focus and central location on the retina . . . Normal vision would be quite impossible without the cooperation of all of these muscular actions, and they must all be taken into account in some fashion in order to assign any spatial meaning to a given stimulation of the retina. In order to know where the distal object is in space we have to know how our eye has moved. Only then could we interpret the image on the retina. (1964, p. 27-8)

The functional relationship between muscle movement and actual perception of moving objects is by no means simple and straightforward. Very similar conditions of movement can, in fact, lead to quite different perceptual results. Consider the phenomenon in which the eye is moved across the perceptual field, say to follow a line of print on this page. If that movement is made voluntarily by the viewer, the line and page remain perfectly stable in the visual field. But if the eyeball is pushed with the finger and thus forced to follow the line, the line is seen to move in the opposite direction. No matter how smoothly and carefully this is done, the line of print goes in a direction opposite to the motion.

Pushing the eye mechanically across the page isn't exactly normal reading practice. But it demonstrates that something more is involved in the voluntary movement which it attempts to emulate. Some additional factor, perhaps another piece of information, is required in the process to produce the stable patterned response. The reflex arc needs to be developed in more detail.

In Chapter 4 it was argued that the space of mental representations acts on the stimulation patterns to produce the response. In Chapter 9 we will see that Pribram argues that the brain acts on the input system and thus controls the nature of the stimulation and also modifies it. In another view, Hochberg claims that there must be an intervening higher-order variable between the external objects which are perceived and the patterned responses which result.

> Whenever observers agree about what they see, the following must be true. No matter how complicated the stimulus is, and no matter how great the effects of past experiences (and of other known factors), there must be some discoverable psychophysical relationship between the objects viewed and the perceptions that result. If there were nothing in the stimulus pattern to govern the response, there obviously could be no agreement (except by chance) among observers. If combining two stimuli changes their appearance, then there must be something about the combination itself which elicits that change. That is, in addition to the local physical characteristics of each stimulus, the relationship between them may be an important variable. A relationship that exists between individual measures is called a higher-order variable. (1964,p. 74)

The higher-order variable is a measured relationship between individual measures which serves to explain the peculiar properties of a perceptual phenomenon, such as the stability of the line of print on the page. Another example is the ratio of the light energy of adjacent regions in an optical array. Whereas the measures of the absolute values of the energy of those regions would be inadequate to predict the lightness perceived, the ratio of those values could possibly do so.

Again, consider the gradient, which is the rate at which a property changes over some region of space. This variable might provide an explanation of size-constancy, for instance. In effect, it identifies a relationship which characterizes the manner in which the visual system perceives physical space.

The ultimate aim in the search for the higher-order variable is the discovery of the basic laws at work in perception. These are the laws in accordance with which the neural mechanisms operate and by means of which it can be predicted what an observer will perceive if given a specific configuration of stimuli.

MOTION PARALLAX

Hochberg (1964) claims "if we consider the higher-order variables which result from the observer's own motions, the stimulation of the eye is completely unambiguous -- at least in principle" (p. 94). The view of an object from a single perspective may be ambiguous, but the ambiguity can be reduced as a result of successive presentations from different perspectives, the change producing what is known as motion parallax.

By incorporating the effects of motion parallax, "the information economy of seeing only one spatial arrangement -- the true or veridical arrangement -- becomes overwhelmingly greater than that of any other. In fact, it appears that, if he uses all of the visual information that is available, there is no way at all of fooling an observer, once we let him determine his own movements" (p. 97).

Underlying this phenomenon may be a higher-order variable which Hochberg identifies as the gradient of expansion. Whenever the observer moves toward a rigid surface, the elements of the field undergo a process of expansion, and this gradient "forms a pattern which will be different for each orientation of the surface, for each direction and speed of motion of the observer, and for each distance of the observer from that surface" (p. 97).

In the game of tennis, motion parallax appears in the form of a relative displacement in the visual field of the ball, net, other players, surface lines and backdrop. Except as modified by the independent motions of the ball and other players, the displacement is naturally greater for nearer objects and less for those farther away. The speed and direction of the perceiving player's motion clearly determine the extent of the parallax; the faster and more nearly at right angles to the line of play the motion is, the greater the parallax.

The boundary lines and texture of the playing surface of the court are particularly useful in depth perception, because it is the gradient of the motion parallax that provides the key source of information. In the absence of any other data, two isolated points cannot be seen in clear depth when the observer moves. What is lacking is the cohesive quality provided by the gradient, which yields the visual array of points converging to the horizon.

The gradient and movement are intimately related in that the gradient underlies the phenomenon of parallax, which movement generates, and at the same time defines the perceptual space within which the movement itself occurs. They are two aspects of the perceiver's unified patterned response, two aspects of his behavioral environment.

Unfortunately, there is virtually no information concerning the physiological processes involved in the perception of the gradient. Presumably we have adapted to some such real characteristic of the world. But the precise manner in which it is used or the specific neural mechanism by means of which the pattern occurs remains unknown.

ACCOMMODATION

While the utility of the gradient as a cue to depth is in doubt, there are other cues whose physiological attributes are more visible. One of these is accommodation, which utilizes the lens of the eye. As a movement in place, accommodation defines the ability of the perceiver to change the curvature of the lens and thus to shift his gaze along the line of sight from an object at one distance to a second object at a different distance. Contracting the ciliary muscle loosens the suspensory ligament, thereby reducing the tension on the lens. Because of its natural elasticity, the lens settles into an increased curvature, reducing the focal length and bringing nearer objects into focus. The reverse occurs when the ciliary muscle is relaxed; the ligament is stretched and tension on the lens is increased, flattening it out and increasing its focal length.

> Accommodation, particularly for near vision, is under the control of the parasympathetic nervous system . . . The pathways for this control have been traced from the pretectal region in the midbrain to the Edinger-Westphal nucleus through the oculomotor nerve to the ciliary ganglion and the short ciliary nerves to the ciliary muscles. While it is widely believed that the visual cortex plays a role in accommodation, the question of pathways from the cortex into the reflex loop governing accommodation is in dispute. Thus it is undecided whether the cortical influence acts in the pretectal region, in the colliculi, or in the Edinger-Westphal nucleus. In any case, even if the cortex does play a role, accommodation is probably not under direct voluntary control. (Kaufman 1974, p. 242)

If the object of the observer's attention is in focus, the appropriate neural signals having been sent and the ciliary muscles appropriately tensed, the proximal image will, for a reasonably normal eye, be sharply etched on the retina. But should the object, a tennis ball, say, move slightly out of focus, blur circles will occur around the image and accommodation must take place in order to bring the object back into focus. Indeed, for Kaufman,

> it is the blur circles that trigger the occurrence of the accommodation of the lens . . . , but these blur circles are effective only if the subject turns his attention to the object producing the blurred image. Thus it is that accommodation involves a voluntary act indirectly and must ultimately be initiated by events in the cerebral cortex. The way in which these cortical events serve to activate the portions of the autonomic nervous system involved in the accommodative reflex is clouded in mystery. At a less profound level, there is some mystery as to how the relative amounts of blurring of objects at different distances may be used as a cue to depth. (1974, p. 247)

There is some evidence to indicate that the direction of correction, or accommodation, occurs in accordance with the color pattern of the blur circles, which have a blue fringe around a red center if the image comes to a focus in front of the retina and a red fringe around a blue center if the image focuses behind the retina (this because of the higher refractive index of blue as compared to red light). But the magnitude of the correction cannot be so determined, because the value is affected by pupillary diameter, which changes with accommodation and convergence.

Astigmatism may be another source of information. This asymmetrical chromatic aberration, which may be different in the two eyes, produces a higher optical power on one axis than on the other. A point source of light, stretched by astigmatism into a line along each axis, will focus as a line at one position for the higher power, say the vertical, axis and in another position for the lower power, or horizontal, axis. Between the two positions is the so-called zone of minimum confusion. The position of the retina relative to this minimum zone will determine whether the proximal image is a blur ellipse with a major vertical or major horizontal axis. Should the observer learn to judge the location of the minimum confusion zone relative to the retina, he could conceivably use the blur data to accommodate accurately.

For Kaufman (1974), therefore, the blur circles, more than accommodation, are the cues to depth, inasmuch as they are the source of information. The curvature of the lens, itself, is "irrelevant to depth judgements, since it simply serves to get one object imaged sharply, and the blur circles around more or less distant objects tell us that they are not in the same plane as the object of regard" (p. 250). This is consistent with the fact that we are able to make depth judgements outside of the range of the physical capability of the lens to accommodate.

In any case, accommodation deals only with the radial component of motion of the distal stimulus; the change in lens curvature applies only along the line of sight from the eye to the external object. But the object may have a tangential component of motion as well. In this event, when one eye follows the object, the other eye will behave in characteristic fashion depending only on the directions of the components. Thus there may result vergent or conjugate eye movements.

VERGENCE AND CONJUGATE MOVEMENTS

There are two possible radial motions -- toward and away from the eye -- and an infinite number at right angles to them. But here we confine attention to the horizontal plane and consider two tangential motions, left and right. Since the eyes happen to be tied functionally, the effect is to create four movement pairs: two of which are called disjunctive, or vergence, movements (convergence and divergence) and two conjugate movements.

To illustrate what is involved, suppose a tennis ball is at a line-of-sight distance, r, from the receiving player at time, t, and moving to the right with no radial component at a velocity, $r\Delta\theta/\Delta t$, as shown in Figure 8.1. After a time, Δt, the ball will have moved a distance $r\Delta\theta$ and the left eye, pursuing it, will have rotated clockwise through an angle $\Delta\theta$ to keep the ball in view. Meantime, the right eye, too, will have rotated

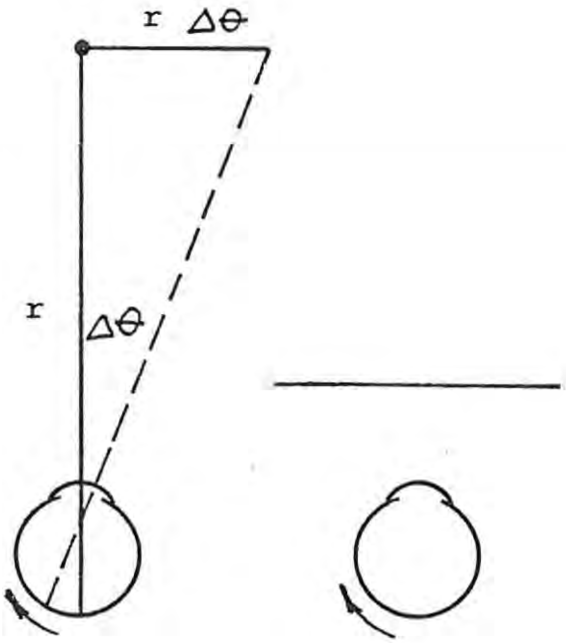


Figure 8.1 Conjugate Movement.

clockwise through a small angle even though it might have been occluded. The two eyes move together in this conjugate fashion as if they were yoked.

However, suppose that the ball at the same line-of-sight distance has both a tangential and a radial component of velocity, $(\Delta r/\Delta t,\ r\Delta\theta/\Delta t)$, as in Figure 8.2.

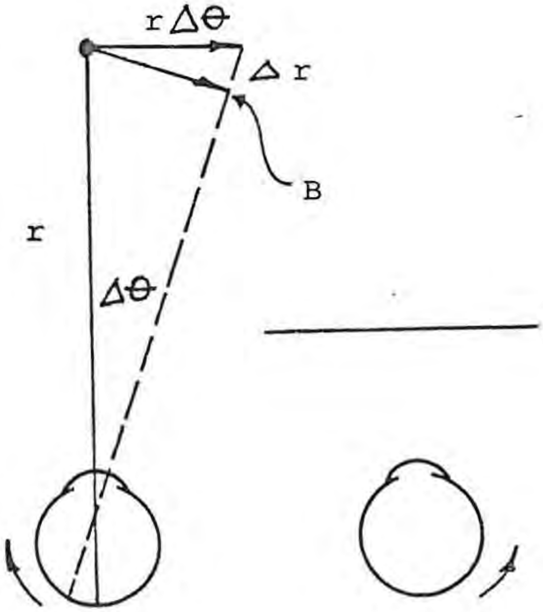


Figure 8.2 Disjunctive Movement.

In this case, after a time, Δt, the ball will have moved to the point B and the left eye will have rotated through the angle $\Delta\theta$ again. The proximal image, too, will have tended to move across the retina along essentially the same path as in the first case when the object moved to point A. The right eye will also have moved, but this time, rather than rotate clockwise, it will have rotated <u>counterclockwise</u>. The two eyes move counter to each other in a convergence movement, yet the proximal image motion is essentially the same as before. The only apparent difference is the occurrence of accommodation.

In the conjugate eye movement, signals to the right eye cause it to do what the stimulated left eye does. But in the disjunctive eye movement, "it is clear that accommodation is involved in reversing the sign of the signal that instructs the non-stimulated eye to move when an image translates across the retina of the exposed eye" (Kaufman 1974, p. 253) for there is no apparent difference in the stimuli to the exposed eye in the two cases.

> In short, if an image were to move from one point on the retina to the other and not change in clarity of focus, the two eyes would move together as the exposed eye tried to keep the image in the fovea. On the other hand, if the image were to move and change only in clarity of focus, then the two eyes would counter-rotate as the exposed eye tried to keep the image in the fovea. (Kaufman 1974, p. 253)

Vergence and conjugate movements involve different nerve centers and are essentially independent of each other. Suppose that a centrally located point were brought close enough to the nose that the eyes had to converge to their maximum amount to keep it in focus and that the point was then displaced laterally to the right, say. Following the point under these conditions the left eye turns even more than it did from convergence alone, indicating that convergence and conjugate movements are additive or superimposable but different systems.

Response times are also different. For convergence, the reaction time is about 160 msec.; for conjugate pursuit movements it is about 125 msec. Convergence to a new position may take as long as 800 msec., while saccadic conjugate movements -- the corrective jumps that occur when the eye has drifted but a few minutes of arc from the fixation position -- take about 200 msec.

In the above we considered only those cases where the tangential motion of the ball was to the right and the radial motion was toward the player, but the reverse cases obviously yield similar results. If the ball moves tangentially left, the occluded eye will follow the stimulated eye. And if the ball moves away from the player, the occluded eye will move counter to the movement of the stimulated eye. In this divergence movement, accommodation again causes the signal to the occluded eye to reverse sign.

BINOCULAR STEREOPSIS

Now if both eyes are able to view the ball, there occurs yet another source of depth information, stemming from the fact that each eye sees the world from a slightly different direction, from a different perspective. Attention to an object has a way of inducing an action of motor fusion. That is, attention changes the vergence angle so that the lines of sight from the eyes intersect at the object, the images are brought into approximate coincidence, producing visual disparity, or parallax, and somehow the two images are fused into one, producing what we recognize as a single object.

This fusion can occur even when accommodation is not possible, so apparently the vergence movements in the two cases must not be the same. Indeed, according to Kaufman (1974):

> Convergence due to disparity or double images is different from convergence associated with accommodative changes. Under normal circumstances accommodation and double images supplement each other. As attention turns to an object at some new distance, the state of accommodation changes, the pupil of the eye constricts, and the amount of disparity decreases to provide a sharp and fused image. Convergence behavior is also exhibited by people who cannot accommodate -- i.e., when

> the accommodation is artifically paralyzed . . . as well as when the lens is removed surgically. Though centers in the midbrain mediate the vergence response, people can learn to exercise voluntary control over the extra-ocular musculature and cross or diverge their eyes at will. It appears that the cortical centers involved in fusional vergence differ from those in accommodative vergence. Moreover, such voluntary changes in vergence may lead to subsequent change in accommodation. It is common observation that when the eyes are crossed voluntarily there is a period of blurred vision that may subsequently clear up. Hence the two systems of fusional and accommodative vergence are not totally independent of each other. (p. 256)

If the visual field contains two objects, at different distances from the eyes, changing vergence to eliminate the disparity of one may still leave the other one disparate. That is, swinging the lines-of-sight from the two eyes to intersect on one of the objects and thus to bring the disparate images of that object into coincidence, may leave the images of the other object separate. There could still be a difference in the horizontal angular separation of the two images in one eye and that in the other eye.

If the fixation point happens to be intermediate to the two objects, both of them might remain disparate though not to the same extent as in the first situation. "As a matter of fact, the total disparity is constant regardless of fixation." Relative to a particular scene, the disparity is invarient and "mathematically sufficient to denote the depth relations of the two objects. The depth response due to relative disparity, as opposed to convergence *per se*, is known as *binocular stereopsis* or simply *stereopsis*" (Kaufman 1974, p. 256).

Stereopsis, it must be repeated, is the experience of *depth* and not the mere occurrence of an intersection of lines-of-sight or coincidence of images. Since disparity leads to vergence and stereopsis depends on disparity, convergence and stereopsis are obviously very closely related; but they are not the same. "Though eye movements have been shown to enhance stereo acuity . . . , changes in convergence are not needed for stereopsis." (p. 268) The mere fact of coincidence is not sufficient to produce the experience of depth, but neither is convergence necessary. The depth effect has been demonstrated under the illumination of a scene for a short enough interval of time as to eliminate the possibility of active vergence, which takes at the least about 160 msec. This means that active vergence is not essential and also "suggests further that disparity may induce a depth effect in its own right and in relative independence of convergence" (p. 268).

Depth information may nevertheless be a byproduct of convergence activity controlled by disparity of visual images (Kaufman 1974). The signals to converge or diverge the eyes to see double images as single may be registered in the brain to indicate the distance to an object. Support for this "outflow" theory derives from the fact that visual portions of the cerebral cortex as well as the motor cortex are involved in convergence.

In binocular vision the world is seen via two overlapping fields (Figure 8.3). Angular dimensions of the fields are shown in Figure 8.4. The fronto-parallel plane cuts through the fields normal to the line from a point half-way between the two eyes -- the point of the so-called Cyclopean eye, providing the primary visual direction of subjective space. In this respect the world is seen as one, though both eyes are stimulated. The maximum width of the monocular field is between 90 degrees and 115 degrees of visual angle, depending on the size of projection of the nose. The binocular field is flanked on both sides by a monocular field of about 30 to 35 degrees.

When the eyes fixate a point in space there is a retinal element in one eye which is associated with a retinal element in the other eye so that, when stimulated, they both give rise to the same subjective visual direction. These elements are said to be corresponding points. Thus, when the two retinas are stimulated on corresponding points (by any means whatever), the object is seen localized in space at the intersection of the lines of direction from the two eyes (Haber and Hershenson 1973).

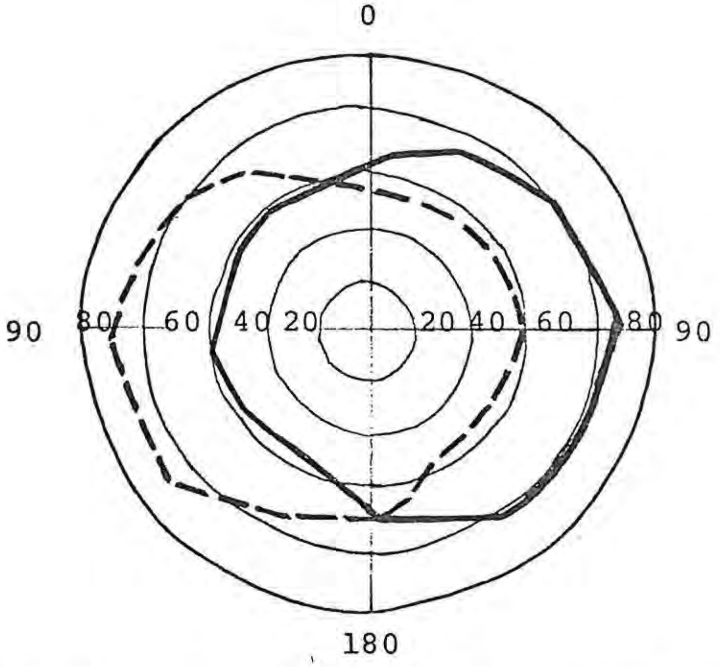


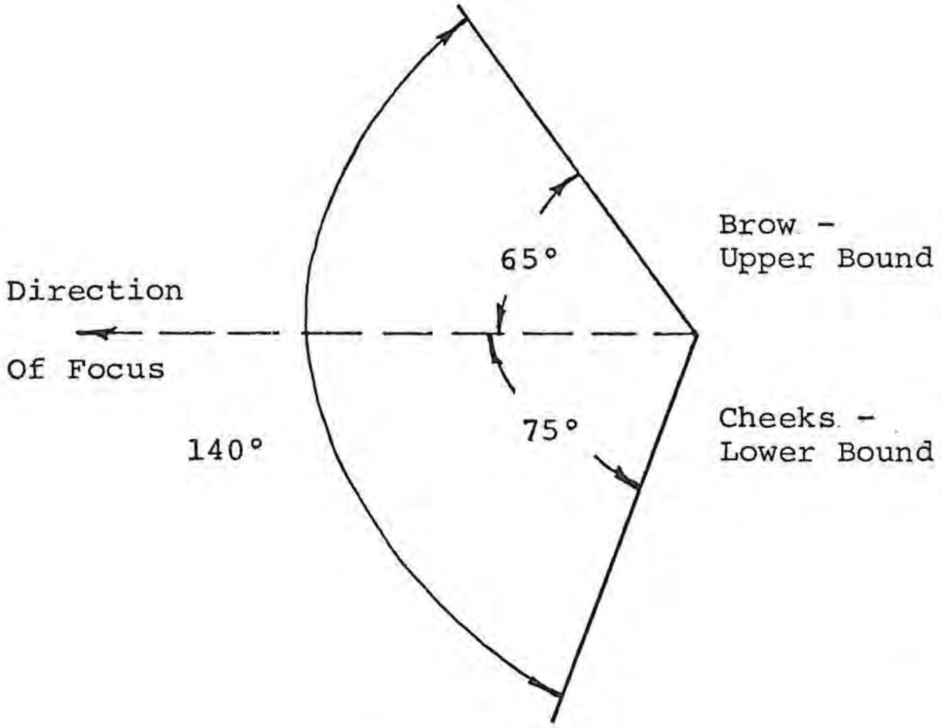
Figure 8.3. Binocular field of vision projected onto a fronto-parallel plane.

The idea of corresponding points thus involves the notion that stimulation of the eyes in a certain way results in singleness of perception.

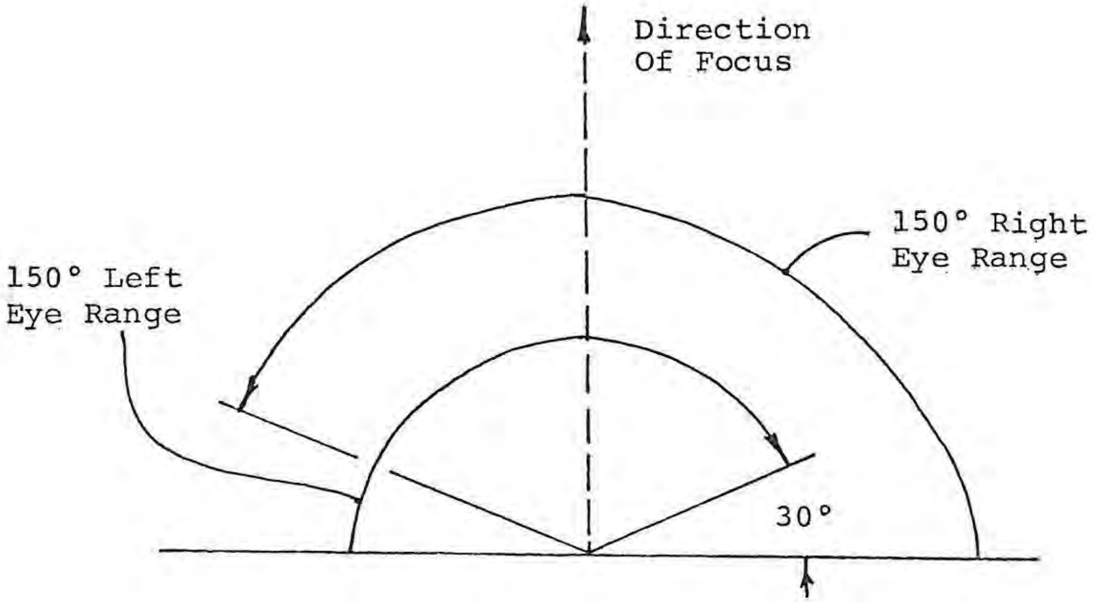
According to Haber and Hershenson (1973),

> There is a strong neuroanatomical basis for the singleness produced by stimulation of corresponding points of the two retinas. The receptive fields of most ganglion cells in one eye are represented in the same column of area 17 cortical cells as the receptive field from the corresponding retinal area of the other eye. In addition, most of the cells recorded from area 18 are binocularly driven, that is, respond to stimulation from either eye. In such cases, they are responsive only to stimulation falling on corresponding points of the two eyes. . . . this forms part of the basis of stereopsis depth as well. (p. 312)

In Figure 8.5 the eyes are shown to fixate on the object F. Objects like A, which lie on the horopter -- the curved plane through F whose points are roughly equidistant from the perceiver --, will project onto corresponding points on each retina. But objects like B and C which are <u>not</u> on the horopter will project on disparate points of the retinas. This binocular dis-



VERTICAL SCAN
OF VISION



HORIZONTAL SCAN
OF VISION

Figure 8.4. Angular dimensions of visual field.

parity is the source of information for stereopsis, and indeed, it is the only source of information necessary for stereoptic depth, according to Haber and Hershenson (1973). Thus:

> In this sense, stereoscopic depth appears to be an independent aspect of depth available to us, available because we have two eyes with partially overlapping projections. It adds some resolution to our perception of depth, but it clearly is not the most important part. We have quite adequate perception of space with only one eye. This can be verified by covering one eye to see how easy it is to locomote and to perceive correctly the spatial arrangements in the visual world. Stereopsis does increase the vividness of depth - - near objects are seen more vividly in front of far ones when seen with two eyes than with one. But even with one, the visual world rarely deceives us. Stereopsis also permits very close judgements of depth for stationary perceivers. This may be important to a creature that works with his hands. Thus, in terms of the evolution of the human brain, disparity may have played an important role. (p. 315)

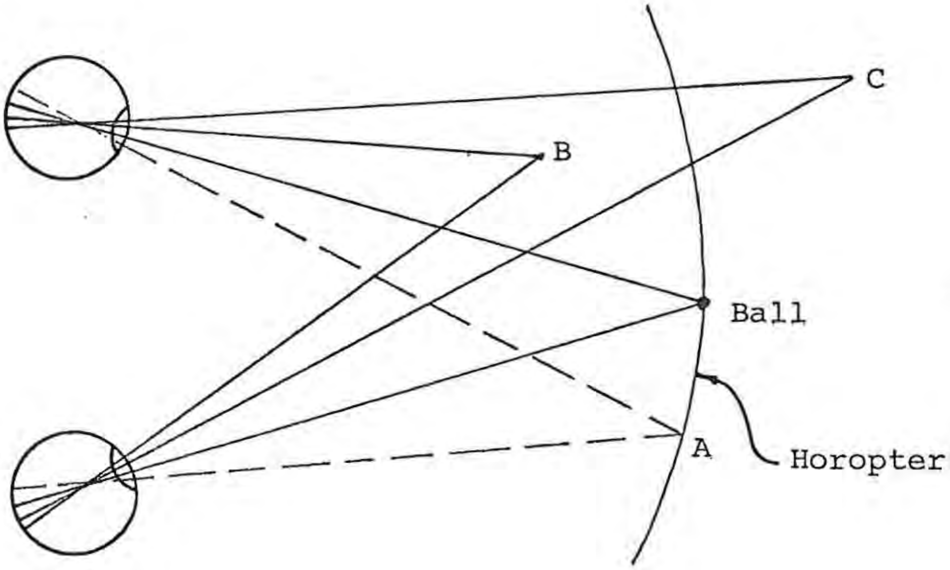


Figure 8.5. Relationships for corresponding points and for disparity.

Suppose now that the observer is the receiving tennis player and that the object of fixation is the tennis ball frozen in position in its trajectory. The point A in Figure 8.5 would then represent segments of the playing surface, net, or side screens lying in the horopter for that fixation point, and points B and C would represent segments lying in front of, or behind, the horopter.

In the next moment, say an increment of time Δt later, the ball will have moved another increment of distance Δs. Assuming that the component of this vector change normal to the line of vision of the player is not zero, if the eye is simultaneously rotated to keep the ball in the center of the fovea, there will be a displacement of the proximal image of the rest of the objects in the view. The angular displacement will correspond in magnitude to the angle of rotation of the eye and be opposite in sign.

In the same interval of time, however, the player will have moved a distance Δd. If the fixation point were to remain stationary and there was a lateral component of the player's motion, there would then be a parallax effect in which the objects on the far side of the fixation point shift in the visual field in the direction of motion and those on the near side shift against the direction of motion, as shown in Figure 8.6.

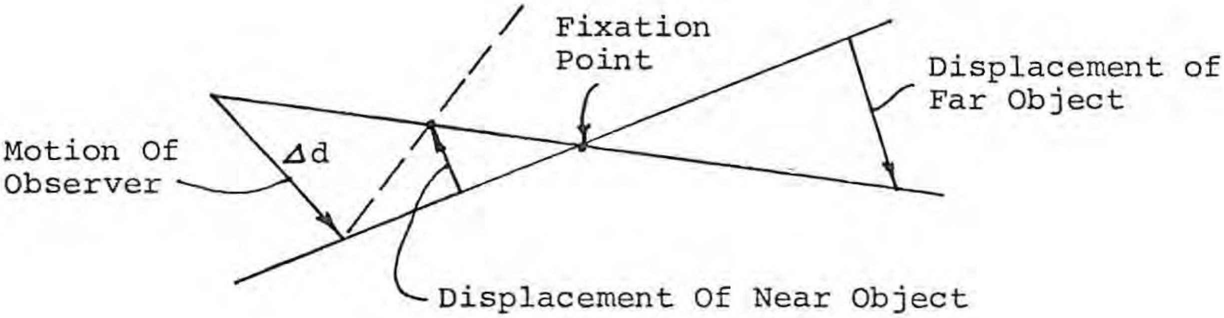


Figure 8.6. Parallax effect due to motion of observer.

Instantaneously, therefore, there is a superposition of two visual effects, the one tending to rotate the whole visual field as a unit and the other tending to shift the far objects of the field in one direction and the near objects in the other direction. If the eyes were able to remain fixated on the ball the whole time, this phenomenon would occur continuously over the full span of the trajectory. Of course, the actual perceptual results depend on the extent of each of these visual effects and others, such as those due to corrective saccadic and random micro-saccadic movements, accommodation, vergence movements, blinking, shift in attention, reaction times, degree of concentration, temporal resolution, etc.; but considered in isolation the two effects appear at least to be additive.

In any case, the ball is sampled visually some number of times during the course of its trajectory. This sampling is represented schematically in Figure 8.7. The receiving tennis player is seen fixating on the approaching ball at points F_1 through F_4 from positions P_1 through P_4, respectively, while moving to intercept it. In the aggregate, then, the visual field is seen to shift slightly to the left, while near surfaces glide more swiftly left due principally to motion parallax.

In general, this shifting from one position to another causes the pattern on the retinas to change from one stationary array to another, and more continuous movements through space create corresponding retinal images that are "better described as flowing according to certain systematic rules," according to Haber and Hershenson. Indeed, for an observer moving forward,

> the transformations of the visual field appear as projected on a spherical surface surrounding the head. The horizon, stars, and field of view upward do not move. However, the ground below him and the world flow past him in a continuous stream. This flow is a continuous transformation of the surface of the earth, and no matter which way the observer looks, the flow decreases upward in the visual field and vanishes at the horizon. In this sense there is a perspective in the flow. The rate at which an element flows, holding the locomotion constant, is inversely proportional to its physical distance from the observer so that the flow decreases the farther away are the stimulus objects. The geometry of this decrease is the same as that for stationary objects. In this sense the flow produces a gradient or change in parallax.

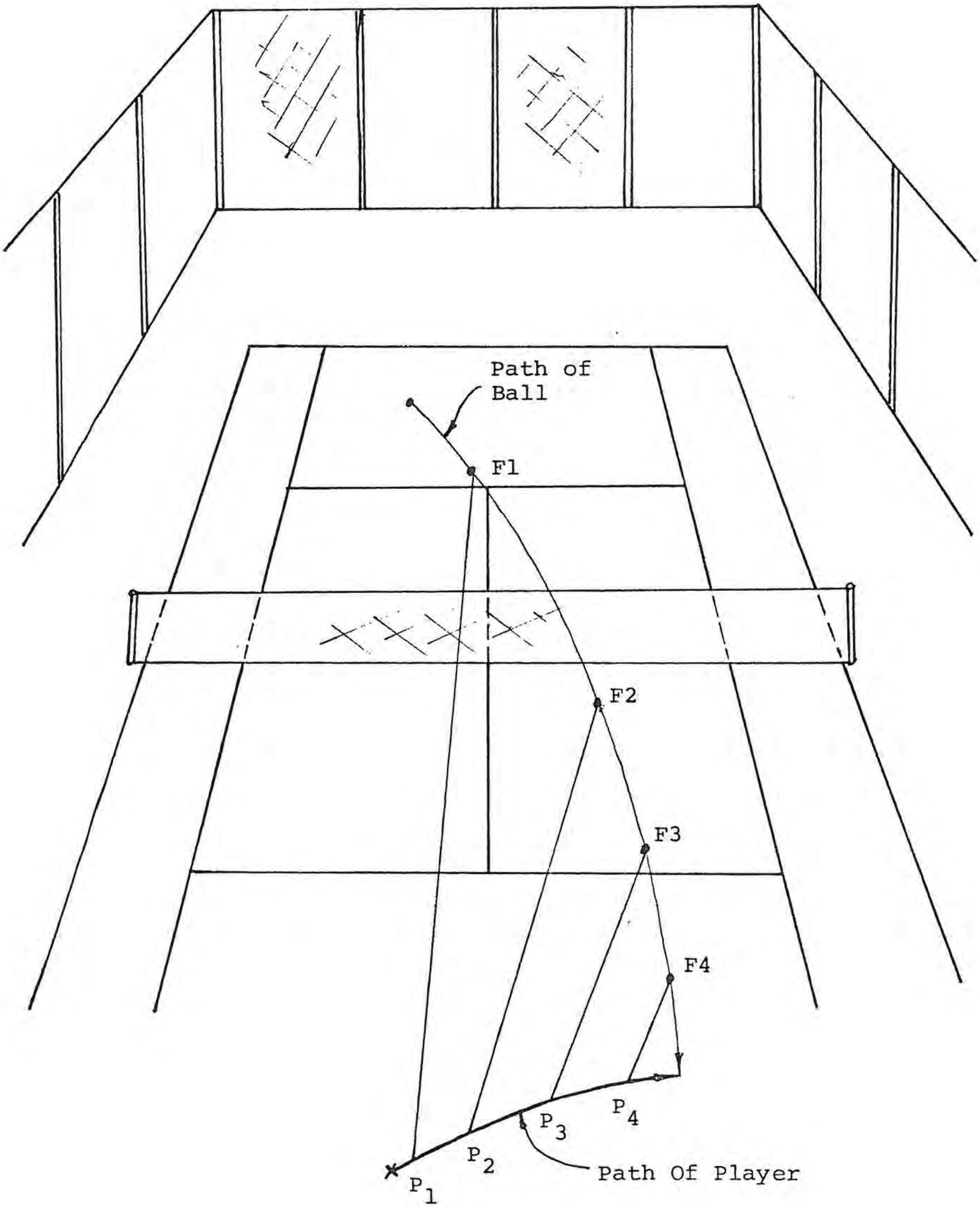


Figure 8.7. Representative fixation points on moving tennis ball.

> The gradients of continuous transformation of angular separation of points in the field, which is a consequence of the movement of the perceiver, is called motion perspective. It is a transformation of pattern rather than a simple comparison of velocities as is motion parallax. Parallax arises when the perceiver moves his head from side to side in order to obtain depth information. The relative velocities of the displacement of two objects associated with such movements is conceived of as a cue. Motion perspective arises when a perceiver is locomoting in space and the retinal gradients of velocities are associated with the movement across the ground surface. Thus motion perspective is the more general source of information.
>
> The direction and speed of motion within this perspective flow vary independently. The direction of the flow as a visual impression depends on the physical direction of movement of the spot in question and the direction of regard. When looking ahead, the flow is downward, when looking to the right the flow is to the right, when looking to the left the flow is to the left, and when looking behind the flow is upward. Thus the visual field appears to expand outward from a focus, the focus being that point toward which the observer is moving. If he changes direction, the focus also shifts. In this sense the visual perceptual system always provides a 'point of aim' for a perceiver who is moving in space. Thus the direction of movement is always present in the stimulation reaching the eye, even if it is sensed directly as change in body position rather than change in perceptual qualities. (Haber and Herschenson 1974, p.320-1)

This treatment of motion perspective derives from the work of J. J. Gibson (1959 and 1966) and expresses the psychophysical theory of visual space perception. (While a Cyclopean view was assumed in the discussion of his views of visual transformations due to motion, it is clear that binocular effects would yield additional information stemming from the disparity between patterns on the two retinas.) The argument by Gibson is that there is enough information in visual perception to generate the perception of space, that nothing else is needed. As Haber and Hershenson (1974) put it,

> (for) Gibson, this tremendously informative (although complex) stimulation produces a scale for the visual world. The changes in this scale over the pattern and across time over changing patterns could arise only if the scale of the visual world were constant -- the space between objects in the distance is specified in the same

> units as that between near objects. It is the recognition of this scaling as a consequence of the spatial and temporal patterning of the information at the retina that has led Gibson to argue that perception of space is given directly. The 'superstimulus' contains all the information necessary for direct perception of space and our movement within it. (p. 324)

The difficulty with this theory is that it remains speculative. For space to be given "directly", the mechanism must be discovered whereby the "superstimulus" is detected, and so far such a neural network has not been found. A very large logico-neural gap has therefore to be filled if a program is to be designed to stimulate the process. It remains to be seen if this mechanism can be formulated adequately.

DISTANCE TO THE BALL

An outflowing signal from the brain to the muscles of the eyes to converge the lines of sight on an object might be a correlate of the distance to the object. If such a signal actually exists, could the brain monitor and use it to compute distance to a moving tennis ball? What might the correlation be?

The physical distance to the ball at any moment can be expressed as a trigonometric function of the distance between the eyes and the convergence angle when the lines of sight intersect at the ball. This gives the angle of image disparity, or parallax. This form of parallax is called absolute disparity or absolute parallax, because it admits of only two points of perspective, viz., the two eyes, which are a fixed distance apart. One need only imagine that it results from opening and closing the eyes alternately to relate it to motion parallax. Perspective is thus seen to change from that of the location of one open eye at one moment to that of the location of the other eye opened at the next moment. The angle of convergence required to get the images of the ball centered on the two foveas is the so-called absolute parallax, or absolute disparity. This is shown in Figure 8.8 as the angle α.

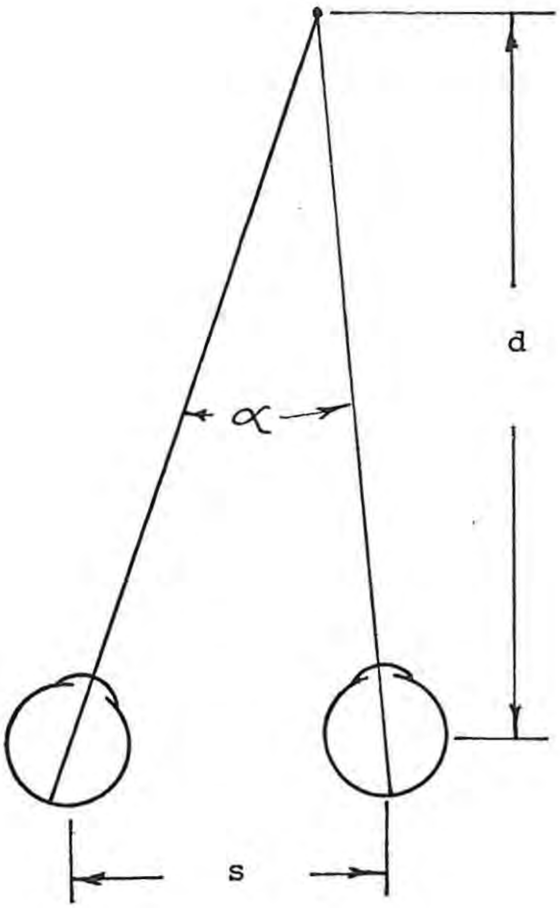


Figure 8.8. Absolute Parallax.

If the ball is positioned such that the perpendicular bisector of α divides the interoccular distance, s, into equal parts, α is given by

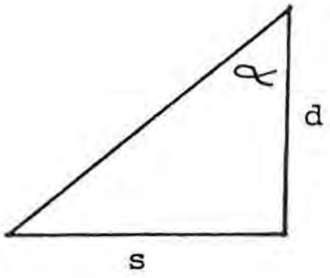
$$\tan(\alpha/2) = s/(2d).$$

For small angles, α, or large distance, d, $\tan(\alpha/2) = \alpha/2$, so

$$\alpha = s/d,$$
$$\text{and } d = s/\alpha.$$

Geometrically speaking, therfore, a knowledge of the convergence angle is sufficient in this case for the brain to estimate a distance to the ball, since the interoccular distance is a constant baseline reference.

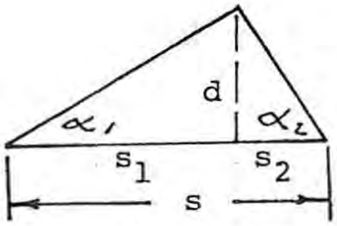
Special cases occur when the ball is on the normal from the baseline to one or the other eye, as follows:



The convergence angle is then simply

$$\tan \alpha = s/d,$$
$$\text{and } d = s/\tan \alpha .$$

If the perpendicular projection of the ball is a point interior to the interoccular line, given the signals for convergence angles α_1 and α_2, a solution can be obtained from the acute angle triangular relationship as follows:



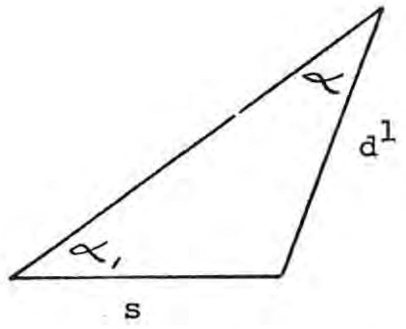
$$\tan \alpha_1 = d/s_1, \text{ or } s_1 = d/\tan \alpha_1$$
$$\tan \alpha_2 = d/(s - s_1) = d/(s - d/\tan \alpha_1)$$

So
$$(s - d/\tan \alpha_1)\tan \alpha_2 = d,$$
$$s\tan \alpha_2 - d\,\frac{\tan \alpha_2}{\tan \alpha_1} = d,$$

and
$$s\tan \alpha_2 = d(1 + \tan \alpha_2/\tan \alpha_1).$$

So
$$d = s\tan \alpha_2/(1 + \tan \alpha_2/\tan \alpha_1).$$

By making use of the law of sines, a general solution for the distance from one eye (rather than the perpendicular) is readily obtained given two angles.



$$\frac{\sin \alpha_1}{d'} = \frac{\sin \alpha}{s}$$

$$\text{or} \quad d' = \frac{\sin \alpha_1}{\sin \alpha}.$$

The distance from an eye seems less complicated than the more subtle distance from a baseline which requires as well some indication of perpendicularity. But the question still remains how much of this kind of information is actually used by the nervous system in the context of a game. The speed with which the tennis ball moves makes it appear unlikely that a measure of absolute distance is useful. By the time a computation has been completed, it seems already too late to use the information, for the position of the ball might well have changed considerably.

Suppose, for instance, that a fairly routine shot were made. A flat shot or a serve, for example, might easily travel more than half the distance of the court in a second, say. This could be an average velocity about 40 feet per second. So the ball would travel about .040 feet in a millisecond, and in the minimum time required for the eyes to converge (about 160 msec.) it would already have moved away more than 6 feet. This alone is a sizeable error. It can only worsen if the computation time for distance is factored in. In fact, unless some kind of anticipatory behavior or feedforward mechanism were invoked, the ball would always appear to be a step or two ahead of the vergence function and therefore convergence at any specific point in its trajectory would be impossible.

TRACKING MOVEMENTS

Use of scale-of-space detectors, either alone or with other mechanisms, is an intriguing possibility for both distance and velocity information, in other words for tracking. However, if the detectors were expected to be used to follow a high speed ball, the neural logic would have to compensate somehow for the long latency periods that are involved, from the receptor to the decision level.

Although at the receptor level the latency time is very small, providing very fine temporal resolution, beyond that stage the resolution decreases dramatically. Between receptor stimulation and area 17 excitation, 50 to 150 ms elapse, and for resolution of temporally separate impulses of light the pulses have to be spaced between 10 and 100 ms apart, depending on the state of light adaptation. Indirect measures indicate that for reactions which involve a single choice, 200 ms might be required for cortical handling of the decision processes (Haber 1969, p. 120).

When the amount of light is high, as would be the case under normal lighting conditions, temporal precision amounts to 10 ms, or less. In this time period, a ball speeding along at the rate of 140 miles/hour (the current upper limit for tennis) will travel a distance of 2 feet or so. Visual acuity along the line of motion must therefore have a best value of two feet, which means the ball could be anywhere along that segment of path at that (10 ms) moment. This temporal summation apparently goes on in the retina, though; not at the receptor level.

If the eyes happen to be fixated at this "moment", the ball should most certainly project as a streak on the retina and might thus stimulate a movement detector cell. However, since these phenomena are properly indistinguishable as to time, a displacement might not be noticed until the next moment, or possibly even the one after that. Eventually, though, a saccadic movement must be initiated to keep the ball centered on the fovea. But this movement has a latency, according to Haber and Hershenson, about 180 to 250 milliseconds (1973).

> (However) if the perceiver has prior knowledge of the time and direction of the shift, he can start his move-

> ment somewhat faster. The estimate of one-fifth of a second is probably more representative of real life. Once initiated, the movement itself is very fast. For example, only about one-tenth of a second is needed for a forty-degree movement (400 degrees per second). Velocities are faster for larger movements, approaching 1000 degrees per second for a 90-degree shift. The movement time for a return sweep after reading a line of print is about 50 milliseconds, and is relatively independent of the length of the line.
>
> Saccadic eye movements are ballistic movements -- like those of bullets or rockets -- in that their path and distance are completely determined prior to the actual motion. Just as the path of a bullet is specified by the direction in which the gun is pointing and the initial force of the propelling charge, the path of a saccadic movement is determined by a program which issues efferent commands to the muscles to move the eyes to a new fixation. Thus, once programmed, a saccadic eye movement will proceed to its destination unchanged, even if new visual information is added after the programming but before the movement starts. (Haber 1969, p. 207)

Saccadic movements are to be distinguished from conjugate pursuit movements, the latter being smoother but also slower, and becoming difficult at target speeds approaching 120 degrees per second. Also, as we saw above, the pursuit (or conjugate) movement has a reaction time about 125 ms, so very likely a different control system is used. Occasionally, pursuit movements are combined with saccades, as when an error occurs and a rapid correction is needed.

Experiments invoking pursuit movements normally involve objects moving across a screen, so convergence plays no part. In ball tracking, however, both radial and tangential components of motion are to be followed, and this may in fact utilize both vergence and conjugate circuits. This is a logical possibility since it appears the two mechanisms are independent of each other.

In ball tracking, the angular rate limitation of pursuit movement can be expressed as a limitation on the lateral component of velocity of the ball relative to the receiver, who may himself be in motion. Since in rotational motion the rim speed increases with radial length, for a given angular rate of rotation, it is clear that the limiting condition is more severe when the ball is closer to the receiver. If for instance the ball moves as shown in Figure 8.7,the lateral component of velocity changes from an initial relatively small value as it leaves the opponent's racquet to a relatively large value as the receiver hits it. In fact it approaches the horizontal velocity of the ball, because the ball passes on the player's right and he turns to view it as he hits it.

We have seen that, due to a normally significant radial component of velocity, accommodation and convergence movements could be involved in ball tracking, though the mechanisms that might be employed would have to be able to overcome severe latency problems in order to be able to perform at all, let alone track with high accuracy.

For pursuit movements the latency problem is not nearly as severe, particularly because saccades can be used to make corrections. High lateral components of velocity can of course occur. For example, when the receiver makes a forehand or backhand return shot, the lateral component almost equals the horizontal velocity of the ball. The reason is that the player's line of sight turns with the ball motion and is practically at right angles to its path at that time. By then, however, tracking is useless anyway; because of the refractory period the player is already committed to action based on earlier data. So the high lateral motion fails to be significant.

Bizzi (1973) says that compensatory movement can be programmed in head-eye interaction, using vestibular information from our biological inertial guidance system -- the ear. Such a mechanism might be available for tracking as well, though for this purpose it would have to be even more elaborate. The target and head are now no longer stationary; both the ball and player are moving in complex ways. Fixating on the ball is therefore more difficult, and translational as well as rotational body data have to be maintained. Just how this is accomplished is not known.

Even the use of the presumably more direct motion detection cells would not be without its problems in tracking. For one thing, the eyes must first focus on the moving ball in order for the detector mechanism to be engaged, and this brings the aforementioned eye movements into play, with their attendant problems. Besides that, however, the relationship between the moving distal stimulus and the moving proximal stimulus is very complex. The relationship is by no means one-one, either. It is in fact many-many. The same proximal image can be laid down by many different ball trajectories, and by virtue of the fact that the eye-head-body system is in motion, a given ball trajectory can lay down many different proximal images. The motion data may thus be only one of many different pieces of information to be incorporated into the tracking capability, and at one time or another any one or all of the various visual mechanisms may be at work.

READINESS TO RESPOND

The possibility that different combinations or all of the eye movements may be active at any time naturally complicates matters. But it also suggests that anticipation occurs as a general condition of movement. In order to track a ball that has vertical and horizontal tangential as well as radial components of motion and that changes direction and velocity, it would seem that some degree of anticipation, or readiness to respond, is essential.

Even the simplest tracking task requires such readiness, according to J. G. Taylor, because the readinesses are inherent in the nature of perception. Interpreting this theory, Kaufman (1974) has the following to say:

> (Any) perception is merely the complex set of simultaneous readinesses to respond behaviorally to objects affecting the sense organs. Thus, perception is not a picture formed on the inner screen by the sense organs. The sensory events produce readinesses to respond -- tendencies toward efferences -- which themselves comprise the perception. That is to say, even though the sensory input were cut off, if the same efferent

> tendencies were present, the observer would report that he is perceiving.
>
> As Taylor holds, readinesses to respond to features of the environment are parts of conditioned responses. Thus, if the eye is confronted by a straight line, eye movement along a straight path may be needed to keep the segment of the line in the fovea while scanning it, and consequently the perceived straightness of the line may be attributed to the tendency or readiness to respond to such a stimulus by a class of eye movements. Even if the eyes do not move in viewing the line (as in a brief exposure), the line appears to be straight because of the aroused readiness to respond to it with a particular kind of eye movement. (p. 424)

The tennis player must therefore be prepared to respond to the many different trajectories that might be encountered on the courts. He has to set his perceptual biases for the "battle zone" conditions. Off-court readinesses have to be transformed into those needed to track the ball and this may require some time. The eyes must be tuned to the trajectories. Adjustments have to be made for the environment -- for the position of the sun, direction of the wind, texture of the court surface, etc.

The effectiveness with which the player establishes his readinesses will determine what is called the "pace" of the ball -- the subjective interpretation of the physical motion of the ball. For any given trajectory the pace may vary considerably, depending on the environmental conditions and the state of the player. A medium speed ball may seem fast or it may seem slow. In a haze or an open, unmarked field, the pace could be very fast, whereas in a well lighted, well marked court with good background, it can be slow.

In terms of Taylor's theory, learning can modify the set of simultaneous readinesses to respond to the ball and thus improve his perception of it. The more he has studied the game, the more he has practiced, and the better his visual acuity, physical conditioning and health, the easier the tracking will be and the fewer mistakes he will make. Such a player can be said to be prepared to program the patterned efferents effectively. But he may nonetheless still practice "getting himself ready for a match" by thinking about it or imagining the action. In Chapter 4 we saw that Billie Jean King prepared as early as the night before by gazing at the ball for 5 minutes. This is merely one technique professionals use to "get into the swing" of the game, or establishing their game readinesses.

CHAPTER 9

VISUO-MOTOR INTERACTION

In the previous chapters we have seen that the visuo-motor system is a fluid, modifiable, self-organizing and highly adaptable neurophysiological structure, which at once gives meaning to, and in some degree changes, its environment as it itself changes. In short, it is a learning system. It is capable of learning; but it can also forget, or unlearn.

We have seen, too, that in the act of perceiving the environment, expectancy is an important component of the mental apparatus, leading the player to anticipate where the ball will be next, thereby directing his attention and behavior. For Pribram (1971), this expectancy plays a comparative function:

> Experimental evidence shows that, at any moment, current sensory excitation is screened by some representative record of prior experience; this comparison -- the match or mismatch between current excitation and representative record -- guides attention and action. (p. 49)

As an act, however, perception also invokes the competence of the brain to organize its inputs. That is to say, perception is directed by the organism. Eyes are oriented to some object in the environment. Attention is purposefully focused. The system is "set" according to expectation. But prior experience also plays a part in determining the nature of the set. For instance, what the person has just perceived might lead him to anticipate some related event. In other words, there is an interaction between the sensory and the motor processes.

> Organisms do not respond to just <u>any</u> occurrences that happen simultaneously, contiguously. Their behavior is guided by the <u>previously established competence of the</u>

> brain to organize stimuli, including those consequent to behavior. Stimuli are thus neurally determined events, "sampled" on the basis of a central competence (a neural "set") which in turn is determined by prior experience and by other central events. An organism's behavior is not only stimulus produced, but, by virtue of the self-adapting properties of the screening process, on occasion also stimulus inducing (i.e., productive of orienting). This happens whenever the outcome of behavior partially matches the central competence that initiated the behavior. In such circumstances, reinforcement takes place and behavior becomes its own guide. (Pribram 1971, p. 264)

The screen -- the junctional microstructure or junctional filter -- constitutes a self-adapting system which contains a coded representation of prior signals generated by the organism-environment interactions and embodies a set of expectancies of environmental occurrences. It initiates departure patterns of nerve impulses and is itself subject to alterations by mismatch of expectancies with actual occurrences. But it is also instrumental in the formation of Images -- the conscious representations of experience -- and Images-of-Achievement -- the learned anticipations of the forces and changes of force required to perform tasks. The Images and Images-of-Achievement, it should be noted, are the now familiar cognitive maps, schemata, motor plans, etc., which have been ascribed in the previous chapters to the mental space of the perceiver.

The problem of perception is now inextricably bound to the problem of behavior. Without the cognitive aspect -- in effect, the identification factor in recognition -- signs cannot be produced and experience becomes meaningless. But signs are achieved through action. When we look out upon the world, we actively select one or another fragment of it. This active selection is clearly motor in part, at the very least energizing the eye muscles. It is a discriminative choice.

> Making the discriminitive choice utilizes the neural apparatus necessary to action. The fact that the pathways from the inferior temporal cortex which affect visual attention lead through motor structures provides the structural basis for the interaction of motor and sensory processes, the influence of those screens giving rise to

> Images-of-Achievement on the screens from which perceptual Images are constructed. Signs are therefore achieved through action. It is this quite active aspect of signing that generates meaning: perceptual learning through reinforcement. The meaningfulness of signs turns out to depend on a mechanism that calls attention to, reinforces, alternatives . . . Monkeys deprived of inferior temporal cortex select from a restricted range of alternatives (display less uncertainty) when making visual choices, whether the alternatives are clearly separated in the form of dime store junk objects, . . . or are the features that distinguish patterns from each other . . . A slowing of recovery of the input systems occurs when the organism is generally attentive or when the inferior temporal cortex is electrically stimulated . . . Such slowing of recovery reduces the redundancy of the input channels; at any moment in time fewer channels are carrying identical signals. (Pribram 1971, p. 327)

It must be pointed out that, according to Pribram, the inferior temporal cortex influences visual processes not so much because it receives visual information from the primary cortex, but rather because it operates through corticofugal connections on visual processes occurring in subcortical structures.

The behavioral aspect of perception is also noted by Granit, who says that movement itself is the interpreter, either of a sensory input or of something stored that emerges as a voluntary or automatic analyzable act. This means that purposiveness, and therefore prediction, is prominant in the motor field, so much so that nonpurposive behavior tends to be regarded as outright pathological.

Relating perception even more intimately with behavior, Taylor (1962) argues that it is the very program of efferent signals that comprises the perception. Any modification of perception therefore comes about through reprogramming of motor behavior.

Such directions are not unlike Pribram's momentary Images-of-Achievement, which contain all the input and output information necessary to the "next step" of an achievement, like typing this line of words, or hitting a tennis ball, or even tracking the ball. Appropriate signals would have to be given to move the eyes in their sockets, and to adjust the head, arms, legs, etc., in order to see, track, and move to converge on the ball. But the signals are not like the notes on a sheet of music indicating which portion of the keyboard to strike next; they do not, in Pribram's view, direct individual muscles to do this or that, pull this way or that, in this amount or that amount. Rather, what are represented in the direction center -- the motor cortex -- are forces exciting muscle receptors. So the motor cortex takes on the appearance of a sensory cortex.

> The conception that the motor cortex anticipates parameters of force is critical. Because reflexes are constituted of servomechanisms, their central representations are constructed not of records of muscle length or tension, but of the parameters of adjustment and compensation to the changing external forces involved in the activity. The convergent properties of these transformations allow this representation to form an Image not just of the prior and current changes of enviromental forces acting on the system but, by virtue of the cerebellar fast-time computation, of the changes that will be engendered by the continuation of the activity.
>
> The motor cortex is thus conceived as a sensory cortex for action. It participates in the spatial modulation of states of readiness via its connections with the basal ganglia and in the fast-time computation of states-of-achievement via its participation in the cerebellar circuits. (Pribram 1971, p. 246-8)

Reflexes and integrated movement, i.e., complex movements made up of reflexes, whether initiated by an environmental or by a central event, cannot be effected by sending signals directly and exclusively to the muscles without disrupting the servo-process. The signals must be sent to the muscle receptors, either exclusively or in concert with those reaching muscle fibers directly; the movement is largely managed by biasing the muscle spindle receptors of the servo loop, the receptors that gauge muscle contraction. Again, Pribram (1971) says:

> (The) neural loop control of behavior is achieved largely through an effect on receptor functions. At the reflex level, receptor sensitivity to the imposition of load initiates and guides an adaptive counter-process in the servomechanism. The sum of such adaptations constitutes the background tonic state against which new adjustments occur. Large-scale adjustments such as changes in posture are controlled by the basal ganglia-anterior

> cerebellar (extra pyramidal) system of the brain, while more discrete movements such as typing or playing the piano are regulated by a fast-time extrapolatory computation carried on by the neocerebellar system. The precise mechanism of these central controls has yet to be worked out, but we know enough to ascertain that patterning of the peripheral servomechanism is involved, and that the patterning is achieved by changing the mechanism's bias. Finally, the conception of the functions of the cerebral motor cortex of the precentral gyrus has radically changed. This part of the brain cortex has been shown to be the sensory cortex for action. A momentary Image-of-Achievement is constructed and continuously updated through a neural holographic process such as in the perceptual Image. The Image-of-Achievement is, however, composed of learned anticipations of the force and changes in force required to perform a task. These fields of force exerted on muscle receptors become the parameters of the servomechanism and are directly (via the thalamus) and indirectly (via the basal ganglia and cerebellum) relayed to the motor cortex, where they are correlated with a fast-time cerebellar computation to predict the outcomes of the next steps of the action. When the course of action becomes reasonably predictable from the trends of prior successful predictions, a terminal Image-of-Achievement can be constituted to serve as a guide for the final phases of the activity. (p. 249-50)

A CONTROL MODEL

Viewing perception as a feedback control process, a mismatch can be seen to provide corrective feedback on a visual function guided by the competence -- the plan of action -- of the self-adapting system. In tracking and interception, the blur circles, retinal disparity and relative displacement of the retinal image (in this case of the tennis ball) constitute sources for error detection and correction; and prior experience and knowledge (of the ballistic action of the ball) establish the grounds for guiding the perceptual process -- the complex behavior involving eye, head, and body movements in the track and intercept task.

The competences which guide behavior are

> hierarchically organized mechanisms (logic modules) of servoprocesses, programs, or Plans set to achieve an environmental effect, an Act . . . An anatomical substrate of point-to-point correspondences between muscles and brain cortex becomes organized into a representation

> that controls whatever movements are demanded by the environmental "terrain" or "field of forces" so as to achieve the effect. The achievement has become encoded in the representation, a state, the junctional slow potential microstructure, by computing a fast-time extrapolation of modulations of recurrent regularities that appear in the series of such field forces encountered to date. (Pribram 1971, p. 300)

The fast-time feedforward computations are made by the cerebellar hemispheres to obtain the predicted next step if the behavior were to continue on its current course. Environmental contingencies rather than patterns of muscle contraction are recorded. The Image-of-Achievement regulates behavior much as do the settings on a thermostat: the pattern of the turning on and off of the furnace is not encoded on the dial, only the temperature to be attained.

Tracking and interception thus involves continuous testing. Purposive in nature, the behavior utilizes feedback technique to determine what has resulted from previous action and feedforward computations to estimate what is likely to happen as a result of current action. Adjustments in behavior are made accordingly.

The feedforward and feedback processes relate to tests on the perceived position of the tennis ball relative to the current state of the eye-body movements that the player makes to follow and intercept the ball. Feedback gives him information about the present condition of that relationship, which has resulted from the movements he has made to this point; and the fast-time computations predict the future position of the ball in terms of the movements he must <u>now</u> make to reach it and effect a return shot.

With this model Pribram reinterprets the stimulus-response representation, allowing that the brain intervenes to determine the process.

> Stimulus → Response → Reinforcement, is, to be sure, the order which an observer sees occurring. As soon as it is realized, however, that the brain of the organism

makes this order happen, the apparent chaining is seen to be the result of a considerably more complex interaction.

Take for instance the fact that reflex organization is not an S-R arc, but a servomechanism. This fact has an important consequence on the definitions of stimulus and response. The usual Newtonian and Sherringtonian chaining of agent and reaction becomes complicated by the introduction of feedback and feedforward operations. Two courses are open: to ignore the internal complexities of the system, or to account for them and deal effectively with the necessary alterations. For the most part, behaviorists have ignored the new complexity. But they can't avoid the problem that stimulus can be defined only by the conditions that provoke it. In other words, the behaviorist's stimulus and response mutually imply one another. This dilemma can be resolved only when the reciprocity between S and R is recognized. $S \leftrightarrows R$ is not just so neurologically but logically as well. A mathematical set and its partitions provides a sophisticated statement of this reciprocity . . . The elements of the set are conceived to be stimuli; the partitions on these elements correspond to responses . . . Or in more familiar terms, the objects classified are stimuli; the process of classifying constitutes response. This resolution of the S-R dilemma demands, however, the exercise of strict discipline in how one talks about one's data. Much of the confusion of tongue in current psychology comes from the failure to fully recognize this reciprocal relationship between stimuli and response -- in physiological psychology, especially, major controversies rage between those who describe their data in stimulus language and those more comfortable with the response mode. And, of course, confusion is frequently perpetrated by mixing languages.

. . . . .

Perhaps most interesting to analysis performed in haviroal terms is the objectivity attained in the definition of reinforcement when the stimulus-response or reflex arc concept is replaced by servotheory. The agent in the servomechanism is the test -- a match or mismatch between spatial representations, the ongoing "state" of the servo and the energy configurations impinging on that state. Thus what psychophysicists have called the "proximal" stimulus is dependent on the states of the system exposed to the input: the cognitive psychologist's "sets" and "expectancies." Parallel considerations make the reinforcing properties of events depend critically on a match between the state which produces the behavior and that which is produced by it. (1971, p. 253)

The stimulus-response relationship becomes more complicated if the inputs themselves are subject to control by efferents. As we saw in Chapter 6, anatomical data now show that small diameter output filters, the γ filters, regulate the organism's receptors and therefore sensory functions, and they also regulate its movements. Thus both input and output, stimulus and response, functions are regulated by the γ efferents (i.e., efferents which are not motor). In general, this is accomplished by changing the bias on the receptors, much as the setting of a thermostat is changed to raise or lower temperature in a room, and as we have already seen, both feedback and feedforward biasing is involved, the latter process making use of the fast computation nature of the cerebellum. This applies to any stimuli whether they be external or internal; sensory, drive, or motor.

Pribram's generalized diagram of the modified reflex is shown in Figure 9.1. Giving a summary description of the process, he says:

> The state or bias part of the mechanism has built into it contrast enhancement achieved through surround inhibition. Testing (comparing input against existing state) involves among other factors, a process of spatial superposition of the excitatory and inhibitory interactions among neighboring neural elements. The operator part of the mechanism involves, among other mechanisms, a decrementing process, a damping of the changes initiated by input in each neuron or neuronal pool. Spatial superposition enhances contrast and thus facilitates coding; decrementing serves as one of a number of forms of memory storage.
>
> Because of the spontaneous activity of neuronal aggregates, whether cyclic or programmed, changes in state are initiated not only from the environment,but by the brain as well. This fact, in addition to the ubiquitous presence of central control over receptor function, makes almost useless the reflex-arc stimulus-response conception of neurobehavioral organization, let alone of psychological function. (1971, p. 95)

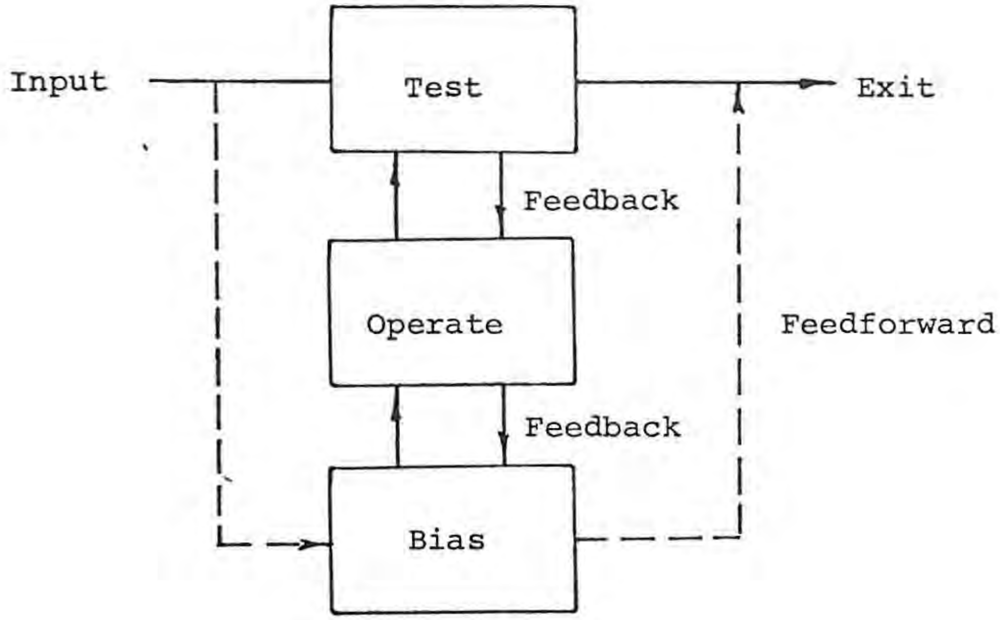


Figure 9.1. Test-Operate-Test-Exit (TOTE) servomechanism modified to include feedforward. Parallel processing is a special feature of the logic. (From Pribram 1971)

A LEARNING MODEL

Taking a stand against Gibsonian empiricism, Taylor has a different approach to the stimulus-response phenomenon. Though Gibson argues that the existence of gradients of texture proves that the visual stimulus contains sufficient data to generate a perception, Taylor does not agree. From his point of view, this is a learning process. A child confronted with a gradient of texture

> has no means of converting this"information" into perception of the spatial ordering of the environment unless he has additional "information" representing his distance from the surface and the uniform size of the units of the texture. Neither of these is directly incorporated in the visual stimulus. The "information contained in the light" appears to Gibson to be sufficient to account for visual perception only because he has failed to recognize that certain items of information that appear in our experience to be carried by light are in fact not caused by light. His error is of the

> same order as that which was corrected by Berkeley when he pointed out that a ray of light reaching the retina carries with it no information concerning the distance it has traveled. (Taylor 1962, p. 113)

According to Taylor, the additional information gets incorporated by virtue of the fact that the floor on which the child walks or crawls offers a gradient expressible in terms of the distance from his head to the floor. The specific values of the gradient of the floor become associated because even neural stimuli regularly associated in time with stimuli for unconditioned or conditioned responses themselves become conditioned stimuli. Taylor says that the result of numerous learnings of this kind is the incorporation into the system of the initially missing information that the diminishing angles subtended by successive units of the texture are derived from a succession of equal distances measured along a plane surface.

This position is a consequence of the general thesis of Taylor's work, which is that all conscious experience is a function of learned behavior. Visual perception, as one form of conscious experience, is therefore a function of learned behavior, and not mere stimulation. Sense-data are not raw material for perception, but are themselves knowledge. A sense-datum

> specifies a piece of matter occupying a position in space and reflecting light into the eyes; it specifies further that the light from this object generates afferent impulses which, in conjunction with proprioceptive afferents determined by the orientation of the eyes and head, activate an engram mediating a response directed to the object, whether the response be actually evoked or not. Now this engram is not something that was there from the beginning but has been built up by a process of conditioning, and it is important to observe that the reinforcement of the conditioned response was not random but was determined by some property of the object, such as its position relative to the subject. The engram, so to speak, represents a portion of the history of the organism's commerce with the environment, written in the form of temporary connections built into the brain. (Emphasis added) (Taylor 1962, p. 340)

For Taylor, knowledge implies the ability to take some action relative to the thing known. This is true for scientific knowledge (i.e., community knowledge) and for sensory knowledge (personal knowledge), although the latter form has the appearance of immediacy while the former is clearly mediated. However, sensory knowledge takes on the appearance of immediacy only because the mediating processes are not conscious events but events that occur at a purely physiological level.

Activation of an engram puts the organism into a state of readiness for the appropriate response. This state of readiness is the knowledge that the object of perception has such-and-such a property. Knowledge is itself a subject-object relation that can be defined with precision, and sense-data are simply the form that knowledge takes at its lowest level, according to Taylor. They are mediated events reflecting the history of the subject's interaction with his environment. By virtue of this fact, sense-data can be erroneous, though they need not be erroneous in every respect. For example, while shapes may be distorted when viewed through a prism, the spatial ordering of the perceived environment can remain intact. Indeed, the limited truthfulness of the erroneous sense-data plays a vital part in the correction of errors.

Considering the movements of the tennis player, should he happen to make an ineffective swing, the direction -- if not the extent -- of his error might easily be known, this by virtue of the limited truthfulness of his sense-data. For example, say that a ball approaching on his right is perceived to be nearer to him than it is, so that the racquet falls short of the true position. But say the ball can be seen passing beyond the racquet head. This relation represents the truthful component of the fallacious sense-data. It defines the spatial order of his perceptual experience. The number of inches by which the racquet missed the ball may not be known, but that the ball passed to that particular side of the racquet is fact.

In Taylor's view, even a blur implies some order, however lacking in precision it may be. At the very least the blur has position -- if not absolute, then at least relative to some other blur. The continuing presence of the blur also implies a temporal order.

Space and time are thus necessary conditions for knowledge of even a blur, which is to say the perception of a blur, or any experience at all.

Insofar as knowledge implies the ability to take some action relative to the thing known, it also implies the existence of an orderly world and a subject and a mechanism by which the perceived structure can be related to the world. Kant contributed the orderliness to the natural conditions of the human mind, as we saw in Chapter 4. But for Taylor the mechanism for order is the conditioning of responses adapted to the world. Since the efferent structure is multidimensional from the beginning, since perception of the position of an object in space depends on retinal stimuli and also on proprioceptive stimuli from the muscles of the neck and eyes, and learning cannot yet have occurred, there can be no "primitive consciousness already possessing rudiments of order." Thus, the infant's world, as presented through his receptors, is totally devoid of order.

> The receptor organs are so constructed that they can respond to various energies in the environment, such as light waves, sound waves, pressures, including pressures within the organism as determined by gravity, and others determined by acceleration, particles given off by volatile substances, temperature, and the like. Stimulation of the receptors generates afferent impulses that travel to the spinal cord or brain stem and thence are relayed to the cortex. On their way to the cortex they stimulate the brain stem reticular activating system (BSRAS) which raises the general level of cortical activity, so that although the afferent impulses reach determinate parts of the cortex, they can be relayed to virtually any other part, and it is largely a matter of chance what behavior will result from any given impulse. That is, at the beginning of life the impulses from the several receptors are differentiated with respect to their cortical termini but not with respect to their ultimate destinations.
>
> The function of the cortex, as Pavlov has shown, is the formation of temporary connections, and we must assume that it starts its characteristic mode of activity as soon as birth exposes the organism to variable stimulation. That is, the cortex first of all produces an apparently random succession of movements involving the whole motor system -- the so-called mass activity of infancy. This includes movements of the limbs and the head, of the eyes and eyelids, of the mouth and vocal

> apparatus. Most of the components of the mass response leave the general condition of the organism unchanged, but when a critical state arises certain specific components are effective as a means of terminating this state. If it can be shown that certain forms of stimulation invariably precede the action that serves to terminate a given type of critical state, we can assume that the stimuli in question become conditioned to the successful response. Then, if there are two or more types of critical state, if the successful responses are different in kind, and if the conditioned stimuli operate on different receptor organs, it follows that the perceptual experiences generated by activiation of engrams mediating the conditioned responses must be qualitatively different. (Taylor 1962, p. 276)

Clearly, the key to the perception of position, and thus of motion, and experience generally, is the conditioning, or reinforcement, of the stimuli that lead to the successful responses. But what precisely is reinforcement, and how does it occur?

THE NATURE OF REINFORCEMENT

For Taylor, the mechanism that meets the requirement is conditioning with the Hullian principle of unlearned behavior:

> According to Hull, . . . a drive stimulus, S_D, in conjunction with a stimulus, s, determined by some feature of the environment, gives rise to a succession of unlearned responses that goes on until one response results in diminution of the drive. The reduction of the drive has the effect of establishing a relatively permanent neural connection such that when the same s and S_D occur again, the response that led to the reduction of S_D is more likely to be evoked than any other response. (1962, p. 6)

The fortuitous response, following a succession of possibly random or haphazard responses, that has the effect of satisfying or partially satisfying the individual's needs thus establishes a neural connection that becomes functional the next time around. This neural link, or engram, isn't just a single chain of neurons connecting a single projection area of the brain to a specific portion of the motor cortex. Rather, it is a complex network involving several projection areas and very likely one of the "silent" or association areas.

Furthermore, says Taylor,

> if we define an action by its terminus alone and not, as we have done, by both its initial and terminal points, there is not just a single engram mediating this response but thousands of them. It follows that extirpation of a comparatively small area of the cortex is likely to destroy some of those engrams but to leave a substantial portion of them intact. Thus destruction of a portion of the striate area receiving afferent impulses from a specific part of the retina will make it impossible to perform a response . . . if the light from the goal object falls on the affected part. But a simple movement of the eyes results in the activation of an intact engram mediating another response having exactly the same terminus. (1962, p.38)

For Pribram, however

> the neural logic that controls behavior, just as the logic that constructs percepts and feelings, is distributed in systems related to a broad class of functions. This distributed logic forms a competent tissue whose expressed function depends on the experience of the organism with particular environmental contingencies. Expression depends on a junctional mechanism akin to that which produces Images-of-Achievements. Mere contiguity of contingencies does not modify behavior; the contingencies must address the innate competences of the organism or their modifications by prior experience (the organism's expectancies). (1971, p. 270)

As already noted, the neural logic is a self-adapting screen through which and against which incoming signals are matched. It is a coded representation of prior signals generated in the interaction of the organism with its environment and is gradually built up. Subject to alterations by signals of mismatch, or partial match, it leads to sets or expectancies of environmental occurrences by the organism. But the organism must be "ready" or "competent;" it must be in a proper state of responsiveness to allow the alterations -- learning, conditioning, modifications -- to occur, to allow induction or inforcement to become effective. At any moment in time, "the central state must be competent, ready to provide the context in which stimuli arise. Contiguity of stimuli is therefore to be seen not as some vague, haphazard, and probabilistic 'association', but as a biologically determined process that organizes a context-content relationship" (Pribram 1971, p. 264).

As we have just seen, the reduction of drive is the reinforcing principle for Taylor. But what precisely is the need-state that gives rise to the drive? What is the drive stimulus? As Pribram points out, what constitutes the "stimulus" is not as simple as it might seem. According to him,

> A drive stimulus, just as a sensory stimulus, results from the operation of a biased servomechanism, a homeostat. Homeostats are outfitted with receptors sensitive to excitation from the World-Within. Specialized areas sensitive to temperature, osmotic equilibrium, estrogen, glucose, and partial pressure of carbon dioxide are located around the midline ventricular system; these areas are connected to mechanism which control the intake and output of the agent to which they are sensitive.
>
> In addition to these central mechanisms, other more peripheral sensitivities also play on the homeostatic process. The homeostat is often supplied with secondary mechanisms which aid in the more-finely-calibrated regulations of the agents in question. Stomach contractions in the hunger mechanism and mouth dryness in thirst are examples, as is the regulation of the circulation of blood in vessels of the finger tips to provide greater or lesser cooling. The blood-finger temperature differentially biases and is biased by the main hypothalmic thermostat. (1971, p. 272)

The mechanisms that produce interest, appetite and affect, modify behavior (reinforce the organism) by engaging the organism's memory mechanism. Enduring memory structures are "induced" in the brain much as tissue structures are induced during embryological development. The superficial similarity between induction and reinforcement is as follows:

> (a) Inductors evoke and organize the genetic potential of the organism. Reinforcers evoke and organize the behavioral capacities of organisms. (b) Inductors are relativey specific in the character they evoke but are generally nonspecific relative to individuals and tissue. Reinforcers are quite specific in the behaviors they condition but are generally nonspecific relative to individuals and tasks. (c) Inductors determine the broad outlines of the induced character; details are specified by the action of the substrate. Reinforcers determine the solution of the problem set; details of the behavioral repertoire used to achieve the solution are idiosyncratic to the organism. (d) Inductors do not just trigger development; they are more than just evanescent stimuli. Reinforcers do not just trigger

> behavior; they are a special class of stimuli. (e) Inductors must be in contact with the substrate to be effective. Contiguity is a demonstrated requirement for reinforcement to take place. (f) Mere contact, though necessary, is insufficient to produce an inductive effect; the induced tissue must be ready, must be competent to react. Mere contiguity, though necessary, is insufficient to produce reinforcement; shaping, deprivation, readiness, context, expectation, attention, hypothesis -- these are only some of the terms used to describe the factors which comprise the competence of the organism without which reinforcement cannot become effective. (g) Induction usually proceeds by a two-way interaction -- by way of a chemical conversation. Reinforcement is most effective in the operant situation where the consequences of the organism's own actions are immediately utilized as the guides to its subsequent behavior. (Pribram 1971, p. 273)

As reinforcers, the consequences of actions can provide information, which is to say they can reduce uncertainty for the subject, or they can place a value on action, i.e., bias it. Actions are guided by the values placed on them. "A change induced in the values of the variables that guide behavior is, in the ordinary sense of the word, of course, providing information. In the more restricted usage of information theory, however, the process is akin to biasing the servomechanism setting around which the process stabilizes." (1971, p. 293)

Suppose, for instance, that our tennis player attempts two different shots, A and B, in a given situation and learns that B succeeds in making a point while A does not; he has thus gained some information about the shots and has attached separate values to them. Should the situation be repeated successfully with the use of B, the gain in information about B will be less than what it was on the first occasion though the value of B may well be enhanced considerably; behavior B generates consequences that are consonant with the bias, or commitment, of the player. This constitutes a feedforward process.

There is a parallel between action and perception. When the input to the sensory channels addresses the competences of the system, that input becomes perceived information. "The amount of information can thus be defined as the amount of match between input and competence. The definition derives from information measurement theory; the amount of perceived information corresponds to the amount of information transmitted by a channel whose capacity corresponds to the neural competence." (1971, p. 298)

But the amount of match determines the degree of similarity. And similarity and reinforcement, according to Pribram, are one and the same -- looked at from the vantage point of stimulus language in one case (similarity) and from response language in the other (reinforcement). Sensory processing, because it is reinforcing, generates meaning. The process of reinforcement progressively increases discriminability and decreases similarity. Trajectories of the tennis ball might be differentiated into more refined classes, for example. So what could initially have been similar shots (trajectories) now become different, calling for different treatment.

For input to become guiding, i.e., meaningful, to the individual, he must process it in successions of information generating steps in terms of his competence and commitments. Thus meaning is formed by the hierarchical nature of the information processing mechanism.

In the motor mechanism what corresponds to the engenderment of meaning is the occurrence of a hierarchical process similar to that which characterizes the sensory system.

> The Image-of-Achievement is not informed by "objects" or "interests" but by the play of forces produced by the behaving organism. From these forces must come the commitments which bias the motor competence toward achievement. Furthermore, because of the cerebellar fast-time circuit, the Image-of-Achievement is predictive. Given (1) that the neural mechanism "because of its selective control over its own modification, allows a change in representation to occur over successions of trials," and (2) that whenever "complete match between representation and input is not achieved the representation is modified to include this information and trials continue . . . until corrective change of the representation no longer occurs," then any succession of predictive representation in essence constitutes a program or Plan. (Pribram 1971, p. 299)

Commitment is necessary because the neural substrate of humans does not contain localized mechanisms that lead to the achievement of an Act. Instead, mechanisms that invoke part-activities are distributed over a range of tissue, and these part-activities must be organized for achievement. Performances achieve results because of the hierarchical nature of the reinforcing (or in stimulus language, the discriminitive) process. Meanings are derived when information is hierarchically processed in sensory systems, and Plans, or programs, are the product of hierarchical processing in the predictive motor system.

In summary, then, Pribram considers the sensory system to be a hierarchical information processing system productive of meaning, while Taylor holds that perceptions are functions of learned behavior, or acts of knowledge of the real world.

Hierarchical sensory processing generates meaning because it is productive. So far as sign learning, awareness and recognition are concerned, however, attentive choice (selection) is involved; signs are constructed when actions operate on perceptual images. The meaning of a sign is in the response; a sign is an Act representing a perceptual Image. Imaging already involves active aspects in addition to the relatively passive neural mechanism thrown into operation by input; for one thing, feedforward is needed to render the Image stable and constant. Discriminitive learning, pattern recognition and selective attention all involve neural choice mechanisms, choices that beget actions, which in turn modify what is Imaged.

A STATISTICAL MODEL

An alternative to the views of Taylor and Pribram is offered by Ittelson, who holds that the primary function of perception is prediction of the future.

> Perceiving -- provides us with predictions of the significances we will probably encounter in the

> external world . . . We discover the significances of the external situation only by experiencing the consequences of our actions. (1960, p. 35)

Every action can be thought of as an experimental test of an hypothesis which is appropriately modified or confirmed as the result of the test through action. Probabilities are unconsciously assigned to the particular assumptions on which the actions are based, and one result of the action is to change those probabilities. A probability is changed in proportion to the weight given to the particular experience, which results in new assumptions, predictions and externalized significance.

> Successful actions can only confirm what we know. Hitches provide the occasions for increasing the scope and adequacy of our assumptions. (p. 36)

For instance, if I catch my toe on a corner of a protruding carpet -- that's a hitch. Or if I think I am going to hit the tennis ball but, instead, miss it altogether, that, too, is a hitch. The hitch arises if we experience a significance we did not expect to experience, or do <u>not</u> experience a significance which we <u>did</u> expect to experience.

> Every hitch is either the result of a failure to achieve a particular goal, i.e., of inadequate "how-to-do" predictions, or else the result of a failure to experience a hoped-for satisfaction resulting from an incorrect "what-for" prediction. (p. 37)

The everyday world is indeterminate for all practical purposes; invariably there is some aspect in the immediate situation that has never been encountered in the past. This is to say there is always some lack of correspondence in every concrete transaction of living. Change is the rule of nature. Every concrete situation potentially involves an element of chance as a product of its degree of novelty. Thus every participant in a concrete occasion of living is faced with a choice among uncertainties. The choice, or evaluation, has to be made in the face of further uncertainty that the novelty of the situation we are about to face is never revealed to us before the action taken. Even the degree of uncertainty itself is uncertain. Every perception is an act of creation; every action is an act of faith. "At any given moment, these functional absolutes are treated as if they were certain but, concurrently, are held open for modification." (p. 38)

COMPARISON OF THE VIEWS

Taken at first glance, these three views seem to be quite different; but closer examination reveals similarities of concept within linguistic variations. Taylor's view in intent is deterministic; nature, for him, is regular (in the sense in which the term is used by Ashby (1952)). Should uncertainties, or instabilities, arise, it is conceivable that they can be removed by the incorporation and evaluation of new variables into the system definition. For instance, a mother may be added to a baby system to resolve the feeding uncertainties or instabilities of the baby system. But for all practical purposes there are always new variables to be added to systems, in order to resolve one uncertainty or another. The mother may have to go to work, for instance, or may become ill. It might then be necessary to add a husband, or a doctor, to the mother-baby system. And this can go on indefinitely. So a degree of uncertainty really characterizes every concrete situation.

The engrams of Taylor correspond very closely to the competences of Pribram, and to the predictions of significances of Ittelson. They are all mental sets. All are products of experience and subject to change as a result of a mismatch between what is anticipated in perception and what actually is perceived.

Ittelson states that every perception is an act of creation. While Taylor doesn't use this kind of language -- and granting that translation from one mental representation to another can be hazardous --, he does say that perception is mediated experience, which means that it is a product rather than raw material; the perceiver plays an essential role in its production. But this is no more than to say it is created; it is an act of knowledge, an act of creation.

Similarly for Pribram. While he accepts the nativism of the Gestaltists that there are inherited built-in neural mechanisms that give rise to Imaging -- the sense data of experience --, he says that the patterns become to some extent independent of cells as units and become instead the designs imposed by the junctional anatomy, the synaptic and dendritic microstructure of the brain. These designs serve, in the proper circumstances, as the neurological equivalents of percepts. The direct immediacy of the sensory inputs can only be an apparent immediacy, therefore. Holding a "Biologist's view" of the mind-body problem, he says that Images have structure; they are made by a complex brain process; they are not the givens of existential awareness. Because the Biologist's view is constructional, it shares the rational approach to epistemology and therefore has a neo-Kantian flavor. The Images are products of the patterns of stimuli coupled with the action of a participating mind. Thus, for Pribram, too, perception is an act of creation.

A hitch is really a perceptual error -- a difference between what was expected, anticipated, or predicted and what was actually perceived. It reflects either a lack of information, insufficient knowledge, a degree of incompetence of performance, or an inadequate perceptual hypothesis as to the potential state of affairs. Now the formation (production, construction, creation) of a perception certainly takes time. As Haber has pointed out;

> (What) is clear from a large mass of research, is that it takes time -- a lot of time -- for the train of pulses, and changes in resting levels, to travel from the receptor surface to the visual cortex and beyond. Further, the properties of those trains of impulses may be changed radically from level to level. (1969, p. 5)

It is reasonable to expect that during this time the world is changing incrementally. This in itself introduces an element of uncertainty. In situations where the conditions may change rapidly, such as occurs with the position of a tennis ball moving at high speeds, the degree of uncertainty can be significant. Normal expectation under these circumstances is an increase in the error rate, which in fact occurs, unless compensatory action can be taken.

To reduce uncertainty and thus avoid the increase in error, new levels of sensory awareness and skills are required; the perceptual-motor problems have to be solved in more effective ways. This necessarily draws on the creative potential of the athlete. Motivation has to be heightened and action redirected to new and "higher" goals. Old practices have to be examined and modified where necessary. Experimentation is needed and new methods tried. The process may be difficult, painful, costly, and even unprofitable, leading to greater rather than less uncertainty; but in the face of possibly intolerable error, there seems to be no reasonable alternative.

SUMMARY

Tracking and intercepting a tennis ball is a complex process involving a high degree of interaction of vision and movement and continuing interplay between the athlete and his behavioral environment. The player must perceive the moving ball, estimate its state variables, determine an intercept point, and exercise control over his muscles to race to that intercept point. This involves plans which interpret the motion of the ball and lead to a judgement of the distance-to-go and time-to-go to intercept. A faulty judgement in this regard is reflected in a difference between what he expected to happen and what he perceives as happening. The feedback alters his running and tracking tactics so that he applies different muscular forces in the process. Meantime, as he runs, he must continue to watch the ball and move his body and racquet so as to be in a striking position for a return shot. This requires a high degree of concentration and an effective system of mental representations in this his specialized tennis environment.

We turn now to a simulation of the processes.

PART III

SIMULATION OF THE VISUO-MOTOR PROCESSES

CHAPTER 10

FORMULATION OF THE SIMULATOR

The previous chapters have characterized our tennis player variously as a conscious, highly adaptive, self-organizing system, capable of pattern recognition and selective attention. He uses a, very possibly, multi-dimensional space of mental representations to interpret or give meaning to the internal and external stimuli bombarding his many sensory elements and to organize and guide his behavioral responses. He directs his eyes to follow the ball and otherwise generally orients his sensory apparatus. At times he must track on the run, as when he races to effect an intercept. By virtue of the information garnered in perception, what he sees reflects what is happening in his environment, and the action that he takes reflects an intention or motor plan within him. His sensory processes, incorporating the motor cortex in an essential way, are highly interactive with his movements. Pattern recognition and selective attention invoke neural choice mechanisms, choices which beget actions. And the actions in turn modify what is seen. As he tracks the moving ball there is the inevitable movement of his eyes, or head or body; and as he runs there is the inevitable change in his perception. He is a skillful but emotional creature who frequently makes decisions based on personal rather than tactical requirements. In short, he is a complicated, multi-faceted, intelligent organism.

Considering the functions he performs as an active information-processing system, this creature collects stimuli from the outside world, interprets it as information, stores and retrieves the information as required or as he is able, orients himself, maintains his posture, detects and identifies objects in his environment, tracks or keeps track of the most interesting of these objects, intercepts one of them and attacks it, if possible.

And in the course of these events, some of which take place concurrently with others, he makes many decisions.

The neuro-physiological structure by means of which this information-processing occurs, has its own levels of complexity. At the anatomical level, for instance, there are hundreds of muscles and bones which constitute components for many bodily movements. Eye movements alone are marvelously intricate. But these are combined with movements of the head, arms, legs and torso, producing many more varieties.

Complexities orders-of-magnitude higher are found at the cellular level. They include a large number and variety of cells and receptive fields (in the retina, geniculate body, and cortex), each with its distinctive logic. Each cell typically connects with thousands of other cells and has thousands of cells connected to it. Fibers conduct at different rates; some slow, some fast. Fibers influence in different ways the various stations of the visuo-motor system. There are millions of receptors in each eye and billions of cells in the brain, and messages (innervations) from each eye are carried separately beyond the geniculate body to be fused eventually in the cortex, while other messages, formed by complex innervations from the many parts of the brain, are carried through the motor cortex to the many muscles and muscle sensors of the body.

To simulate this creature, it is apparent that our representation of him must be simplified considerably. Some steps in this direction have already been taken. For instance, at the outset it was decided that, for a trial or prototype program, only tracking and interception are to be mechanized; the other functions are merely assumed to occur, as needed. Further, it was taken for granted that only the visual, as the most important, mode of perception will be incorporated.

It is necessary now to cut away as well the detail found at the cellular and anatomical levels of the organism. There are simply too many neurons, muscles and bones to deal with on an individual basis. Indeed, much of the neuronal structure is unknown. The neural pathways and interactions are still relatively undetermined, and the innervation patterns are even less well defined. In effect, this cuts away the structure of the organism and leaves only the functions.

Even with this additional slicing, however, the simulator remains essentially unspecified. We know only that the player is to exhibit visual tracking and interception and that he will have a personal as well as an objective environment. How this is to be rendered is undefined. The kind of program to be written is unspecified. And as yet it has only been tacitly assumed that the context for the player's action would be the tennis court. No description of the events to take place in that environment has been presented, though we know that some of them are to be performed concurrently with others. Indeed, we know that both tracking and interception, as ongoing operations, occur together. The player runs to intercept the ball even as he is following it in its trajectory, and each operation has its effect on the other. The problem remains, however, to state how this interaction is to be programmed.

The fact that the player is presumed to have a subjective as well as an objective space, implies that there are two distinct representations in the simulation, and that, therefore, there must be two distinct sets of computations, one for each space. For instance, the ball is known to move in physical space, and it is also a component of his phenomenological space. To develop these implications further, we will now observe the actions of the player in his natural setting -- the tennis court --, considering both subjective and objective aspects.

THE PLAYER'S PHYSICAL ENVIRONMENT

The playing volume for the game of tennis normally includes the air space over the court surface and the surrounding area out to about 12 feet on each side and 21 feet at each end of the court, as shown in Figure 10.1.

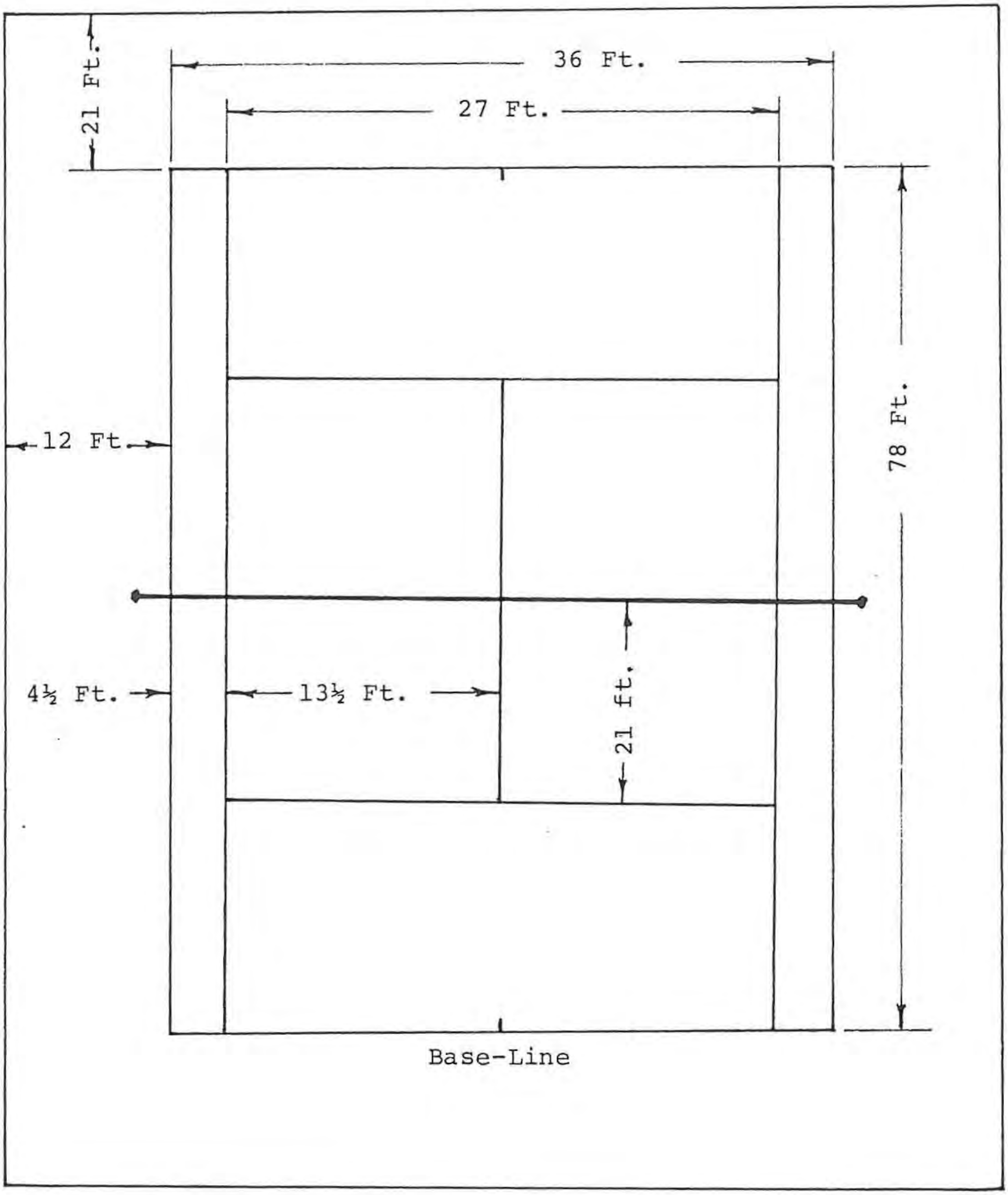


Figure 10.1. Plan of the playing volume for tennis.

According to Rule 1 of the Official Code of the International Lawn Tennis Federation, the court for the Singles game has to be a rectangle, 78 feet long and 27 feet wide. It has to be divided across the middle by a net suspended from a cable, the ends of which are attached to posts 3 feet 6 inches high and three feet outside the court on each side. The height of the net has to be three feet at the center and held down by a strap.

Service-lines on either side of the net and parallel to it are 21 feet away. The space on each side of the net between the service-line and the side-lines has to be divided into two equal parts by a 2 inch wide center service-line parallel to the side-lines. Each base-line has to be bisected by a center mark 4 inches long and 2 inches wide. All other lines have to be between 1 and 2 inches wide except for the base-line which may be 4 inches wide. All measurements have to be to the outside of the lines.

According to Rule 32 of the Code, the court for the Doubles game has to be 36 feet wide, or 4½ feet wider on each side than the Singles court. In other respects, the court is the same as that for the Singles court.

By Rule 3 of the Code, the ball has to have a uniform outer surface. It has to be between 2½ and 2 5/8 inches in diameter and weigh between 2 and 2 1/16 ounces in weight. For a drop from 100 inches above a concrete base, the bound has to be between 53 inches and 58 inches.

Assume now that our player is playing Singles on a regulation court. (Doubles is richer in some respects and perhaps more interesting to analyze, but it considerably increases the complexity of the simulator without adding materially to the principles being developed in this report). Figure 10.2 describes graphically the physical space representation of happenings for a given segment of play. It shows the opponent on the far side of the court, at point 0_1, and the receiver on the near side, initially at point R_1. The ball is shown moving from the opponent along a trajectory to the receiver's right. The receiver

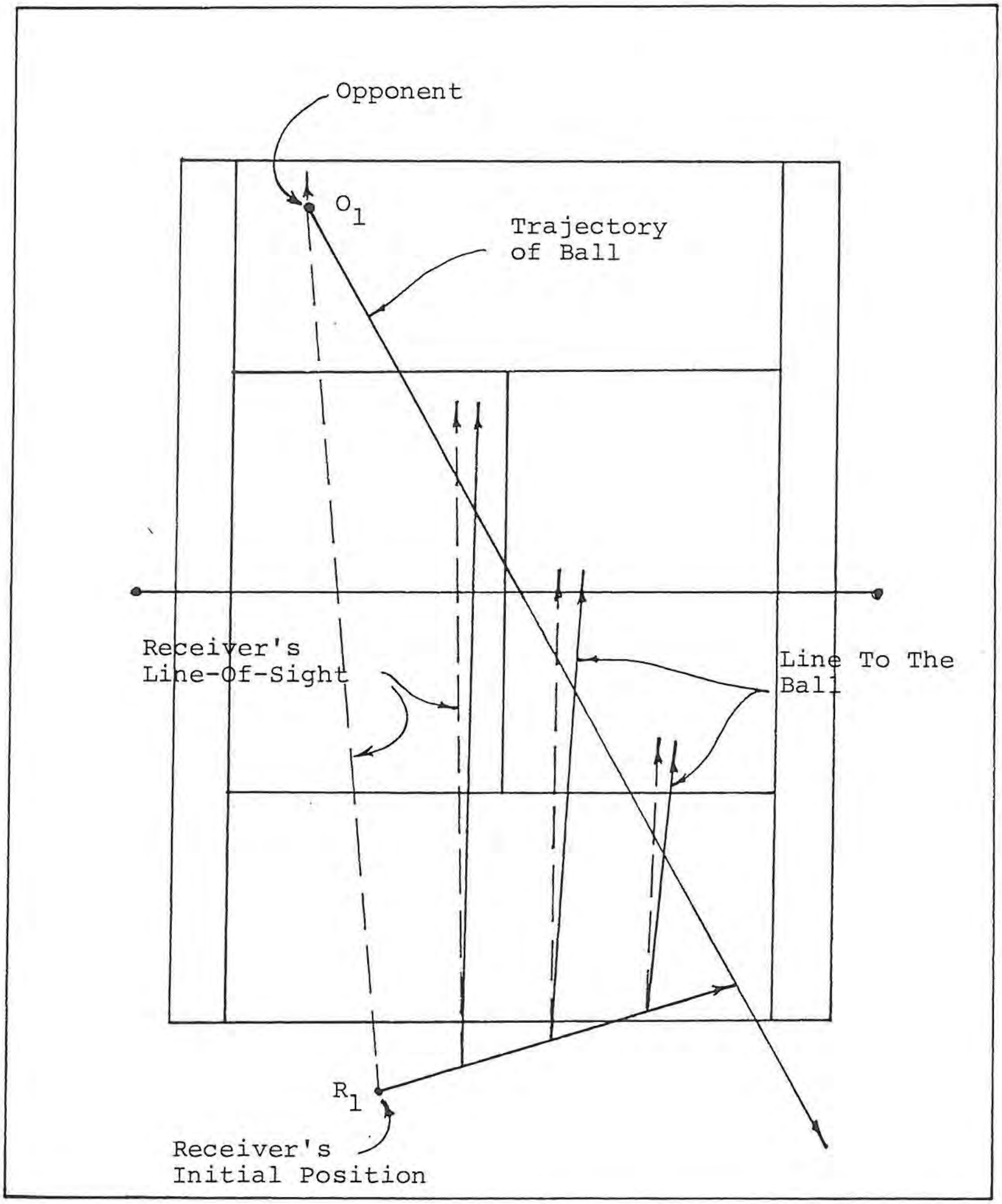


Figure 10.2. Physical representation of ball and player movements.

is moving to intercept it. Dashed and solid lines emanating from points along the receiver's path identify, respectively, his line-of-sight and the actual line from him to the ball. Initially, the receiver is looking directly at the ball, but then his line-of-sight is shown to lag behind the ball.

The portion of the simulator that deals with this representation would have to compute 1) the position of the opponent, 2) the characteristics of the path of the ball, 3) the characteristics of the path of the receiver, 4) the characteristics of the line-of-sight of the receiver, and 5) the characteristics of the line from the receiver to the ball. All of these computations would have to be in physical space. A rectangular coordinate system seems the most reasonable for the first two computations, whereas a polar coordinate system would seem to be best for the others.

THE PLAYER'S PERCEIVED ENVIRONMENT

In this representation, the program takes the receiver's point of view and presents his perception, decisions, attitudes and movements related to the happenings of Figure 10.2 <u>as he might experience them</u>. The receiving player is seen as a decision-maker competing within the context of the tennis court and constrained by the "rules of the game." Within that framework he is also bound by limitations due to the physical environment, his biological endowment, his level of development and his level of competence of the various aspects of the game.

For the indicated segment of play, the opponent has hit the ball and imparted to it a specific trajectory. Our receiver now responds to the ball by attempting to follow it with his eyes at the same time that he is running to intercept it. That response will be determined by the physical conditions of the court, his biological development, his skill levels in the game and his psychological makeup. These factors have to be identified.

As indicated above, adequate detection and identification are presumed to occur and are not explicitly mechanized. This presupposes that the physical environment has been illuminated properly and that the incident radiant energy has been interpreted by the receiver's input system. But it also means that the structure of the visual system doesn't have to be mechanized. It is only necessary to represent the direction, rotation rate and the angular acceleration of the line-of-sight, as estimated by the receiver. The perceived values, it is to be noted, might be different from the publicly observed, or objective values.

A further implication is that neither the ball nor the opponent have to be represented as having spatial extension, though they are still to be represented as in space. The ball and players can thus be given merely as points, an implication which greatly simplifies the programming task.

In normal use the eyes are hardly ever still. This is due to the occurrence of perhaps several saccades a second, each lasting usually less than a twentieth of a second. The saccades, themselves, are more or less mixed with almost continuous minor tremors -- the micro-saccades. As Neisser states, "the retinal images are at the mercy of every irrelevant change of position; their size, shape and location are hardly constant for a moment" (1964, p. 140). Yet the perceptual field is quite stable. Objects don't jump around like the proximal images; they are appropriately placed in the perceptual space. Order is created out of chaos. The visual system filters out the noise and smooths-over the many variations.

The extent to which these saccades and micro-saccades affect tracking is not clear, but such extraneous movements of the eye might not always be smoothed out. It is quite possible they could reduce the effectiveness of tracking and even cause the player to lose sight of the ball momentarily. A more detailed analysis and ultimate mechanism of the tremors could be useful. For the prototype model, however, it will be assumed that the smoothing function is part of the input system function and that it is adequately performed. Our receiver will thus have a smoothed perceptual field.

INTERACTION OF THE TWO REPRSENTATIONS

It is assumed here that there is an objective world of things and events and that the particular organization of that world at a given moment in part determines what is perceived. But the perception in turn can lead to some action which may alter the objective arrangement and lead to a different perception. Thus there is an interaction.

In our simulator, one representation describes the objective world of the tennis court and locates in it the ball and players. Another representation takes the point of view of the receiving player and interprets in his terms what is happening on the court. Tracking and interception are thus effected in a manner determined by his own estimates, judgements, decisions, attitudes and skills. His decisions and movements are intuitive rather than formal, more qualitative than quantitative, and his reference is Ego-centered. What he believes to be the case may not coincide with things as they are. The objective representation is used to establish the differences.

Different formulations are therefore required for the internal and external points of view, and the two segments must be operated concurrently. Since there is a differential interaction between perception and movement, each one affecting the other on an incremental basis at each moment of time, it is necessary for the simulator to keep a running account of the processes on a moment-by-moment or time-slice ledger. At each time-slice, both psychological and physical occurrences and the mutual affects of one upon the other are to be recorded and made available for the next time-slice, where the changes are felt.

Any given event, then, is to be treated on a moment-by-moment schedule. Consider, for example, the event depicted in Figure 10.2. The total time for this event to happen may be 1.5 seconds, but the program could operate on a 10 millisecond schedule, thereby performing 150 sets of computations. Each computation set would include both physical and psychological computations, as appropriate.

For the prototype model of our simulator, it will now be assumed that the ball, as pictured in Figure 10.2, will move in a piecewise ballistic trajectory. Specifically, a (right) forehand, cross-court shot will be assumed to be hit from the opponent's right base-line corner. It will be presumed to move in physical space in accordance with standard laws of dynamics. Every 10 ms the position, velocity and acceleration of the trajectory will be computed.

The two players are also part of the objective world, so their behavior will also be tracked. In the prototype model it will be assumed that the opponent remains fixed in position during the event, but the receiver will move to intercept the ball. His position, velocity and acceleration in physical space will therefore be computed on a regular basis also -- every 10ms.

The player's movements will of course have to satisfy standard laws of motion; there can be no discontinuities in position, velocity or acceleration. But psychological influences will be felt. The player is presumed capable of altering his behavior and choosing his courses of action. The estimates, strategies and decisions within his competence which affect his movements are dealt with in the concurrent program segment representing the player's subjective space. In this segment, the ball is represented as perceived from the perspective of the player. Every 10ms the state of the ball from this point of view will be computed in accordance with the presumed bio-physical endowment of the player, his perceptual and running strategies, and his skills. Polar coordinates will be used as the reference frame.

If the player's estimates are unrealistic, i.e., if his expectations don't coincide with actual happenings as determined in the physical space representation, errors will arise. The differences are to be incorporated as feedback to new estimates and expectations, which incorporate the so-called fast-time or feedforward computations. The comparison and predictive operations will make use of the player's presumed refractory period and reaction times.

REVIEW OF SPECIFICATIONS

The structure of the problem is now quite specific. Its context is considered to be the tennis court, the attacking player is presumed to make contact with the ball to initiate a trajectory, and the receiving player is considered to respond to the trajectory by racing to intercept it. Specifically, a cross-court shot is hit to the receiver's right. The moving ball is viewed as an object in physical space and as a phenomenal object from the perspective of the receiver. The receiver tracks and runs to intercept in a manner commensurate with strategies and motor plans determined by presumed skill levels. The simulation ends at the time expected for interception.

A number of simplifying conditions are to be noted for the prototype model. For one thing, the ball is the only object of perception and it is represented as a point. Each player is also symbolized as a point. The point also identifies the origin of the receiver's line-of-sight. At each time-slice the properties relevant to the ball, the receiver and his eyes are computed, for each space.

Starting conditions are incorporated into the first time-slice. The data includes starting values for the state properties of the ball and players. It also includes information presumed to be obtained by the receiver as his opponent swings at the ball, namely, an expectation regarding the direction and speed of the ball. Thus, the ball is considered to be "in motion" as the simulation begins; that is, it has an impact velocity. And the receiver has some idea which way to run. The anticipatory schema is given in the form of a starting acceleration,or force on a point mass.

The schema is a measure of the player's competence in anticipation. Some players are better than others in anticipating where the ball will go when his opponent hits it; they have more skill, are more competent; in this regard, they anticipate with better results. The simulator will reflect this with a starting acceleration and a reaction time.

INTERCEPT STANDARDS, STRATEGIES AND COMPETENCES

The player's perceptual history depends on the path he takes to intercept the ball and it depends on the changes in direction of his gaze as he traverses the path. But the choice of path, itself, is a function of his "reading" of the trajectory of the ball, i.e., on his ability to discriminate classes of trajectories. In turn, his ability to discriminate trajectories, and thus the character of his perception, is determined by his knowledge of the game and by his perceptual skills. It rests on his ability to recognize standards of play. The greater his knowledge and skills, the higher his standards.

Each situation has its potential discriminations and its potential standards of response. For a given individual, at a given stage of development, with specific knowledge and skills, certain levels of discrimination and specific standards of play will be actualized for each of the possible situations that could occur. In our simulator a particular situation has been devised in the form of a cross-court trajectory with designated direction and pace. The player is presumed to be at some specific stage of development with designated knowledge and skills. He must therefore respond in accordance with some standard characteristic of his attainments. We must now decide on the standard.

Selection of this standard, or standards, should be possible if the tactical structure of the situation is elaborated on. This can be accomplished somewhat as follows. We first examine the possible starting positions for the receiver and select from them those typical or commonly accepted defensive positions of advantage. Baseline center is one such position. Net center is another possibility. From these positions, then, standard moves are prescribed for indicated shots by the opponent. Some of these paths are schematized in Figure 10.3.

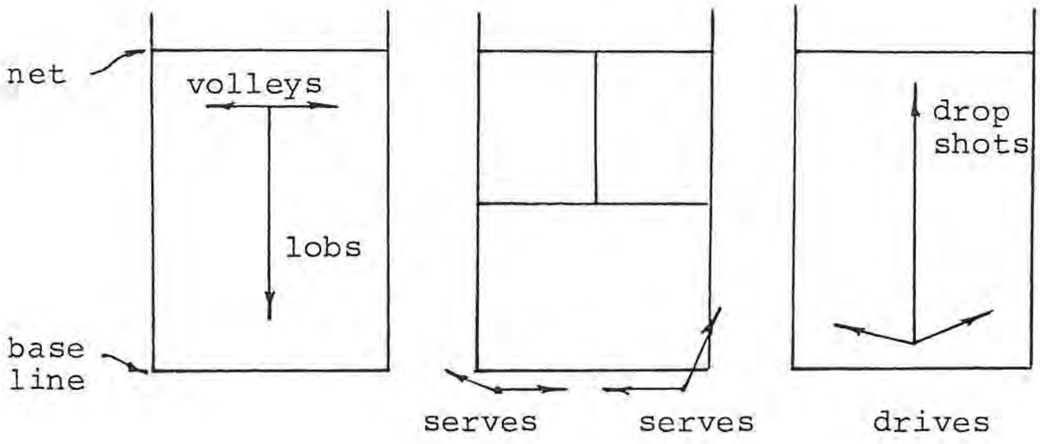


Figure 10.3. Representative standard moves for designated starting positions and indicated shots.

For our cross-court shot it is convenient to select a path of the type shown in this figure. But a more refined description is needed to provide for different competence levels. For this purpose we refer to Figure 10.4. In this diagram, three approaches from baseline center to the path of the ball are shown, each corresponding to a different guiding policy. One policy says to glide backwards with the ball to meet it waist high. The appropriate move for this policy is given in (a). Another principle says to stand your ground and take the best shot; this is shown by path (b). The third idea, represented by (c), is to race forward to cut off the trajectory. These alternatives are usually selected, respectively, by beginners, intermediates and advanced player.

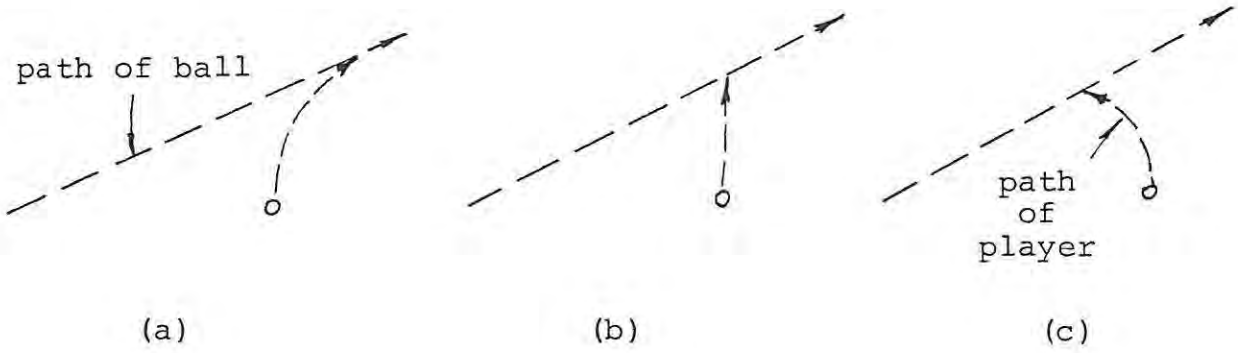


Figure 10.4. Schematic of standard path intercepts movements for a) beginner, b) intermediate, and c) advanced player.

For the prototype model it is assumed that the player is intermediate in caliber in this intercept function. His strategy is to "hold his ground." He is to move neither forward nor backward, but laterally, as necessary. Given the appropriate trajectory, he will begin the movement by accelerating in a direction parallel to the net toward the path of the ball. As he approaches the ball he will decelerate as needed to be stable enough to take his shot.

In this case, the decision to run to the right is made as soon as our player reads the trajectory -- the type of shot it is, its speed, and its heading. According to his ability to read the shot, he will either be late, in time, or slow to respond. Skill will dictate whether he accelerates too much, about right, or too little. It will also determine whether his average speed is reasonable or not, and whether he fails to slow himself down and thus over-runs the ball, decelerates just right, or decelerates too much and has to stretch to reach the ball.

Our player is presumed to recognize the situation relatively late. He then over-reacts by accelerating too long and ends by having to decelerate at the maximum rate in his try to meet the ball properly. Whether he overruns the ball or hits it reasonably well depends on certain random factors, due primarily to his lack of precision reading the trajectory. This is accomplished in part by using delays. In the state-to-state format, a profile of average velocities is taken as the standard of movement. The profile is optimum for a certain class of curves. But the player attains too high a speed and can't decelerate adequately to reach the ball, reflecting his inexperience.

This interception procedure might be characterized as a velocity-following technique, in the sense that the player attempts to adjust to a best velocity while following an intercept line to the ball; but he does this by applying or producing acceleration (force). Ideally, a best profile would be computed at each time-slice <u>for the remaining segment of the path</u>, using the acceleration-deceleration model as the guide. The need to change the velocity schedule arises because of failure to reach expected states, the failure being due to errors in judgement. This shifts the velocity-time structure and results in the formation of a new starting point for computation and the construction of a new profile to apply over the remaining segment of the intercept path. For practical reasons, construction of this new profile in the prototype model is carried out in accordance with certain simplified guidelines. In other words, the space of possible profile segments is very restricted.

In effect, the player follows a standard of action more or less accurately and smoothly, as he is able. If he is a strong player his movements will be precise, his transitions regular; he will anticipate changes well and make his adjustments smoothly. If he is a weak player, however, his movements will be inaccurate and erratic; changes will generally be abrupt. The player's movement schemata, or schemata systems, dictate his responses. They reflect his interpretation of the standard -- the way he sees the standard. And they determine his skill level within that category of capability.

Thus the skill of a player relative to a particular task is reflected not only in the standard he adopts but also in the meaning that standard has for him. In the simulator our player is presumed to be "intermediate" relative to the intercept path he adopts. Even relative to that standard, however, he still is not the best player. He overestimates the desired velocity, so his actions fall short of the ideal.

The procedure adopted to simulate this function might be criticized on the grounds of artificiality, that neither the path nor the velocity profile constitutes a reasonable component of accepted strategy. This is justified in part. In actual play, adherence to a line parallel to the net is in no way important, as such. Seldom does this type of movement occur without at least some forward or backward adjustment. But the path is used here to represent a half-way point, a simplified approach useful for purposes of simulation. Weaker players do, in fact, tend to move back with the ball, to have an easier shot; and better players do tend to move in on it, to gain a step advantage on the opponent.

Consequently, the intermediate player might reasonably be characterized as taking the mid-line path.

So far as the velocity profile is concerned, we have seen that photographs indicate the existence of sub-movements. The sub-movements appear to be ballistic in nature and they carry on almost as if they were launched by a sling shot. Nevertheless there is a continuum of movement and there is a starting acceleration and a closing deceleration, however small. The velocity profile used by the simulator tends to be like this movement continuum.

Even if considered acceptable, however, such a procedure still does not completely define the player's intercept capability. One must account as well for delays in response to the information content in the visual field -- the display. It is also necessary to account for the refractory nature of the organism in his race to intercept the ball.

So far as the delay in response to information in concerned, it is clear that a greater delay would, in general, be more detrimental to effective play than would a lesser one. Hence a weaker player in this respect would be said to be slower; a stronger player, faster. The absolute standard or ideal would, of course, be zero reaction time; it would not be possible to do better than this. For the simulation, then, an instantaneous response sets the ideal, and our player is seen to fall short of this ideal by some number of units -- time-slices. He might be a five time-slice delay player, say, or a ten time-slice delay player. Since we are not here concerned with analyzing the game of a person with any particular neural network, the numerical choice is quite arbitrary. The principle nevertheless remains intact.

A similar mechanism may be employed to characterize his refractoriness in running. To represent the fact that the player detects the need for a change in response -- due, say, to an awareness of a change in conditions, such as the occurrence of an error -- it is necessary only to specify the discrimination and decision processing times, then keep track of the elapsed time and initiate the new response at the appropriate moment. The number of time-slices used to represent this reaction time is quite arbitrary, too, up to a point, again in the sense that no specific individual is under study. However, the time isn't arbitrary insofar as experimental evidence is concerned.

Theoretically, in both cases, the best condition obviously would be zero reaction time, but this would require infinitely fast circuits. A more realistic construction would set a minimum for all players, thereby taking into account the indicated biological constraints. The stronger players in this regard would then have reaction times closer to this limit than poorer players.

The standard for direction of motion in the intercept function is defined to be the straight line parallel to the net. To represent the player's ability (or lack of ability) to move laterally, minor drifts off the line can be used. Thus the player might be programmed to drift two or three times in off-parallel straight lines, for instance. Other more complex movements could be incorporated. Statistical techniques might be used as well. However, the use of such a drift mechanism does not add materially to the utility of a prototype model, so the mechanism is left for a later version of the simulator.

TRACKING STANDARDS, STRATEGIES AND COMPETENCES

Having described briefly the mechanism used to deal with our player's body motion to intercept the ball, it is now required to introduce analogous procedures to characterize his eye movements used to track the ball. Both the movement of the body and the movement of the eyes contribute to the perceptual perspective, or point of view, and thus influence tracking. Normally, the body contributes both translational and rotational components of motion. For the prototype model, however, the two sources are uncoupled and it is assumed that the eyes alone provide the angular components. It is sufficient, therefore, to consider only the angular position and angular velocity of the line of sight as projected from the position of the center of gravity.

To begin with, it is clear that the ideal follow movement for the eye is to keep the ball in the center of the fovea at all times. This is the standard against which any special movement is to be measured. Whether anyone is able to attain the ideal is another matter, however. As we saw above, the practice of keeping one's eye on the ball is certainly favored, and some considerable concentration is usually needed to perform the task properly.

But just how close anyone can come to the ideal is a matter of some considerable doubt. There may be a large gap between what is supposed to be seen and what is actually seen. How the eye actually picks up the ball and follows it to the racquet has not been fully explained, if at all. The exhortation to keep one's eye on the ball may be meaningful only to the extent of minimizing distractions. It may mean simply: Don't look to see what your friends at the sideline are doing! It could go so far as to mean one must not even look at one's opponent, as Don Budge believed. But it need not imply that the player must have the ball foveated at all times. Indeed, it could not mean this if the task was impossible. As will be developed below, there is good reason to believe that the moving ball cannot be usefully perceived for roughly the last quarter second of its trajectory, so the matter of foveating it in this interval is irrelevant.

Fortunately, however, the possibility that nobody can attain the ideal in no way diminishes its value as a standard. It is still meaningful to say that the best anyone can do is to keep the ball in the center of view at all times, or at least for as long as he needs to be able to intercept it. One must either do this or fall short of doing it. We can therefore use the construction as a basis for the follow strategy and as a reference to compare players in the skill.

If keeping one's eye on the ball at all times is the reference, what might the recovery strategy be when one falls short of the ideal? What, for instance, does the player do when his line of sight is slightly behind the ball? What procedure might the simulator adopt?

In principle, the processes involved in the movement of the eyes are no different than those involved in the movement of the body. It seems reasonable, therefore, to adopt similar techniques in the simulator. Hence, should the line of sight lag behind the ball, the natural response would be to close the gap; this could be done by speeding up the angular rotation of the eyes. If, on the other hand, the eye should lead the ball, it is only natural to decrease the angular rotation.

The task isn't just that simple, however. More properly, the rate of change of the angle between the line of sight and the line to the ball has to be considered. If the line of sight lags the ball but the angle is closing, a different strategy may be called for. One has first to test what the rate of closing is. This rate may be low, intermediate or high, according to which it would be necessary, say, to speed up, or continue at the same pace, or slow down. If the angle is getting wider, the proper response would seem to be to increase the angular rotation of the line of sight, presuming that the direction of motion isn't negative (i.e., opposite to the direction of motion of the ball). Similarly, if the line of sight leads the ball, the action would seem to depend again on the rate of change of the lead angle. If the angle is decreasing, it would be necessary to see whether the rate was low, intermediate or high, as before. The appropriate decisions might then be to decrease the line of sight rotation rate considerably or a little bit or not at all, respectively. Whereas, if the angle is increasing, the appropriate response would appear to be to decrease the rotation rate.

The tracking or "follow" decision thus depends on whether the eye lags or leads the ball, whether the separating angle is small or large, and whether the angular rate of change is small, intermediate or large. But what magnitudes constitute small, intermediate and large values on these properties?

For the simulator, a small lag or lead is defined as the condition such that the image of the ball is still on the fovea. A large lead or lag would put the image near the perimeter of the retina. And an intermediate lead or lag would put it somewhere in between.

Small, intermediate and large velocities can be defined in a similar way. A low velocity is a just noticeable speed, meaning that the eye rotates at a very low rate; whereas a high velocity pushes the upper limit of the eye's ability to rotate. An intermediate velocity is then somewhere in between. Similarly, just noticeable differences in the rate of separation or closing of the angles are considered small. Angular changes that reach the upper limits of the eye's rotation ability are large. And those in between are intermediate.

The Follow logic can now be defined in terms of the visual limits of the eye. But how is the player's skill to be mechanized? Though the process is not altogether one that is conscious, there is no doubt that some players are better able than others to perform the required eye movements to follow the ball in its flight. This could be simply because some people are better able to monitor their movement circuits and more skillfully reset biases to effect changes as needed. Not all neurological nets have the same reaction time; some are naturally slower than others, so they take longer to correct. But the difference in ability could also be due to the fact that some players have inefficient follow habits, that they haven't learned to use their eyes to the best advantage. In either case, however, whether it is built-in or learned, there is a time delay in the application of the rotation needed to adjust the direction of the line of sight.

In the simulator, this delay can be dealt with as before. It is needed only to add a delay in the start time for a designated correction. Thus if the eyes lag the ball and it is detected that the angle of lag is increasing, for instance, a correction for the line of sight is noted but is not put into effect immediately; the correction is to be held up for a designated period of time -- a specified number of time-slices -- before it is applied.

Another component of this skill is the ability to make the appropriate adjustment when the need is recognized. No matter how quickly corrective action is taken, wrong action is unproductive. It may in fact be counter-productive. For example, if the player's eyes lag the ball and he over-accelerates in an attempt to close the gap, his eyes might suddenly be leading. This could result in an oscillation about the line of the ball. On the other hand, if he is too conservative with his correction, the gap could increase rather than decrease. A particular player's skill level in this regard is determined by his actual acceleration profile. In the simulator, the player subscribes to the above indicated decision logic but tends to over-accelerate and to over-decelerate in his reactions, in a manner similar to that of his body movements.

Before our player can react, however, he must first recognize that some action is necessary. He must be able to read the existing situation. He can only do this to the extent of his ability, of course. He has to be able to see what is happening, and this requires a certain amount of skill. The more skill he has, the more subtle are the distinctions that he can make. The smoother, too, are his follow movements, therefore. It depends on the precision of his coding, to use Welford's terminology.

The ability to discriminate rests on the ability that enables Welford's musicians, dyers and furnaceman to identify their musical notes and colors. It characterizes the level of development of the necessary schemata, to use Neisser's language. The player needs to be able to identify the appropriate local and global trajectory properties. The more refined or precise his signs (codings, schemata), the more subtle his discriminations. The more able he is to differentiate among trajectories and among states of any given trajectory, the more precise is his coding and the more specialized are his responses.

This kind of precision should be incorporated into the simulator if the qualitative aspects of the track and intercept functions are to be represented properly. But how is the process to be mechanized? What standard can be used as a basis for the mechanism and how is skill level to be characterized? The questions ask, in effect, how information is to be coded in the simulator and how the coding can be used to define skill level.

The basis for the answer has already been suggested above. The key is the word 'precision', which refers to the accuracy or to the degree of refinement on some property. By using the notion of a range of value on some scale as a measure of the value of the property, that property value can be said to be more or less precise as the range is narrower or wider. For example, range of frequencies is used to define hue. The more precisely a color is to be specified, the narrower must its range of frequencies be. Using such a device in the simulator, the quality of the player's perception of speed, say, would be given by a range of values of speed on a physical scale. Similarly, his perceived distance would be a range of physical values, the range actually defining the quality.

Differences among trajectories can be characterized in analogous ways. In effect, the set of all trajectories would be partitioned into numerous sub-classes. The trajectories within any given class would be indistinguishable one from the others, but trajectories drawn from different sub-classes would differ from one another in certain significant ways. The manner in which the trajectories are partitioned determines the type of path identification skill. Specification of the skill level, however, is by no means simple and direct, for trajectories may be partitioned in many different ways, each depending on the properties considered to be significant. And significance, in part, is determined by the player's style, strategies, shots and objectives. Fortunately, it isn't necessary to define these levels for the prototype model, since only one very special and highly artificial trajectory is used. The player's skill is thus arbitrarily described.

INTERPLAY OF TRACKING AND INTERCEPTION

When a player tracks an oncoming ball, he does so not for the sake of tracking, as such, but rather because he wants to intercept the ball. He does this by directing his gaze along the trajectory and concurrently moving his body along a path designed to get to the ball before it passes him. In this process he collects information which influences his movements, which in turn alter the information he gets.

But information collection requires schemata; the player must be predisposed to accept certain kinds of information and he must have some idea where to look for it. That is, he has to anticipate what he finds and he has to direct his attention to certain places to find it. An expectation set establishes the nature of the information, and a motor plan guides him in the search.

To say that he tracks the ball, then, is to say he is prepared to see 1) general characteristics of the trajectory, such as the type of shot it is, its general shape and its direction across the court, and 2) special attributes, such as its position and speed at different times. This is a guidance function. The data serves to guide the player along an intercept path and it directs his gaze along the projected trajectory. The continuing movements are made as a consequence of information already received. A schema directs the gaze in anticipation of locating the ball again and accepts additional data made available by the look. Perception is directed by expectations, the schema determines what is picked up, and perception provides information which changes the schema. And the process continues.

But tracking also has a control function. This operation yields information, too, but the data is useful only in maintaining track of the ball. It keeps the line of sight from drifting too far from the line of the ball. Expectation is built up by the track history of the ball; based on the history, the player anticipates the future. But he could be wrong. If he is, his line of sight won't match the line of the ball. A correction is then in order, the type depending on the nature of the mismatch, as noted above.

When the guidance and control functions are combined, an information loop is completed. Based on history of the track, the future state of the ball is predicted. This prediction directs the eye forward. Perception now provides data as to the actual position of the ball, and any deviation of actual from expected values leads to a correction. With the adjustment made, the feedback-feedforward loop is complete and the next cycle begins with a new prediction.

There is an information loop in the intercept movement as well. The track history of the ball, as we have said, serves to guide the player along his intercept path, but so also does the player's own movement affect what he can do next. If for instance he is running at high speed, he can't suddenly be standing still; he must decelerate, and this takes time. If he is following a velocity pattern along a straight-line path as indicated above, and if the expected velocity and position don't match actual values, a correction in profile is necessary for the intercept to occur as desired. The guidance-control cycle is completed as the correction is effected and a new cycle begins.

It is to be noted that the history of the trajectory of the ball in this matter is not independent of the history of the player. What is involved is the relative position and velocity of the ball. The player is running as he looks at the ball. The trajectory as it appears to him is therefore different from what it would be like if he were standing still. We are concerned here with the history of the ball as it relates to the player. The movement of the player is thus a determinant of the expectation of state of the ball and must be so used in the simulator.

This analysis presumes a "central control system" level of display; i.e., the ball environment is presented as a finished product, characteristic of normal experience. Only this level of the complex processes is simulated in the prototype model. Perception is smoothed. The problems of spatial and temporal integration, like those of detection and identification, among others, are left for the future. They are beyond the scope of this first effort, which is to show that a program can be written with a significant degree of realism. The serious questions as to how stimuli at the peripheral sensors are ultimately formed as perceptions and whether and in what form peripheral displays (the analogues to radar displays) are formed, are left to a later time. These aspects of the overall problem are not part of the prototype program.

REPRESENTATION OF THE TRAJECTORY

In the simulator the moving ball is represented both in the objective mode and in the subjective mode. That is, it is given as a physical object moving through space, expressed both in ordinary Euclidean 3-space over the court and in polar coordinates from the perspective of the player; and it is given as a perceptual object in the space of the player, expressed again through the use of polar coordinates.

Consider first the physical trajectory. Because of the short distances involved in the action, we assume the surface of the court to be a Euclidean plane and the gravitational field to be everywhere perpendicular to the plane. It is assumed, further, that there is no spin on the ball and that the aerodynamic drag is zero. The entire path of the ball therefore lies in a plane normal to the surface, the horizontal component of its velocity is constant, and the vertical component is the same as that of a ball thrown into the air and allowed to fall to the ground. The motion is depicted in Figure 10.5.

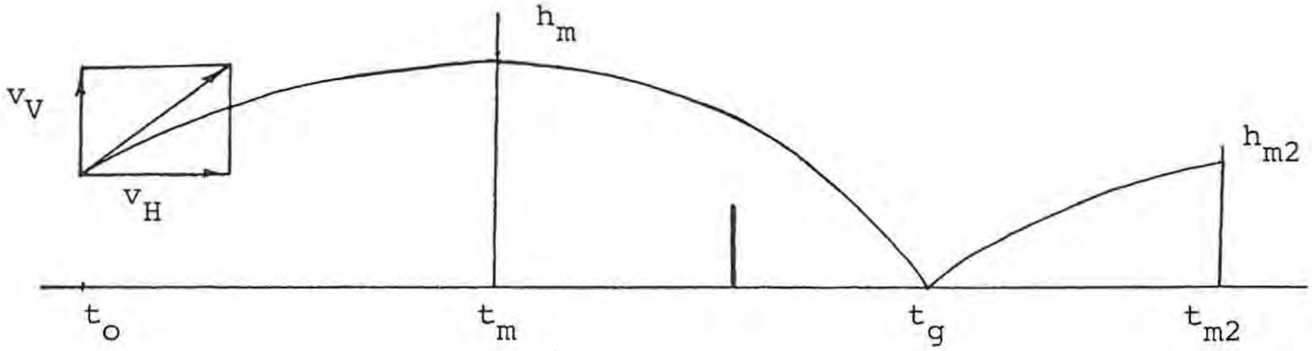


Figure 10.5. Planar motion of ball with no aerodynamic drag or spin moving in a uniform gravitational field.

The drive, as indicated, is presumed to be a (right handed) forehand, cross-court shot, going corner to corner. Let the horizontal component of velocity, v_H, be 60 ft/sec $\cong$ 18.3 m/sec and the vertical component, v_V, be 14 ft/sec $\cong$ 4.3 m/sec at the point of origin of the trajectory. Set the starting height at 4 ft $\cong$ 1.2 m.

The task for the simulator is to determine the position and velocity of the ball at every time-slice, $t + n\Delta t$, where $n = 0, 1, 2, 3, \ldots$ and t is the starting time. Let the 3-dimensional position coordinates be (r,h), where $r = r(x,y)$ is the distance along the path and h is the altitude. Since v_H is constant, the increase in r at each time-slice is the constant, $\Delta r = \Delta t v_H$. The value of h is obtained from the equations

$$s = v_o t \pm \tfrac{1}{2}gt^2,$$

where g is the gravitational acceleration, v_o is the starting velocity, s is the height and t is time. The sign of the gravitational term is + or - according as the vertical component of motion is down or up, respectively.

There are four trajectory segments of possible interest. In the first segment the vertical motion is up and the maximum height, h_m, is reached at time, t_m. Using the equation, $v = v_o - gt$, we can obtain the values for h_m and t_m. Since $v = 0$ at t_m, we have $0 = 14 - 32t_m$, or $t_m = 7/16$. Hence, for the segment from $t = 0$ to $t = 7/16$, the increment of height, Δh, is given by

$$\begin{aligned} \Delta h &= (\Delta h/\Delta t)\Delta t - gt\Delta t \\ &= v_V\Delta t - gt\Delta t. \end{aligned}$$

For the segment from t_m to the time when the ball hits the ground, t_g,

$$\Delta h = v_V\Delta t + gt\Delta t.$$

The value of t_g is obtained after first finding the height at t_m. That is,

$$\begin{aligned} h_m &= v_V t_m - \tfrac{1}{2}gt_m^2 + 4 \\ &= 14(7/16) - 16(7/16)^2 + 4 \\ &= 7.0625 \text{ ft} \cong 2.15 \text{ m}. \end{aligned}$$

Then, from $s = \tfrac{1}{2}gt^2$, we have

$$\begin{aligned} t &= (7.0625/16)^{\frac{1}{2}} \\ &\cong .664 \text{ sec}, \\ t_g &= 7/16 + .664 \\ &\cong .437 + .664 \\ &= 1.101 \text{ sec}. \end{aligned}$$

At t_g the vertical component of velocity is $v_g = 32(.664) \cong$ 21.25 ft/sec $\cong$ 6.48 m/sec. We set the coefficient of elasticity of the ball such that the starting vertical component for the upward segment is 16 ft/sec $\cong$ 4.88 m/sec. The time interval to the maximum height of this segment is obtained from the equivalence, $16 = 32t$. That is, $t = .5$ sec, so $t_{m2} = 1.601$ sec. For this segment the increment of height is determined by the equation

$$\Delta h = v_V \Delta t - gt\Delta t.$$

Since the horizontal component of velocity of the ball is 60 ft/sec, it takes about 79.1/60 $\cong$ 1.3 sec to traverse the trajectory, so the ball will either have been intercepted or gone by the receiver before this segment is completed. A fourth segment is thus not needed.

The starting point of the trajectory is assumed to be at the opponent's right baseline corner, as shown in Figure 10.6. The path is assumed to project to the <u>receiver's</u> right baseline corner. Hence we have

$$x = r \cos\theta$$

and $$y = r \sin\theta,$$

where $$\theta = \text{arc tan } 27/78.$$

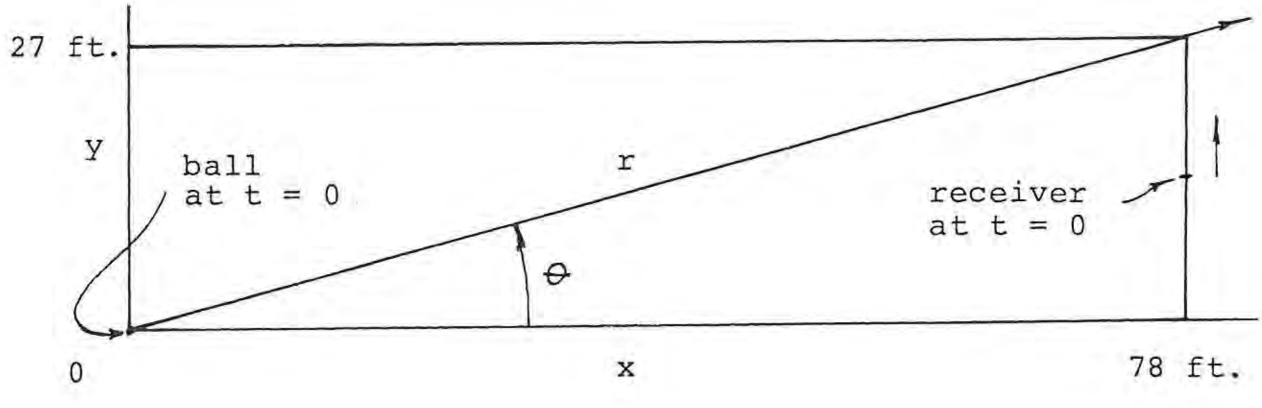


Figure 10.6. Coordinate system of the court.

The starting point of the trajectory is thus $(r,h) = (0,4)$. The starting velocity is $v_o = (v_H, v_V) = (60, 14)$. And the starting time is $t = 0$. By using the above equation set, the values for x, y, r, h, v_H, and v_V can be obtained for every time-slice thereafter.

We must now examine the motion of the ball from the player's point of view. Let us suppose that his position on the court at time zero is center baseline and that his velocity is zero. Consider that he is looking directly at the ball, which is at the origin of the (x, y) coordinate system; as represented in that coordinate system, he is at (78, 13.5).

The visual reference, as mentioned above, is from a point conveniently identified with the player's center of gravity. Using a point source has certain implications, the upshot of which is that we are dealing with a finished perceptual field. That is, it is presumed that radiant energy has already stimulated the retinas, that the neural responses have been processed, that binocular data has been synthesized, and that, basically, a perception is formed as if it were projected from a source between the eyes. The center of this field defines the direction of the line of sight. Motion of the ball in physical space is transformed into movements of this field and characterizes the subjective experience of the player.

The simulator is simplified in another respect as well, namely, that the ball is the only object in the field. The player is presumed not to peek at the boundaries of the court or at his opponent, so there is no need to include the many surfaces of the playing volume in the model. No doubt the player uses some kind of cognitive map to maneuver around the court. He probably uses the boundary line or net, for example, to assist him as he races to intercept the ball. In doing this, likely he relies on processes similar to those involved in establishing his position relative to the ball. In any case, the complexities in simulating the court can be obviated by incorporating the maneuver characteristics into aspects of the ball. The player can then still "know" how to run laterally for an intercept even though there is no reference object in the field.

If the ball is the only projected object, a question naturally arises as to the tactics to be used should the player "lose sight" of it. If the ball goes out of his field of vision, how is he to find it again? The answer is: there is no need. A "follow" tactic that lags or leads the ball to that extent that it can no longer be seen, may simply be interpreted as a poor one. The player's competence level in this respect is considered low.

Confining attention solely to the player's relationship to the ball, then, it is necessary to convert physical properties into perceptual properties and to generate the player's follow and intercept movements. The player, it must be remembered, experiences only qualitative properties. Precise physical quantities have to be converted, therefore, into relatively less precise qualities. As discussed before, the conversion is effected by constructing a range or cluster of values around the indicated quantity. The more subtle the player's ability to discriminate, the narrower the range.

The conversion is by no means straightforward, however, due to the nature of the retina, the link between the objective realm and the subjective realm. On the objective side, the physical object is presumed to move in a three-dimensional space. So too on the subjective side, the <u>perceptual</u> object moves in a three-space. But there is involved in the transformation between the two spheres a contraction of data to a space of <u>two</u> dimensions; the radiant energy reflected from the surfaces of our three-dimensional objects, <u>collapses</u> to the two-dimensional space of the retina. It is probably only because of the translational and rotational movements of the eyes that the perceptual three-space can be constructed; but for this reason, too, this construction must therefore be symbolic.

Needless to say, the retinal two-space is not the perceptual three-space. The tennis ball that the player "follows" with his eyes is the 3-d symbolically projected response, not the 2-d stimulus. Yet the projection occurs as it does because the actual shape of the retinal image matches the shape that one has learned it is <u>expected</u> to have for that projection. It is reasonable, therefore, for the mathematical transformation to collapse 3-d external objects onto the 2-d retinal screen.

To understand the transformation, consider the three components of velocity of a ball at an arbitrary point in its trajectory. In Euclidean space, the velocity can be written as $v = (v_x, v_y, v_z)$, the components configured in (x, y, z) coordinates as shown in Figure 10.7 (a). In the player's perceptual space, however, the components would follow perspective lines and appear more like the configuration shown in Figure 10.7 (b). The problem is to construct the representation in (b) from that in (a), using the retinal two-space as the intermediary.

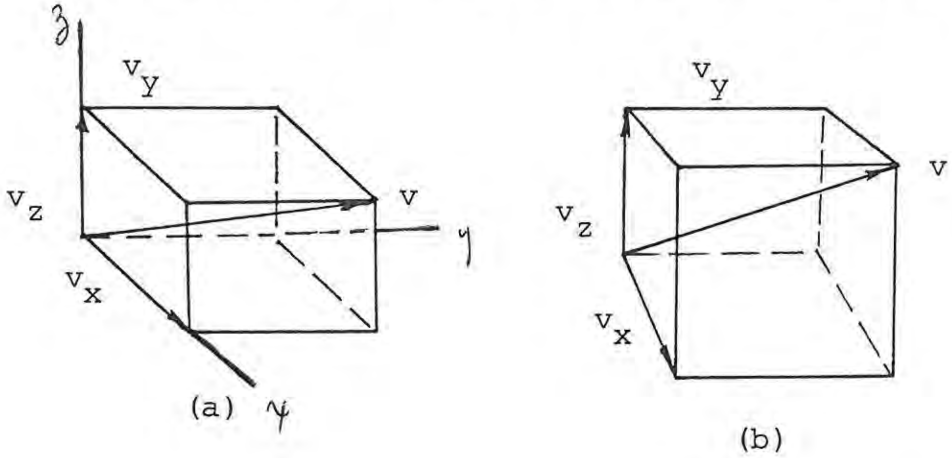


Figure 10.7. Instantaneous velocity components of a moving ball in (a) Euclidean space, and (b) perceptual space.

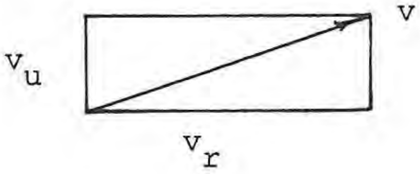


Figure 10.8. Retinal projection of 3-d motion.

If we were to imagine the velocity arrow of the ball being painted on the retina as it evolved, the direction in which the paint application progressed would represent the instantaneous relative motion of the ball. This retinal projection would appear roughly as shown in Figure 10.8, where v_u and v_r label the "up" and "to the right" velocity components, respectively. The image might form to the left, of course, or down. The direction is a function of the angular velocities of the line of sight of the eye and the line to the ball. It would appear to be moving backwards, for example, if the line of sight were catching up with the ball. To effect the transformation, a retinal reference is needed for the up-down motion. But the difficulties can be minimized by assuming that the player maintains an erect posture.

The problem now is to find the angular movements of the eye, using the available information as the basis for the transformation. This means using the position and velocity in physical space for both the ball and the eye. To do this, consider each appropriate component of velocity of the ball as the speed of the rim of a wheel of constantly changing diameter and center, the player being at the center of the wheel. Consider the starting condition of the simulation, to begin with. The ball is presumed to be hit with a horizontal component of velocity, v_H, equal to 60 ft/sec, in a plane running cross-court, corner to corner, and with a vertical component in that plane, $v_V = 14$ ft/sec. The diameter of the wheel is the distance, d, from the player's position at center baseline to the opponent's right corner. That is, from Figure 10.9,

$$d = ((78)^2 + (13.5)^2)^{\frac{1}{2}}$$
$$\cong 79.1 \text{ ft} \cong 24.1 \text{ m.}$$

So the vertical component of angular velocity of the line to the ball $\dot{\alpha}_V(d,v_V) = v_V/d$, becomes

$$\dot{\alpha}_V(79.1,\ 14) \cong .18 \text{ rad/sec.}$$

To find the horizontal component of angular velocity of the line to the ball, $\dot{\alpha}_H$, we must obtain the component of v_H normal to the line from the eye to the ball, as drawn in Figure 10.9. The ball is moving to the player's right at the rate

$$v_r = v_H \sin(\theta - \phi)$$
$$= v_H \sin(\text{arc tan}(27/78) - \text{arc tan}(13.5/78))$$
$$\cong 60(.17) \cong 10.2 \text{ ft/sec} \cong 3.1 \text{ m/sec.}$$

So the horizontal component of angular velocity, $\dot{\alpha}_H = v_r/d$, is

$$\dot{\alpha}_H(79.1,\ 10.2) \cong .13 \text{ rad/sec.}$$

The vertical and horizontal components of the angular velocities of the line of sight, $\dot{\beta}_H$ and $\dot{\beta}_V$, are computed by adopting the designated competence level of the player's "follow" strategy. For the starting condition of the simulator it has been assumed that his gaze is directed at the opponent's right baseline corner (i.e., at the ball) and that the angular velocity of the eye is zero. For the first time-slice, then,

$$\dot{\alpha}_V - \dot{\beta}_H = \dot{\alpha}_V = .18 \text{ rad/sec}$$

$$\dot{\alpha}_V - \dot{\beta}_H = \dot{\alpha}_H = .13 \text{ rad/sec.}$$

The simulation thus begins with the line of the ball already moving away from the line of sight. Because of the built-in delay in the player's neural "circuits," an even greater lag will occur before compensatory movements begin.

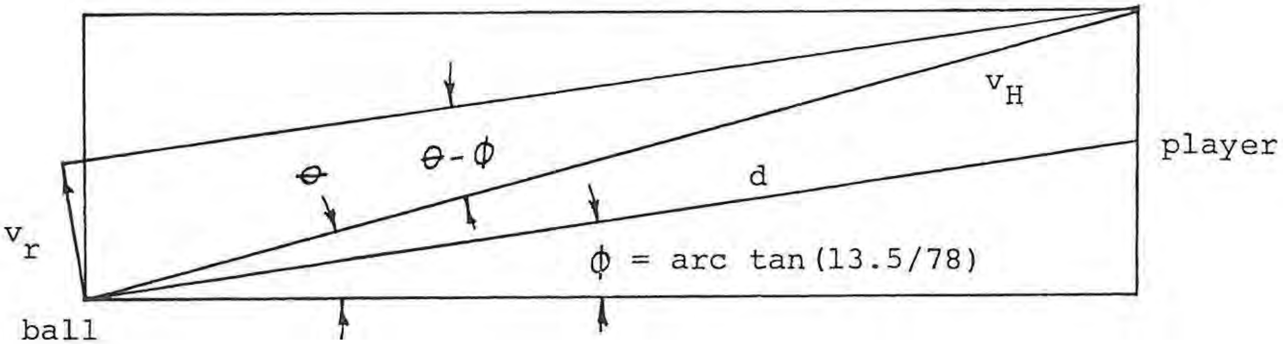


Figure 10.9. Components of v_H about line from player to ball.

The player's strategy, as indicated, is simply to "close the gap," which means that the eye must be rotated to put the ball in the center of the field of vision. That is, $\dot{\beta}_V$ and $\dot{\beta}_H$ must be driven to send both $(\dot{\alpha}_V - \dot{\beta}_V)$ and $(\dot{\alpha}_H - \dot{\beta}_H)$ to zero.

Affecting the drive are the player's competences: He has to be able to detect an information difference (sensitivity to the properties of the ball-environment), his circuits have to be tuned to respond to the differences he perceives (delay), the future state of the trajectory has to be estimated (prediction), an acceleration to overcome the difference has to be calculated (feedforward computation), and he has to execute the drive (reaction time) by the application of a corrective action.

These characteristics are simulated, respectively, by: constructing an equivalence class of values for each quantitative value, imposing a time-slice delay on responses to perceived differences, applying linear dead-reckoning to trajectory using average velocity of trajectory, extending current line-of-sight rate to estimate angle and angle rate differences and from them obtaining decision from logic table, applying time-slice delay for reaction time, and driving the line-of-sight with a corrective acceleration.

In order to effect this continuing loop of information processing, it is necessary to have a general relationship between the perceptual aspects of the situation and the physical aspects. It is necessary, first, to establish the distance, d, in general. The geometry is shown in Figure 10.10. The values for the position of the ball and the player are presumed to be known; they will have been computed in the previous time-slice. The ball will be at the distance (82.5 - r) ft from the player's baseline corner, and the player will be at a point (13.5 + s) ft from his left baseline corner. The distance, d, is therefore given by the expression

$$d = ((78 - r\cos\theta)^2 + (13.5 + s - r\sin\theta)^2)^{\frac{1}{2}}.$$

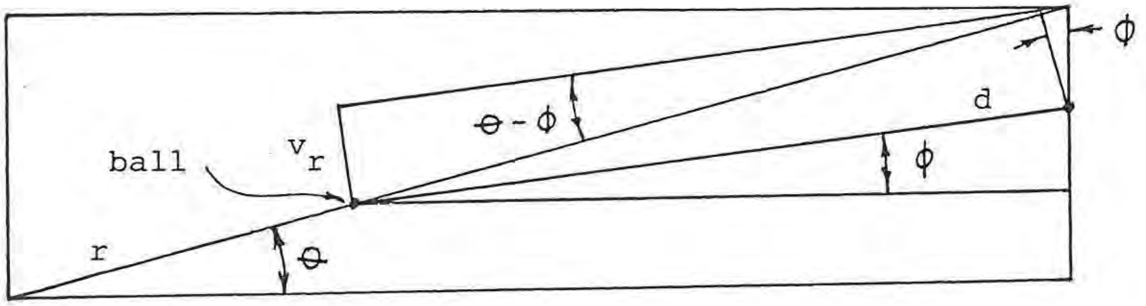


Figure 10.10. General relationship between ball and player.

In order to compute the horizontal component of the angular velocity of the line to the ball, the player's own movement has to be taken into account; his motion across the court modifies the apparent velocities. As can be seen in Figure 10.10, the player's velocity, v_p, is at an angle, ϕ, relative to the direction of v_r, the horizontal rim speed (using the wheel analogy). The projected value of v_p onto the rim speed is when $v_p \cos \phi$, and the rim velocity, itself, expressed in terms of the horizontal velocity is

$$v_r = v_H \sin(\theta - \phi).$$

So the actual horizontal component of angular velocity is

$$\begin{aligned}\dot{\alpha}_H &= (v_r - v_p \cos \phi)/d \\ &= (v_H \sin(\theta - \phi) - v_p \cos\phi)/d \\ &= (v_H \sin(\text{arc tan } (27/78) - \text{arc tan} W) \\ &\qquad - v_p \cos(\text{arc tan} W))/d,\end{aligned}$$

where $w = (13.5 + s - r\sin(\text{arc tan}(27/78)))/(78 - r\cos(\text{arc tan}(27/78)))$.

To compute the vertical component of the angular velocity, the simulator has to select the appropriate set for the given trajectory segment equations. For the first segment, the position and velocity are given by

$$\begin{aligned}s &= 14t - 16t^2 + 4 \\ v &= 14 - 32t.\end{aligned}$$

For the second segment, the equations are

$$\begin{aligned}s &= h_m - 16t^2 \\ v &= 32t.\end{aligned}$$

And for the third,

$$\begin{aligned}s &= 16t - 16t^2 \\ v &= 16 - 32t.\end{aligned}$$

Using the appropriate equation for v_V, the vertical component of angular velocity is given by

$$\dot{\alpha}_V = v_V/d.$$

Had the actual rather than the horizontal distance to the ball been used, the correct rim speed to apply would have been

$$v_{d'} = v_V/\cos\mu$$

and the correct distance would have been

$$d' = d/\cos\mu,$$

so that

$$\dot{\alpha}_V = v_{d'}/d' = (v_V/\cos\mu) \; / \; (d/\cos\mu) = v_V/d,$$

which is the same as before. μ is the angle of inclination of the line of the ball with the horizontal, as shown in Figure 10.11.

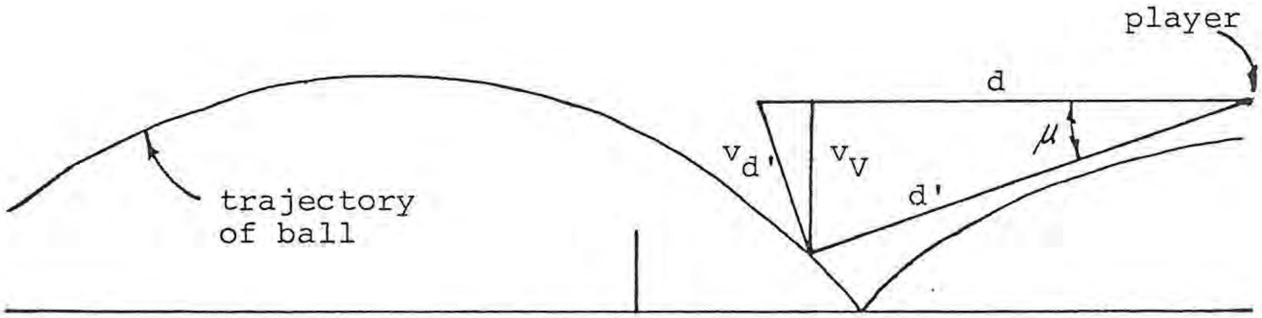


Figure 10.11. Angular acceleration of line to the ball using actual or horizontal distance to the ball.

It is necessary now to obtain the horizontal and vertical components of the angular position of the line to the ball. For reference, we take the "zero" position to be the horizontal line from the player drawn normal to the net. Deviations up and to the right from that position (from the player's point of view) are positive, while those down and to the left are negative.

Referring to Figure 10.12, the horizontal angle is given as

$$\alpha_H = \text{arc tan}(y - 13.5 - s) \; / \; (78 - x)).$$

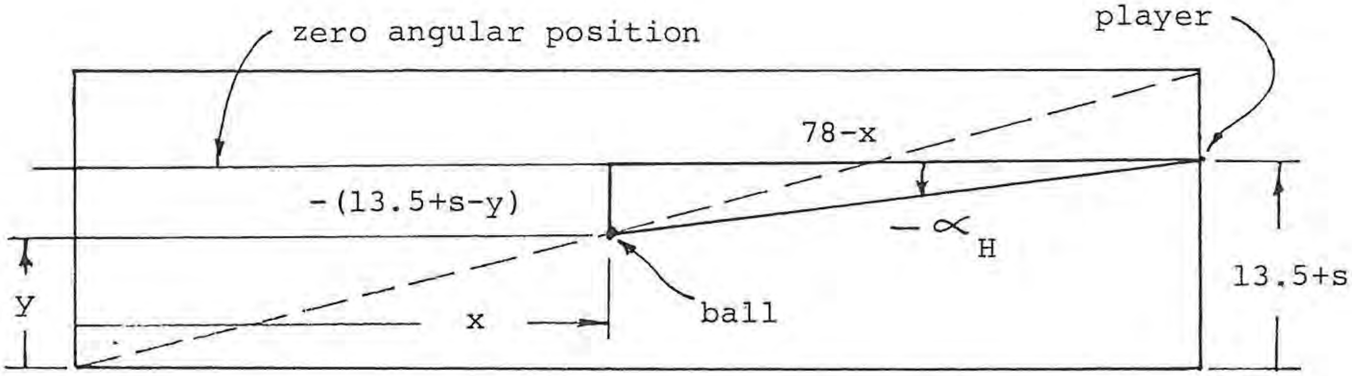


Figure 10.12. Horizontal component of angular position.

Similarly, from Figure 10.13, the vertical component can be seen to be

$$\alpha_V = \text{arc tan}((h - 5)/d),$$

where

$$d = ((78 - r\cos\theta)^2 + (13.5 + s - r\sin\theta)^2)^{\frac{1}{2}}$$

$$= ((78 - r\cos(\text{arc tan}(27/78)))^2 + (13.5 + s - r\sin(\text{arc tan}(27/78)))^2)^{\frac{1}{2}}.$$

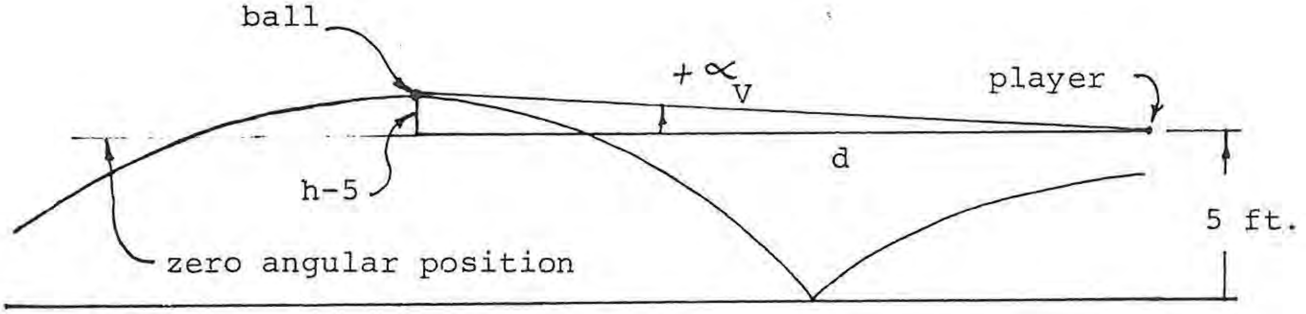


Figure 10.13. Vertical component of angular position.

TRACKING MOVEMENT

To devise a detailed strategy of the player's eye movement in following the ball, we use the notation $\beta_H, \beta_V, \alpha_H$, and α_V to identify the horizontal and vertical angles for the line of sight and for the line to the ball, respectively. Suppose, first, that the line of sight lags the ball by the angle, γ_H, in the horizontal direction; that is,

$$\gamma_H = (\alpha_H - \beta_H) > 0.$$

If the lag is small, it seems reasonable for the player simply to continue his present action. For an intermediate size lag he should perhaps accelerate slightly. Finally, if he has a lot of ground to make up, his acceleration should be quite large.

On the other hand, if his eye leads the ball, i.e., if

$$\gamma_H = (\alpha_H - \beta_H) < 0,$$

he should make small changes if the angle is small, decelerate slightly more for a medium size angle, and decelerate even more for a large angle.

This strategy would appear to be sound when $\dot{\beta}_H \cong \dot{\alpha}_H$. But suppose that $\dot{\beta}_H$ is much greater than $\dot{\alpha}_H$ -- meaning that the angular velocity of the line of sight is much greater than that of the line of the ball. Now if his eye leads, it seems the player should decelerate his line of sight even if the angle is small, for otherwise he will soon be ahead of the ball. And if his eye lags, he might still be better off to decelerate, to avoid a large overshoot. Similar considerations apply to other combinations of values.

Had we not presumed a "central control system" display for the simulation, another factor would have to have been taken into account: Any single data input must suffer from unreliability; there are simply too many physiological mechanisms and too many perceptual-motor skills involved in the process to believe that adjustments on the raw stimuli for each and every movement that occurs can take place without error. A smoothing of these data, on the other hand, tends to reduce the errors. In the simulator this complex operation is obviated; the perceptual model is considered to be smoothed and unbiased. Use of such a model doesn't eliminate player errors, however. A smoothed picture is less chaotic, more orderly than an unsmoothed representation of the facts and therefore more amenable to reasonable decision-making. But the player's skills are still short of ideal development. Errors are still possible. Tracking disruptions or intercept failures can still occur.

In the simulator the values for β, α, $\dot{\beta}$, and $\dot{\alpha}$, as well as those for d, x, y, r, θ, ϕ and others, are known precisely; these quantities reflect the objective facts of the playing situation; they identify exactly what the player does. His own judgement, however, is less precise; his decision-making is more intuitive -- he has no time-outs for computations. In the simulator, these subjective values are expressed as clusters of values on the objective quantities; they are equivalence classes on the quantities.

For instance, if the precise distance to the ball at some time, as it is measured in physical space, is 19.1 ft, the player might have an idea that the distance is "about 20 ft." The line of sight, viewed on the 'objective side,' might lag by .07 radians; on the 'subjective side' it could be seen as "very small." Or, the required acceleration could be 8.3 ft/sec/sec; the player might think he has to "speed up a bit."

For the sake of simplicity, each cluster in the first program will be formed by bracketing a given quantity with a range of values equal to plus or minus 5% of the quantity. Hence, the physical distance, 20 ft, will be "seen" by the player to be the quality "19 to 21 ft." (Unfortunately, there are few, if any, names for these qualities.) The angular difference, $\alpha - \beta$, likewise, has the quality: $((\alpha \pm 5\%\alpha) - (\beta \pm 5\%\beta)) = ((\alpha - \beta) \pm 5\%(\alpha + \beta))$. And $(\dot{\alpha} - \dot{\beta})$ goes into $((\dot{\alpha} - \dot{\beta}) \pm 5\% (\dot{\alpha} + \dot{\beta}))$.

To tie angular values to properties of the eye, a small lag (lead) can be defined as a condition such that the image of the ball is still on the fovea. A large lag (lead) would put it near the perimeter of the retina. And an intermediate lag (lead) would put it somewhere in between. Small, intermediate and large velocities can be defined in a similar way. A low velocity would be a just noticeable speed, meaning that the eye rotates at a low rate. A large velocity pushes the upper limit of the eye's ability to rotate. And an intermediate velocity is somewhere in between.

To determine the player's eye movement, a desired value at which the eye should accelerate has to be computed. Given estimates of the impending change in the angular position and velocity of the line to the ball, which can be obtained by projecting forward the latest values on these qualities, the expected changes in lag or lead can be obtained and added to the current lag or lead. Based on these adjusted requirements, the desired increase or decrease in the angular velocity of the player's line of sight can be computed. The extent of the adjustment depends on whether γ (the lag or lead) is small, medium or large and whether $\dot{\alpha} - \dot{\beta}$ is small, medium or large. Both the horizontal and the vertical components of these qualities have to be considered.

For the prototype model, the maximum values for the horizontal components of the velocity of the line of sight and the angular difference between the line of sight and the line to the ball are assumed to be:

$$\gamma_{\text{Hmax}} = 1.1 \text{ rad}$$

$$\dot{\beta}_{\text{Hmax}} = 2 \text{ rad/sec.}$$

The qualities: small, medium and large on these properties are then defined as in Table 10.1.

	Small	Medium	Large
γ_H	0 to .18 rad	.18 to .9 rad	.9 to 1.1 rad
$\dot{\beta}_H$	0 to .3 $\frac{\text{rad}}{\text{sec}}$	.3 to 1.6 $\frac{\text{rad}}{\text{sec}}$	1.6 to 2 $\frac{\text{rad}}{\text{sec}}$

Table 10.1. Meaning of qualities: small, medium and large on velocity and angular difference of LOS.

Now let small, medium and large accelerations of β_H be defined as 5, 10 and 20 rad/sec/sec, respectively. For 10 ms time-slices this means that the horizontal component of angular velocity, $\dot{\beta}_H$, can increase by 1 rad/sec in 20, 10 and 5 time-slices, respectively.

To develop in detail the acceleration logic, note that $\alpha_H - \beta_H$ can be positive or negative, or small, medium or large, or zero.

Similarly, the relative velocity, $\dot{\alpha}_H - \dot{\beta}_H - \Delta\dot{\beta}_H$, where $\Delta\dot{\beta}_H$ is corrective increment of velocity, may have these values. For example, if the line of sight lags by a small amount, then $\alpha_H - \beta_H$ is positive, small. If the angular velocity of the line of sight is much greater than that of the line of the ball, then $\dot{\alpha}_H - \dot{\beta}_H - \Delta\dot{\beta}_H$ is negative, large.

Suppose, now, that the weights: 0, 1, 2, and 3 are assigned to the qualities: no noticeable difference, small, medium and large, respectively. By so doing, it turns out that the sum of the weights for the respective pairs defines the acceleration to be applied when this combination occurs.

For example, if the player's line of sight lags far behind the ball (+3) and his angular velocity is slightly larger than that of the line of the ball (-1), the sum is +2, which represents medium acceleration. For a medium lag (+2) and slightly smaller angular velocity (+1), his decision would be to accelerate to the maxium (+3). Again, if his eye leads by a medium amount (-2) and the angular velocity is relatively large (-3), he must decelerate to the maximum (i.e., $-2 -3 \leq -3$). In general, if the sum is positive, he has to accelerate; if it is negative, he decelerates. If the absolute magnitude of the sum is 1, the velocity drive is small. If the value is 2, the action is intermediate. If it is three or more he drives to the maximum. And if it is zero, he makes no changes. The sign of the sum identifies the direction in which the velocity drive is to be made. These logical conditions are summarized in Table 10.2.

A similar strategy can be defined for driving the vertical component of the angular velocity. In the real world there are differences in capability between the vertical and horizontal movements, but for the prototype model it is assumed that the competences are the same. The acceleration rates for β_V are thus 5, 10, and 20 rad/sec/sec, as they are for β_H. The decision logic therefore has the same pattern. For both the horizontal and vertical movements, then, the logic table defines the procedural standard for the simulation, and the player's interpretation of the properties (i.e., the way he "sees" the qualities; the range he allows for each of small, medium or large) defines his schemata for this action. Since the selection of a competence level is somewhat arbitrary for the simulator, it is assumed that the player operates at standard.

His response to the properties is not assumed to be immediate, however. There is a time delay, reflecting his competence level in this specific regard. For purposes of simulation, a three time-slice response is assumed initially. That is, for a given condition in the i^{th} time-slice, the response is not initiated until the $(i+3)^{rd}$ time-slice. For example, if a correction for angular lag is determined for the 45th time-slice, the correction won't be allowed to occur until the 48th time-slice. At that time the appropriate values of acceleration from Table 2.2 will be applied.

Line of Sight
(Lag, +; lead, -)

Angular Velocity (LOS) (Less, +; More, -)	0	1	2	3	-1	-2	-3
0	0	1	2	3	-1	-2	-3
1	1	2	3	3	0	-1	-2
2	2	3	3	3	1	0	-1
3	3	3	3	3	2	1	0
-1	-1	0	1	2	-2	-3	-3
-2	-2	-1	0	1	-3	-3	-3
-3	-3	-2	-1	0	-3	-3	-3

Table 10.2. Acceleration strategy for tracking correction. (Inputs relative to line of ball)

INTERCEPT MOVEMENT

As already indicated, our prototype simulator uses two standards to characterize the intercept movement. One standard defines the direction of motion and uses a straight-line path parallel to the net to guide the player. It is presumed that the player interpretes the standard flawlessly; his competence level is perfect and he follows the line without error. Later programs may incorporate practices which are less than ideal; the player may be allowed to drift, for example. But for this first version there is insufficient gain in principle to warrant the additional complication.

The second standard gives an ideal velocity profile to be adhered to. In this instance, the player's behavior is less than perfect. While the standard frames his action around a best velocity structure for any given distance- and time-to-go before intercept, his motor plan falls short of ideal and he tends to over-react, resulting in speeds and rates of change that are higher than necessary.

For the given trajectory, when the ball is hit the player has 13.5 feet minus the length of his arm-racquet system, or a net distance approximately 10.5 ft = 3.2 m to run, and he has $((27)^2 + (78)^2)^{\frac{1}{2}}$ ft/60 ft/sec = 1.36 sec to do it in. At any moment thereafter, the distance and time remaining clearly depend on his average speed to that moment. The distance remaining for him to run is

$$s_g = 10.5 - s$$

and the time-to-go is

$$t_g = 1.36 - t,$$

where s is the distance along the straight-line path the player has to run and t is the time that has passed. For the remainder of the path to intercept, therefore, the average velocity of the standard profile must be

$$v_a = (10.5 - s)/(1.36 - t),$$

if the player is to reach the ball.

Projected from the starting conditions, where $t = s = 0$, the average velocity has the value $10.5/1.36 \cong 7.7$ ft/sec $\cong 2.3$ m/sec. If ½ sec is allowed for the time needed to accelerate to maximum velocity, v_m, and .36 sec for deceleration to a manageable hitting speed (a running speed at which the ball can still be hit reasonably well), say $v_m/3$, a profile for the 1.36 sec run can be constructed as in Figure 10.14.

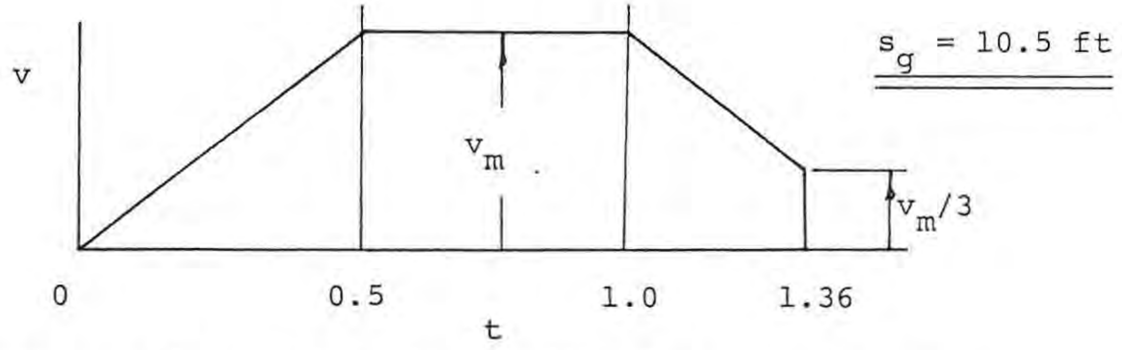


Figure 10.14. Velocity profile for intercept run.

Expressing the average velocity over the run in terms of the velocities of the profile, we can compute v_m. That is,

$$v_a = \frac{.5v_m/2 + .5v_m + .36(v_m + v_m/3)/2}{1.36}$$

$$= .99v_m/1.36 \cong .73v_m.$$

But v_a has already been computed to be 7.7 ft/sec, so

$$v_m = 7.7/.73 \text{ ft/sec} \cong 10.5 \text{ ft/sec} \cong 3.2 \text{ m/sec.}$$

The player's action, now, does not match this profile exactly; as already indicated, he tends to over-react. To simulate this over-reaction, the actual profile is projected for a run at a higher maxium velocity. The player is thus shown to accelerate more than necessary and then to decelerate more in order to compensate for the excess speed. We therefore set his competence level in this skill by assuming that he overaccelerates to a maximum velocity equal to 115% of the ideal maximum. His maximum for the first projection is thus (1.15) (10.5) = 12.08 ft/sec = 3.7 m/sec, and in general,

$$v_{pm} = kv_m, \text{ for some value } k.$$

So long as the player's "motor plan" matches the profile exactly, he is moving at the "best" velocity for the given situation. That is, his velocity is as it should be for the remaining time- and distance-to-go. He will have run a distance

$$
\begin{array}{lll}
 & s = vt/2 & \text{if } t \leq .5, \\
\text{or} & s = .5v_m/2 + (t - .5)v_m & \text{if } .5 < t \leq 1.0, \\
\text{or} & s = .5v_m/2 + .5v_m + (t - 1)(v_m + v)/2 & \text{if } 1 < t \leq 1.36,
\end{array}
$$

where v is the profile velocity at the specified time, t, for the distance, s_g.

However, if he realizes that he has failed to match the profile and may miss the intercept should he continue as scheduled, he will have to alter his plan. In other words he must adopt a new standard, or profile segment, for the remainder of the path to intercept. In the prototype model this standard takes the form shown in Figure 10.15. But like the old plan it must still satisfy the condition that $v_p = 12.08/3 \cong 4.03$ ft/sec $\cong$ 1.23 m/sec at $t_g \approx s_g = 0$.

Clearly, the player has to move faster, on average, to reach an intercept point in a given time if he has farther to go, and slower on average if he has less far to go. When our player sees that he is too close to the ball for the plan in effect to succeed, he either stops accelerating if he is in the acceleration mode, or decelerates to the maximum possible value if he is in the constant velocity mode. Otherwise, he has no choice.

On the other hand, if he happens to detect that he will not reach the ball in time continuing with the present plan, he can either accelerate to a higher maximum velocity than planned if he is in the acceleration mode, or decelerate at the smallest possible rate if he is in the constant velocity mode. These are his only options.

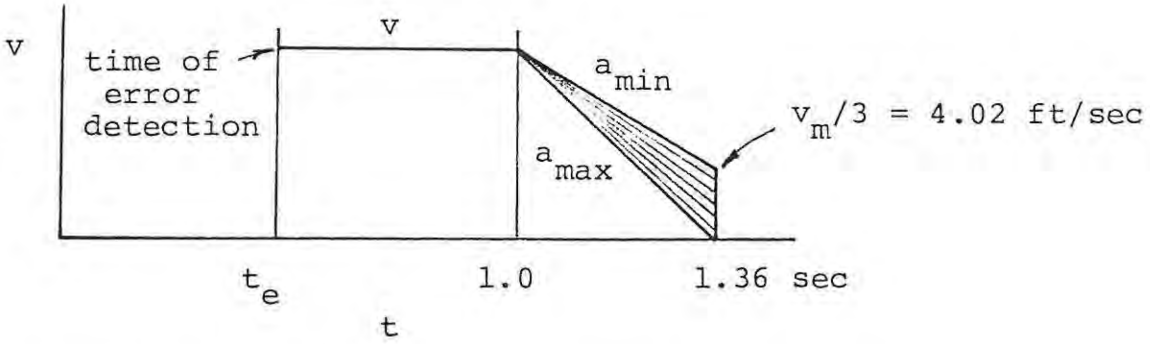


Figure 10.15. Optimum path segment for specified distance-to-go and time-to-go to intercept.

The player's deceleration is constrained to lie either at the maximum, defined by

$$a_{max} = \frac{v_{pm}}{1.36 - 1.0} = \frac{12.075}{.36} \cong 33.5 \text{ ft/sec/sec} \cong 10.2 \text{ m/sec/sec},$$

or at the minimum,

$$a_{min} = \frac{v_{pm} - v_{pm}/3}{1.36 - 1.0} = \frac{12.075 - 4.025}{.36} \cong 22.4 \text{ ft/sec/sec} \cong 6.8 \text{ m/sec/sec}.$$

Failure to reach the ball properly within these constraints constitutes a missed intercept.

To attain an intercept, the velocity must be such that the average over the remaining segment lies between the maximum,

$$v_{amax} = \frac{v(1.0 - t_e) + (v + 4.02)(1.36 - 1.0)/2}{1.36 - t_e} = \frac{v(1.0 - t_e) + .18(v + 4.02)}{1.36 - t_e}$$

$$= \frac{v(1.18 - t_e) + .72}{1.36 - t_e},$$

and the minimum,

$$v_{amin} = \frac{v(1.0 - t_e) + v(1.36 - 1.0)/2}{1.36 - t_e}$$

$$= \frac{v(1.0 - t_e) + .18v}{1.36 - t_e}$$

$$= \frac{v(1.18 - t_e)}{1.36 - t_e}.$$

Since $v_a = (10.5 - s)/(1.36 - t_e)$, we have either

$$v_{amax} = \frac{v(1.18 - t_e) + .72}{1.36 - t_e} = \frac{10.5 - s}{1.36 - t_e},$$

in which case

$$v(1.18 - t_e) + .72 = 10.5 - s,$$

so that

$$v = \frac{9.78 - s}{1.18 - t_e};$$

or

$$v_{amin} = \frac{v(1.18 - t_e)}{1.36 - t_e} = \frac{10.5 - s}{1.36 - t_e},$$

in which case,

$$v = \frac{10.5 - s}{1.18 - t_e}.$$

Therefore, if the player is to effect an intercept, his velocity during the constant velocity mode of the profile must lie in the range

$$\frac{9.78 - s}{1.18 - t_e} \leq v \leq \frac{10.5 - s}{1.18 - t_e}.$$

CHAPTER 11

DESIGN OF THE PROGRAM

The visuo-motor processes in tennis are tightly interwoven. The player perceives the moving ball and in anticipation of its future state rotates his eyes to pick up more information about it while at the same time moving his body to intercept it. These movements in physical space alter his perception even as the ball is changing state. The information changes and his perception changes, so the effect is to alter his anticipation schemata and the accompanying anticipatory behavior. That is, he perceives the moving ball and imagines where it will go next and how he should move his eyes and body to deal with it. The resulting movements alter his perspective in space so his perception changes; meanwhile, the ball has taken a different position and velocity. This alters his image of where the ball will go next and how he should react to it.

This cyclic process is simulated in the program by using operational time-slices, like frames of a cine film. At each moment it loops through a sequence of instructions depicting the process, picking up data from the prior moment and updating it. Operations are performed to represent the motion of the ball, the movement of the player along his intercept path and the movement of the player's eyes as they track the ball.

The idea is to represent these activities from the standpoint of the player. But the program also simulates the public, or objective point of view. The position and velocity of the ball as well as the position and velocity of the player (in court coordinates) and the player's line of sight, the distance from him to the ball and the angle of the line to the ball (in polar coordinates), are aspects of this objectivity, expressed mathematically.

Subjective aspects of the movements are symbolized through the player's interpretation of the trajectory of the ball, by "qualitative" estimates of the distance, angular position and angular velocity of the ball, by estimates of the angular position and velocity of his line of sight, and by estimates of his own position and velocity along the intercept path as well as that of the time and the distance- and time-to-go to intercept.

The movements are effected via the use of <u>plans</u> which guide the player's actions and maintain control over their detailed functioning through the use of information feedback and feed-forward loops. In the simulator they are represented objectively as formal standards and strategies interpreted at the competence level of the player. Measured on a "public"scale of such plans, our player's interpretation falls short of the best; his standards, in general, lack perfect clarity and his execution of the strategies suffers from imprecision. In other words he is not a perfect player.

To begin the program it is necessary to have starting data. The ball is presumed to have just been released from the opponent's racquet from his right baseline corner with an initial velocity directed cross-court. The player is presumed to be standing at center baseline and directing his gaze at the ball in its corner position. Assuming further that he has observed the opponent swinging his racquet at the ball, we can say he has begun to build up anticipatory behavior, i.e., that he is preparing to move in a certain direction and that he is getting ready to move his eyes. <u>The direction is specified as a starting condition expressed by means of a starting acceleration</u>. However, the position and velocity of both the player and his line of sight are considered to be zero. Because of an inherent delay in his response and a less than perfect reading of the trajectory, he remains immobile for several time-slices before the acceleration takes effect.

In the $i^{\underline{th}}$ (or arbitrary) time-slice the program updates the position and velocity of the ball in physical space and transforms these values into angular position and velocity of the line to the ball. A precondition for this computation is an update of the position and velocity of the player, since a change in perspective is involved. These values are updated using the intercept strategy in effect at the previous time-slice.

The player's current position and velocity are used as well to determine the angular position and velocity of the line of sight, based on the tracking or "follow" strategy in effect at the previous time-slice. With this data he can decide where next to direct his gaze and at what angular rate, and how fast to run for the intercept point. These responses are carried out in accordance with the level of his skills, which encompass his ability 1) to perceive appropriate attributes of the moving ball, such as its distance and angular velocity, 2) to gauge his own position and velocity, or more specifically, his distance- and time-to-go to intercept and his current velocity, 3) to discriminate differences in angular position and angular velocity between his line of sight and the line of the ball, and 4) to estimate the linear and angular accelerations needed to change the state of his line of sight and the state of his center of gravity.

To determine his tracking response, the player must interpret the position and velocity differences between his line of sight and the line to the ball. However, because of reaction time and a certain degree of refractoriness in his movements, if the response is to be appropriate at the time it becomes effective, some measure of prediction is necessary. Thus he must anticipate the state of the trajectory in the future and adjust the position and velocity differences accordingly. Based on this adjusted difference and his "feeling" for the categories defining the character of the differences (i.e., whether they are small, medium or large), he applies decision logic which generates the desired acceleration or deceleration. His interpretation of the categories of acceleration (i.e., whether, again, they are small, medium or large) then determines the nature of the drive on his line of sight. From this "qualitative" response the simulator computes its quantitative correlate -- the"objective" counterpart of the motion of the line in physical space.

To define the player's "intercept" response, a cognitive map or motor plan is simulated. This plan has two components, as indicated above: The first part identifies the route to be taken by him -- a straight line path parallel to the net; the second identifies his velocity profile along the path. It is presumed that the straight line path is followed perfectly but that his use of the profile is less than best.

For a given distance- and time-to-go, the player projects a desired velocity schedule for the remaining segment of the path to intercept. As he runs, he estimates his distance- and time-to-go and compares his actual velocity with the desired velocity for that position-time circumstance. If the difference is small he continues with the plan in effect; otherwise, he adopts a new plan. The magnitude of acceptable error is taken to be a function of the distance- and time-to-go, though initially only as a constant function.

It is evident that the player's selection of a velocity profile is contingent on his reading of the trajectory of the ball, for otherwise the estimate of a distance- and time-to-go is without meaning. The ball is moving in a certain way and the player has to adjust to that motion. He predicts where the ball is going and then "adjusts" to the trajectory by matching his own movements to it. Based on his projection of a match with the predicted trajectory, he estimates the distance- and time-to-go to intercept and anticipates a velocity profile capable of effecting the intercept. The action that he takes generates a new relationship to the ball and this leads to a new prediction of trajectory and a new projection of behavior. Thus the data at one moment are used to update the data at the next moment.

TIMING OF EVENTS IN THE LOOP

Probably the most difficult and least well understood aspect of the visuo-motor processes is the mechanism of scheduling, or interleaving, its various components. This is the problem of timing, whereby the components are brought into play in proper

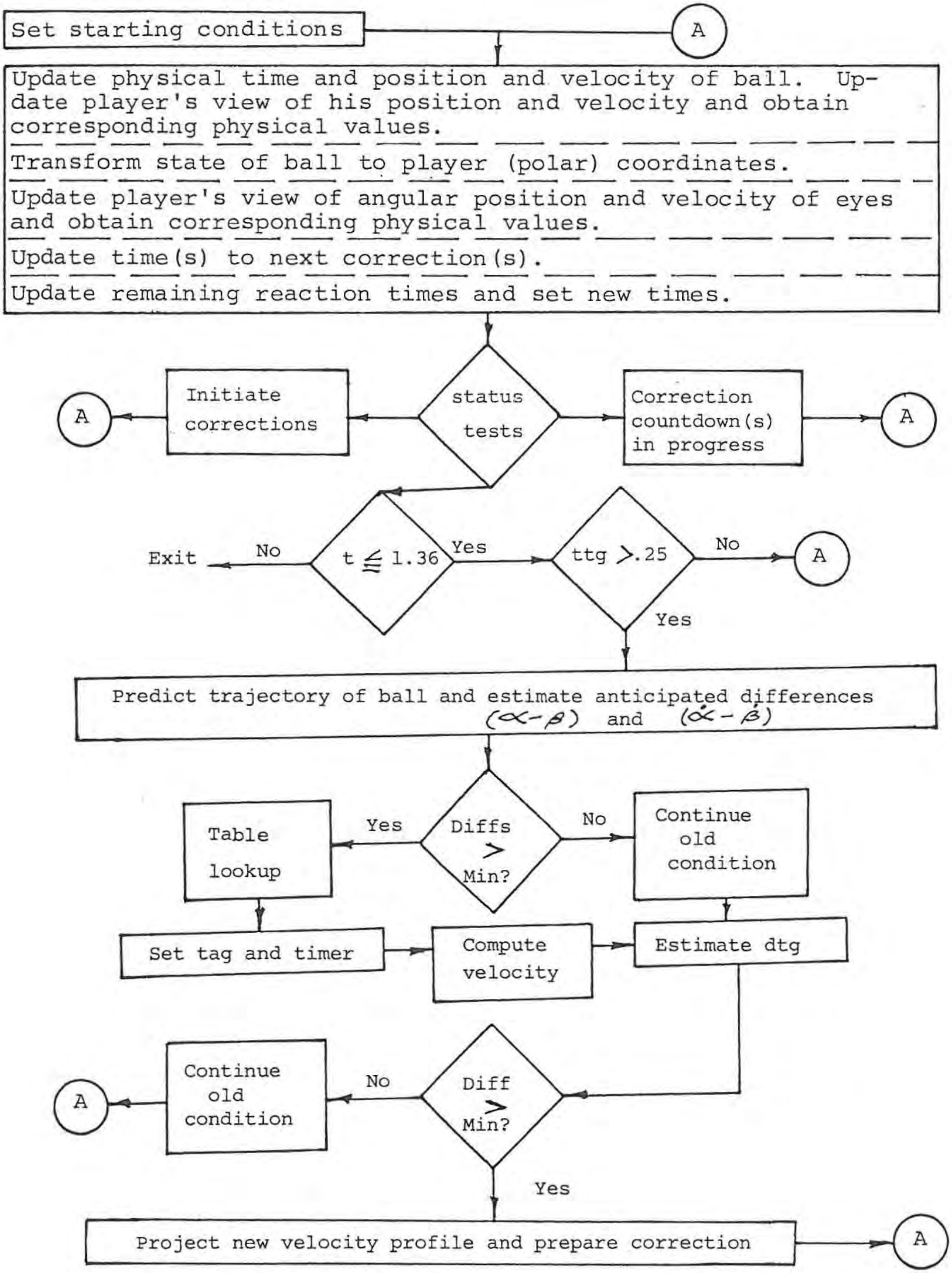


Figure 11.1 Schematic of program flow for $i^{\underline{th}}$ time-slice.

order and at appropriate moments. It is the problem that was discussed in the previous section, namely, coordinating the track and intercept movements with information gathering and decision-making under the constraint of multiple reaction times and the refractory nature of the system. Indeed, it is the problem which must be formulated precisely if a simulator is to be developed. By the same token, a simulator is an ideal vehicle for studying the effects of various combinations of reaction times, reflecting divergent skills in this regard.

For the prototype model, the so-called single-channel hypothesis is assumed to be valid. Reference here is to the capacity of the translation mechanism to deal with only one signal, or one group of signals, at a time. Applied to the tracking and interception problem, this view implies that signal processing is concurrent with the associated movements, because these movements appear to be continuous. But this means that the movements are ballistic (visually open loop) for the period of time that lapses before they can be "adjusted" in accordance with relevant feedback information. That is, they are active during the time that data are collected and the new decision made. As to the length of the ballistic movements, this will be determined in the simulator by the (somewhat arbitrary) delay assignments made to the pertinent functions and by the degree of refinement of the awareness of errors ascribed to the player, factors individually reflecting particular skill levels.

To represent the organization of events, the information flow diagram given in Figure 3.1 is transformed to that shown in Figure 11.1, which identifies the operations to be executed in the $i^{\underline{th}}$ time-slice. The perceptual, translation and motor functions are specialized to deal with one particular situation, and the translation function is necessarily simplified. Since the path of intercept is pre-established and only one trajectory is used, decision-making is confined to choosing the appropriate eye movement and selecting a velocity profile. Nevertheless, due to the reaction times for the various functions and the predictive techniques used to compensate for them, the situation is still quite complex.

As the diagram indicates, the program updates the physical time by the amount of the time-slice interval, or .010 sec for the prototype model. Using the equations of motion for a uniform gravitational field, the position and velocity of the ball expressed in court coordinates are then calculated. These values have to be transformed to the local, polar coordinate system of the player. But since his movement can affect his perception of the ball, the program must first obtain the current values of his position and velocity.

This condition is determined by the plan of action being carried out from the previous time-slice, the subjective events having their influencing counterparts in the objective sphere. An update of the angular position and velocity of the line of sight is then computed, and here again the player's latest decision is the determining factor; he may choose to accelerate, decelerate, or continue with the same eye movements. His interpretation of the information, his image of the action and the manner in which he carries out the action are all dependent on his capability and are specified at definite skill levels, arbitrarily chosen. In effect, the player is virtually <u>constructed</u> by this process of selection of competences.

Coincident with the moment-by-moment computations of the physical state of the ongoing events of the player are the computations characterizing the events, themselves, as units of action. The events are considered to have continuity over a succession of time-slices, the number of time-slices depending on the nature of the unit and the competence levels of the various associated skills by means of which they are carried out. In the prototype model there are only tracking units and interception units. These may be processed separately or jointly, depending on the time lapse between the correction signals that stimulate the actions. The critical time period is taken to be 100 ms. Should both the "follow" and the "intercept" tests to determine if their differences exceed their respective minimums begin within this 100 ms limit, processing of both functions will occur before any corrections are applied. Otherwise, the second item in the queue will have to wait until the first has been processed.

Processing for both of these basic units requires predicting the trajectory of the ball. In the simulator it is presumed that the ability of the player to predict is at a level somewhere between that of the novice, who appears to base his prediction on the position of the ball, and the expert, who is attuned to higher order attributes such as acceleration or even rate of change of acceleration. Our player is considered to be able to extrapolate the path using the average value of velocity. Projecting forward the values of his line of sight, based on the current muscular drive, he computes the expected differences between the line of sight and the line to the ball. In a "table lookup" procedure he interprets the magnitudes of the argument and function values and thereby obtains the corrections to be applied to the movement of his line of sight. If no correction is called for, the current movements continue unchanged.

Similarly for the intercept function. The player projects the distance- and time-to-go and compares the appropriate estimated desired velocity with the estimated actual velocity for that future point. Interpreting the difference, he computes the corrective drive to be applied to his own movement. If the difference exceeds a designated minimum, he projects a new velocity profile, which he then attempts to match. Otherwise, his current movements continue uncorrected.

As indicated, the predictive technique is used because it takes time to put an operation into effect. By the time an action is taken, the condition that called for it will have changed. The player thus needs to take into account where he and the ball will be at the time that the elected response is to be applied, which is some time after the computational process begins. The response must therefore be selected to meet the predicted condition. Now for optimum results the player must incorporate into his computations the exact value of the projected elapsed time. This means he must know in advance how long the feedforward process will take. For repetitive tasks this might be a reasonable expectation, although it is hardly likely in general, particularly if batch processing is involved.

Otherwise, the player must use an estimated (less than optimum) value of the time. He would thus make a best-guess computation and his accuracy would depend on his level of competence performing the task. The ideal estimate would of course be the optimum defined above, and the player's ability could be specified as some functional variation on the optimum.

Legge and Barber (1976, p. 134) suggest another possibility. They feel that if the player implemented responses at fixed times, the time for the next response would then be predictable and corrective action would be planned to occur at those times, resulting in intermittent corrections in an otherwise continuous process. This procedure would call for corrections to be made at intervals taken to be multiples of 250 ms, the approximate length of the observed ballistic units (p. 50-1).

Unfortunately, each of these approaches requires some knowledge of the processing time. Even for the Legge-Barber procedure, a maximum time would have to be designated for the set of possible computations if a conflict is not to occur, because the corrections can only be applied after the computation has been completed. One would think, too, that some strategy must be employed to avoid excessive delays after computation and hence to minimize the errors in prediction. Overall, it might in fact be best to apply the correction too early occasionally and miss that occasional correction than to be ultra-conservative and never miss but have larger than necessary errors. This would require a skill of some considerable complexity yet would account for the variations in extent of the ballistic unit of movement.

A deeper study of the timing problem is needed before a full-fledged mechanism for the computational processes can be simulated fruitfully. This includes finding answers to such questions as to the degree of similarity or compatibility of the computations expected of the tennis player or the effect of practice on those processes. The matter of the possible number and kinds of processing channels -- say, for instance, whether some are "wired-in" (innate) or are capable of being modified through experience (learning) -- has to be examined as well. This would most likely depend on the results of experimental investigations as well as logico-mathematical analysis.

For the prototype model a simplified version has to be employed. So it is presumed that the player is able to estimate time to the precision of physical time and that therefore he is capable of using a 250 ms time advance for all of his feedforward computations. The time will be measured from the moment that he finally reacts to his perceptual information and begins the predictions. Corrections revealed by the computations will be applied after the 250 ms interval, the time lapse depending on the assigned value of a delay time. The corrections will be in error to an extent determined by the errors in position and velocity estimation, the quality of the predictive technique employed and the amount of the correction delay interval.

STARTING CONDITIONS

As already stated, initial values of the pertinent variables must be specified as starting conditions for the program. We therefore set the values as follows:

1. Time from start: $t = 0$
2. Position and velocity of the ball in court coordinates (re. Figures 10.5 and 10.6):

$$x = y = r = 0$$

$$h = 4 \text{ ft}$$

$$v_H = 60 \text{ ft/sec}$$

$$v_V = 14 \text{ ft/sec}$$

3. Distance and angular position and velocity of the ball in player's (polar) coordinates (re. Figure 10.9):

$$d = 79.1 \text{ ft}$$

$$\alpha_V = \text{arc tan}((4 - 5)/((78)^2 + (13.5)^2)^{\frac{1}{2}}$$

$$\alpha_H = - \text{arc tan}(13.5/78)$$

$$\dot{\alpha}_V = .18 \text{ rad/sec}$$

$$\dot{\alpha}_H = .13 \text{ rad/sec}$$

4. Associated variables:

$$\theta = \text{arc tan}(27/78)$$

$$\phi = \text{arc tan}(13.5/78)$$

$$v_r = 10.2 \text{ ft/sec}$$

5. Angular position, velocity, and acceleration of player's line of sight:

$$\beta_V = \text{arc tan}((4 - 5)/((78)^2 + (13.5)^2)^{\frac{1}{2}})$$

$$\beta_H = -\text{ arc tan}(13.5/78)$$

$$\dot{\beta}_V = 0$$

$$\dot{\beta}_H = 0$$

$$\ddot{\beta}_V = 20 \text{ rad/sec/sec}$$

$$\ddot{\beta}_H = 20 \text{ rad/sec/sec}$$

6. Position and velocity of player (center of gravity) in court coordinates:

$$x_p = 78 \text{ ft}$$

$$y_p = 13.5 \text{ ft}$$

$$v_p = 0$$

$$v_p = 24 \text{ ft/sec/sec}$$

COMPUTATIONS IN THE $i^{\underline{th}}$ TIME-SLICE

Since there is no aerodynamic drag on the ball, its horizontal component of velocity is constant at $v_H = 60$ ft/sec. The distance, r, in the $i^{\underline{th}}$ time-slice is therefore precisely determined by

$$r = v_H t, \qquad \text{for } 0 < t \leq 1.36 \text{ sec.}$$

The height of the ball in its trajectory, h, and the vertical component of velocity, v_V, are determined by the equation set appropriate to the segment of the trajectory currently defining the ball. In accordance with Figure 10.5, if $0 < t \leq .44$ sec,

$$h = (14t - 16t^2 + 4) \text{ ft}$$

and

$$v_V = (14 - 32) \text{ ft/sec.}$$

For $.44 < t \leq 1.10$ sec, it is convenient to use the equation set:

$$h = (7.06 - 16(t - .44)^2)\text{ ft}$$

and

$$v_V = 32(t - .44)\text{ ft/sec.}$$

For $1.10 < t \leq 1.36$ sec,

$$h = 16(t - 1.10) - 16(t - 1.10)^2$$

$$= 16(t - 1.10)(2.10 - t)\text{ ft}$$

and

$$v_V = (16 - 32(t - 1.10))\text{ ft/sec.}$$

Knowing the horizontal and vertical components of velocity of the ball and the distance from the player to the ball (i.e., v_H, v_V and d), the horizontal and vertical components of angular velocity of the line to the ball are, again:

$$\dot{\alpha}_H = \frac{v_H \sin(\theta - \phi) - v_p \cos\phi}{d}$$

$$= \frac{v_H \sin(\arctan(27/78) - \arctan w) - v_p \cos(\arctan w)}{((78 - r\cos(\arctan(27/78)))^2 + (13.5 + s - r\sin(\arctan(27/78)))^2)^{\frac{1}{2}}},$$

where

$$w = (13.5 + s - r\sin(\arctan(27/78)))/(78 - r\cos(\arctan(27/78)));$$

and

$$\dot{\alpha}_V = \frac{v_V}{d}$$

$$= \frac{v_V}{((78 - r\cos(\arctan(27/78)))^2 + (13.5 + s - r\sin(\arctan(27/78)))^2)^{\frac{1}{2}}}.$$

The horizontal and vertical angular position, again, are:

$$\alpha_H = \arctan((y - 13.5 - s)/(78 - x))$$

and

$$\alpha_V = \arctan((h - 5)/d)$$

$$= \arctan \frac{h - 5}{((78 - r\cos(\arctan(27/78)))^2 + (13.5 + s - r\sin(\arctan(27/78)))^2)^{\frac{1}{2}}}.$$

In the computation of the angular position and velocity of the line of sight of the player, it is assumed that positive action by the eye muscles is required to rotate the eyes; i.e., the player's movement along the intercept path doesn't affect the angle of the line of sight. The current update on angular position and velocity can therefore be derived from the values in the previous time-slice using the acceleration strategy in effect from the previous time-slice. The new horizontal and vertical components of angular velocity are then

$$\dot{\beta}_H(i) = \dot{\beta}_H(i-1) + \frac{d\,\dot{\beta}_H(i-1)}{dt}\Delta t$$

and

$$\dot{\beta}_V(i) = \dot{\beta}_V(i-1) + \frac{d\,\dot{\beta}_V(i-1)}{dt}\Delta t.$$

And the new horizontal and vertical components of angular position are

$$\beta_H(i) = \beta_H(i-1) + \frac{d\,\beta_H(i-1)}{dt}\Delta t + \frac{d^2\beta_H(i-1)}{dt^2}(\Delta t)^2$$

and

$$\beta_V(i) = \beta_V(i-1) + \frac{d\,\beta_V(i-1)}{dt}\Delta t + \frac{d^2\beta_V(i-1)}{dt^2}(\Delta t)^2$$

Similarily, the new position and velocity of the player in his intercept path are given by

$$x_p(i) = 78 \text{ ft, for all } i,$$

$$y_p(i) = 13.5 + s(i-1) + \frac{ds(i-1)}{dt}\Delta t + \frac{d^2s(i-1)}{dt^2}(\Delta t)^2$$

and

$$v_p(i) = v_p(i-1) + \frac{dv_p(i-1)}{dt}\Delta t.$$

TRACKING LOGIC IN THE $i^{\underline{th}}$ TIME-SLICE

Before the program enters its tracking or "follow" logic section, tests are made to determine whether the logic is "active" or not or whether a correction or correction countdown is in order or not. If a countdown is in progress, the follow logic is by-passed; no follow action is taken and the program procedes to test the intercept logic. If an angle or velocity difference greater than the acceptable minimum has been detected by the player, a correction is readied and the countdown to application is set in motion; then the intercept logic is examined.

As indicated above, the test for a correction is effected at a point 250 ms into the future. Thus our player projects the trajectory forward and compares the results at that time of the movements that are currently active. Because of the non-linearity of the trajectory, the future states of the ball cannot be predicted accurately, in general, without using some kind of quadratic projection technique. However, our player is presumed not to be an expert in this skill category: He extrapolates only an average velocity. (As it happens, the constant horizontal velocity trajectory used in the prototype model is compatible with the average velocity tactic and makes it more effective than would normally be the case. But this is merely coincidental. In any event, large errors should occur in the vertical component, which isn't constant.)

In order to extrapolate average velocities, the player must be able to detect or somehow estimate "instantaneous" velocities from which the averages are computed. In either case, whether there are velocity detecting cells in the retinal system or whether the player uses differences in position over time to integrate velocity, some small period of time is necessary to get the results. The implication is that velocity is determined more than once in the course of the 250 ms information processing interval. In the prototype model this number is set at five, and each of the five velocities is obtained as an average of values from five time-slices.

It is to be remembered that these velocities are presumed to be perceived by the player, which is to say that they are qualitative values detected up to his ability to discriminate differences. For our prototype player, the level of discrimination has been defined by the range of values from 5% less to 5% more of the objective quantity, so that, for example, the qualitative estimate of velocity of a ball moving at the physical rate, 60 ft/sec, would be (57 to 63) ft/sec. The objective value would then have to change by more than 5% if a qualitative difference was to be perceived.

In the prototype model, it is presumed that the player is able to detect instantaneous velocity and that he is able to synthesize velocities over any five consecutive time-slices. Provision is made for the incorporation of the qualitative feature in the velocity estimation but does not actually include it. The reason is simply that the resulting change in average velocity is so small relative to the gross estimation errors as to be insignificant. Later versions of the program will, of course, have to deal with the matter. But for the current model we assume that the player's velocity estimation skill is ideal.

Given the position and velocity of the ball (i.e., the angular position and velocity of the line to the ball), by extending the angular position of the line of sight using the last value of velocity, direct comparisons of angles and velocities can be made to establish the need for a correction on the movement of the line of sight. The player reads the projected differences, interprets them as to their quality: small, medium or large, and judges the magnitude of the indicated drive (acceleration) on the line of sight. Table 10.2 provides the framework for the player's decision logic in this regard. The input and output interpretations are as given on page 10-42.

Inasmuch as the "follow" procedure is extended over a number of time-slices, care must be taken to keep track of the detailed operations. One way to deal with the problem is to use a variety of counters, one for each kind of operation. This means that, at any moment, one or another of the counters must either be initiated, updated, or closed out.

In the first place, it is necessary to know whether the procedure is already active or not. This designation is specified by a status indicator which is set to unity when the function is first activated. The indicator is zero while the process is tentative and is set to -1 when the 100 ms counter renders the logic inactive.

An indicator is also needed to keep track of the elapsed time to the point of correction, which occurs 250 ms later than the start time of the process. With each active time-slice, the counter must be updated by adding 10 ms to it. At 250 ms it signals that a correction is to be initiated if it is necessary.

Since five velocities, one from each of five successive time-slices, are to be averaged, a counter is needed to record the number of times data is put into the hopper. Since a second-tier average velocity may be qualitatively different from a first-tier value, a different counter is needed to keep track of the number of average velocities, since five values are used in the projection of the trajectory.

INTERCEPT LOGIC IN THE $i^{\underline{th}}$ TIME-SLICE

It is assumed that our player tends to accelerate beyond the optimal running speed and therefore has to decelerate more severly than would otherwise be necessary to intercept the ball. For the sake of simplicity it is further assumed that the over-reaction is due principally to the fact that he over-estimates the distance-to-go to intercept, particularly in the early segment of the trajectory when information is minimal. Assuming that he already knows his position and time along the intercept path, the implication is that he must re-evaluate his actual velocity regularly by comparing it against the desired velocity of the estimated distance-to-go for the given time-to-go. The comparison is not made at the current moment, however, but as projected to a point 250 ms into the future, as in the "follow" logic.

For the first segment of the trajectory, then, the player is assumed to read the distance-to-go to be 15% higher than its actual value. The excess drops to 10% in the second segment, and to 5% in the last segment. These quantities constitute a bias on the distance-to-go. In addition to the bias, there is also the -5% to +5% bracketing that converts the objective value into a subjective estimate, following the usual practice for the prototype model.

Time-to-go has its subjective counterpart, too, but in the interests of simplicity as well as to maintain visibility on the effects of the bias on distance-to-go, it is assumed to be free both of bias and bracketed interpretation. This means, in effect, that time-to-go is known precisely.

In the forward extrapolation, then, the state of the player is projected to a point 250 ms ahead, for which point the distance-to-go is estimated and, based on this, the difference between the actual and desired velocity is determined. By virtue of the player's bias, the desired velocity is seen to be greater than it would otherwise be; the player believes he has farther to run than in fact he has and therefore believes he has to run faster than necessary to get there in the given time. By virtue of the lack of precision in his estimates (the ±5% bracketing), a difference of more than 5% has to occur before a change in the property value can be perceived.

The player's estimated actual velocity projected to the (t+250) ms mark is then

$$\hat{v}_p(t+250) = \hat{v}_p(i+25) = v_p(i) + 25(\Delta v_p),$$

where t is the time at the $i^{\underline{th}}$ time-slice when the interception test begins, and Δv_p is the constant increase in velocity each time-slice.

His estimated position, similarly, is

$$\hat{s}(i+25) = s(i) + 25(\Delta s) + \sum_{j=0}^{23} (24-j)(\Delta v_p),$$

where Δs is the constant increment of position and Δv_p is the constant increment of velocity each time-slice.

Estimated distance-to-go from the point reached at the 250 ms mark to the point of interception is therefore

$$\hat{s}_g = 1.15(10.5 - s) \qquad \text{if } t \leq .5$$

or

$$= 1.10(10.5 - s) \qquad \text{if } .5 < t \leq 1.0$$

or

$$= 1.05(10.5 - s) \qquad \text{if } 1.0 < t \leq 1.36,$$

with each quantity being bracketed by -5% to +5% of its value.

Using this estimated distance-to-go, the desired velocity is read from the velocity profile currently in effect. This profile is either the original one, interpreted with $\hat{s}_g = 1.15(10.5) \cong 12.1$, or the latest one to be incorporated. The estimated actual velocity and the estimated desired velocity are then compared. If the difference is less than or equal to 5% of the desired value, no correction is needed (the player can't differentiate between them), and the current profile remains in effect.

A technical problem arises from the fact that the new profile is constructed from an error point which is a distance, $s_e < 10.5$ ft, from the intercept point; whereas s_g (estimated) can exceed this value. To eliminate this difficulty, let the velocity at $s_g > s_e$ be the same as the velocity at s_e.

If now the estimated actual velocity is smaller than the estimated desired velocity by more than 5%, then consider the player's velocity mode to determine the course of action. If he is in the acceleration mode, he continues accelerating. If he is in the constant velocity mode, he chooses the minimum rate of deceleration. If he is already in the deceleration mode, he continues as he is.

Otherwise, if the estimated actual velocity is <u>larger</u> than the estimated desired velocity by more than 5%, again consider the player's mode. If he is in the acceleration mode, he enters the constant velocity mode immediately. But if he is already in the constant velocity mode, he chooses the maximum rate of deceleration. Otherwise, he continues as is.

In a manner analogous to that of the "follow" procedure, a status indicator is used to show whether the intercept logic is active or not. The indicator is at zero so long as the process is tentative, but it is changed to unity as soon as the logic is begun. If the 100 ms counter counts out before the intercept process starts, then the indicator is set to -1.

Again, as with the "follow" logic, an indicator is needed to keep track of the elapsed time to the point of correction, which occurs 250 ms after the logic is begun. In the prototype model the two processes are tied together, so one counter for both is adequate.

INTERACTION OF THE TRACKING AND INTERCEPT LOGICS

The tracking and intercept procedures may or may not begin at the same time. But if they do so begin, the processing for both occurs "simultaneously" (the logic for each is activated in the same time-slice) and any necessary corrections are computed for the same moment in the future, although the correction delays may not be the same for the two cases.

If the procedures are not initiated together, the second to occur must wait for the first to be completely processed and any necessary correction applied before it, too, can begin. However, as indicated above, if processing for the second is to begin at a time less than 100 ms after the first has started, it is incorporated immediately into the program loop.

To reconcile this matter of joint processing, the program is constructed always to be ready to handle both. Hence, whenever either of the two is begun, both procedures are activated and the logic continues on both for the full 100 ms period. If by that time the second has not yet started, processing for it is discontinued, the extrapolation now being considered too old to be useful. This practice corresponds to the player always being alert to the need to check his follow and intercept tactics.

INPUT-OUTPUT REQUIREMENTS

In effect, the simulator performs a sequence of transformations on data, beginning with the first time-slice. Starting data are therefore required. These data have been summarized above.

Data are also needed as part of the machinery of the transformations. These data establish the conditions or limits on the transformations but are not themselves transformed. So, for instance, decision tables are used in the follow logic to change the values of the angular position and velocity of the player's line of sight. Other tables used in the process give interpretation to the meaning of the subjective estimates: small, medium and large angles, angular velocities, and acceleration. These data, too, are summarized above.

As part of the intercept logic, whenever velocity errors are detected, it is necessary to construct velocity profiles to serve as new standards. For the most part, these constructions use data generated by the program, itself. But they also require other information, such as the velocity restrictions on the terminus of the profile at the intercept point, as indicated above. This and other incidental data form the input package for the program and are appropriately stored before the program is executed.

As the simulator transforms its inputs it generates outputs, some of which are issued as printed read-outs. In a prototype model it is particularly important to be able to evaluate the mechanisms which effect the transformations and this can best be accomplished by making visible as much of the processed data as possible. For this reason, the printout list is quite extensive. It includes: 1) program constants, 2) values on the physical properties characterizing the ball, the player and the player's line of sight on a time-slice basis, and 3) the player's subjective interpretations, discriminations, decisions and corrections, as they occur.

Later versions of the simulator may incorporate techniques to represent learning. This might be accomplished in part by formulating changes in the transformation parameters so as to occur from one run of the program to the next. An additional category of printouts would then be needed.

The following format for the data is adopted:

Names of Parameters
(in array)

Initial Values of Parameters
(in corresponding positions)

Values at 1st time-slice
(in corresponding positions)

Values at 2nd time-slice
(in corresponding positions)

Values at last time-slice
(in corresponding positions)

The program prints out the parameter names in the first array, prints out their starting values, and then with each successive pass prints out the resulting values. The array is as follows:

I	TIME	BHEIGHT	ALPHAV	ALPHAH	PDIST
IFOLLOW	INTERCEPT	BDIST	ALPHAV25	ALPHAH25	PDIST250
NDELYIN	NDELPIN	BDIST250	VALPHAV	VALPHAH	PVEL
NDELYCOR	NDELPCOR	BVELV	VALPHAV2	VALPHAH2	PVEL250
N5CTR	N25CTR	R	BETAV	BETAH	PACCEL
N100CTR	IFLAG	PHI	VBETAV	VBETAH	PACCSTD
DTGO	TTGO	BETAV250	ABETAV	ABETAH	VBETAV25
DTG250	TTG250	BETAH250	ABETAV25	ABETAH25	VBETAH25

Table 11.1 identifies the parameter names. Items with numerical suffixes (i.e., 2, 25 and 250) designate estimated values of the root parameters for the 250 ms feedforward computation. For example, BDIST250 represents the estimated ball distance (BDIST) for that future point. Status indicators include: FLAG, IFOLLOW and INTERCEPT. The indicators IFOLLOW and INTERCEPT specify the status of the follow and intercept logics, respectively. If either is set to -1, the logic is inactive and must wait until a correction by the other is effected or shown not to be needed. If either is 0, the logic is a candidate for action. The logic is already active if the indicator shows 1.

FLAG is used to signal that the deceleration from TIME = 1.0 has been estimated. The counters N5CTR and N25CTR are used in the computation to find the average vertical and horizontal components of velocity of the trajectory for projection to the 250 ms point in the feedforward loop. The counter N100CTR tracks the time since initiation of one or the other (not both) of the follow or intercept logics.

i	I	s	PDIST	v_r	BVELR
t	TIME	s_g	DTGO	v_p	PVEL
t_g	TTGO	d	BDIST	$\dot{\alpha}_V$	VALPHAV
x	X	α_V	ALPHAV	$\dot{\alpha}_H$	VALPHAH
y	Y	α_H	ALPHAH	$\dot{\beta}_V$	BVETAV
r	R	β_V	BETAV	$\dot{\beta}_H$	VBETAH
θ	THETA	β_H	BETAH	γ_V	VANVDIFF
ϕ	PHI	γ_V	VANGDIFF	γ_H	HANVDIFF
x_p	PX	γ_H	HANGDIFF	$\dot{\nu}_p$	PACCEL
y_p	PY	ν_V	BVELV	$\dot{\nu}_{pstd}$	PACCSTD
h	BHEIGHT	ν_H	BVELH	$\ddot{\beta}_V$	ABETAV
h_p	PHEIGHT			$\ddot{\beta}_H$	ABETAH

Table 11.1. Glossary of parameter names.

ORGANIZATION OF THE PROGRAM

The prototype simulator, written in Fortran, is organized into program segments, in accordance with standard Fortran practice. (See Appendix A for the complete program list.) There are three segments, namely, a main or control segment and two slave segments.

The main segment, called MASTER TENNIS, contains the overall logic of the simulator. It controls input and output, regulates time-slice computations, processes the intercept logic as needed, and performs feedback and feedforward computations as required. When necessary, it brings into play one or the other of the "slave" segments, namely, SUBROUTINE COMPUTE, which computes state data for the ball, and SUBROUTINE FOLLOW, which processes the tracking logic. (Since the track and intercept functions are equally important in this program, it may seem strange that a formal subroutine wasn't used for the intercept logic. Indeed it might have been neater to do so. But in the course of coding, the need for such formality never seemed pressing.)

Heading the master segment code list is the block of names identifying the variables used in the program, use of such a block being a formal Fortran requirement. (The words COMMON/BALL identify and name the block, and the symbol R is the first variable name.) Just after the variable name block are listed the starting conditions for the track and intercept functions, the status indicators used as logical tags, delay counters to emulate latency times, and incremental constants or time increments used for regular and feedforward computations. (Lines beginning with the letter C, it should be noted, are not operational instructions or data words; they are merely aids to the reader.)

Output instructions are next on the list. The blocks of output words involving WRITE and FORMAT are instructions to the teleprinter to type out a title page first, and then to print a second page containing an array of variables for which data is required on a time-slice basis, followed by a corresponding array of starting values for the variables.

As a printout example, the first command in this cluster is WRITE(6, 6000). It orders printer #6 to type out "TENNIS" according to the format spelled out in word numbered 6000. The format says to print the title just above center of a new page.

Just preceding word #100 there is a bit of logic involving the counter K. This logic is used to be able to make a one-time printout request using only part of a block of WRITE commands normally performed on a recurring basis. This is the group beginning at word #102.

The program has now been initialized and can begin the repetitive operations, each pass performing computations corresponding to each time-slice. The first pass originates with instruction #105, which increments counter I by one, taking it from 0 to 1, thereby identifying time-slice #1. TIME is then incremented (by .01 seconds), and TTGO (time-to-go) and DTGO (distance-to-go) are calculated. A logic check intervenes to determine player deceleration requirements, but then the COMPUTE subroutine is called into action to calculate the current state of the ball. After that, all counters are updated.

The program next performs status checks preparatory to using the track and intercept logics; the checks are performed using instructions in the sequence from word #200 to word #820. The first check determines whether delays are in effect or not. If both delays are still active, no action on tracking or interception is taken and the program returns to instruction #100, which now becomes the starting point for the second pass processing and all subsequent processing. Otherwise, if either the track delay or the intercept delay is not active, then either the track logic or the intercept logic, whichever is appropriate, is tested for active status. If neither is active, then both are activated. But if only one is active, a further test is made to determine if less than 100 ms has passed from the moment the other was activated, in which case the inactive one is made active; otherwise it is not. Processing then continues for the active logic for this time-slice.

Beginning with instruction #820, counters and variables are readied for player's estimates of appropriate current and feed-forward data, including ball velocity and distance player has run. These results are then used to process the tracking and/or the intercept logic, as required. For the tracking logic, SUBROUTINE FOLLOW is called in, whereas the master segment handles the intercept logic, as mentioned.

The intercept logic is processed whenever instruction #920 shows it to be active. Estimated <u>projections</u> of distance-to-go (DTG250) and of time-to-go (TTG250) are then computed using estimated projections of player distance (PDIST250). The projection extends 250 ms into the future, hence the suffix 250 in the variable name tag. In a similar manner, projected comparisons between anticipated <u>actual</u> player velocity and anticipated <u>desired</u> player velocity are made. On this basis the player's current acceleration (PACCEL) is determined.

The .250 second projections are also used to determine current horizontal and vertical components of angular acceleration of the eyes required to maintain track. These components are called by the names ABETAH25 and ABETAV25. The values for these acceleration components are obtained by anticipating angular position and velocity of the line of sight and of the line to the ball, forming differences, and comparing the differences against the player's standards of magnitude of such differences. The logic then performs the equivalent of a table lookup to obtain the driving accelerations.

RESULTS OF THE PROGRAM

The output of the program in any given run depends on the values assigned to the parameters of the program. Certain key items, as we have seen, reflect the capability of the player. For instance, NDELYIN and NDELPIN characterize the player's reaction time to stimuli or to the information content in the display. ABETAH and ABETAV indicate the nature of the visual response to the trajectory and PACCEL defines the character of the body movement to intercept the ball. In the first trial, the values: 7, 11, 20.0, 20.0, and 24.0 were selected, respectively, for these properties. Some of the results are shown in Figure 11.2.

It is clear from these curves that our player expected his relative angle to the ball to be large and positive, whereas it was actually small and, in fact, negative. This means that our player's speed kept him ahead of the ball as measured in the lateral direction. By the time he effected his first correction -- at time-slice 34 -- his eyes were already rotating at the rate of 5.4 rad/sec. The correction was only large enough to eliminate the acceleration, so he continued at a constant rate of rotation for another 28 time-slices, when he finally applied the second correction.

His response in the vertical component was similar to that in the horizontal component. He exaggerated the relative position of the ball so that his eyes flew up to three radians above the ball, and it took two corrections to get the eyes rotating back to the line of the ball. At time-slice 87 a third correction was necessary to begin to slow the rate of approach of the line of sight to the line of the ball. For the horizontal component the third correction wasn't made.

As Figure 11.2 shows, the player's starting acceleration was delayed and was slightly higher than the profile acceleration. He over-reacted to the velocity requirement and was late to correct his movement (time-slice 92). He then had to apply the maximum possible deceleration in his power, but he failed to meet either the distance or the velocity requirement for a successful intercept. The computer listing for the program and for this particular output is given in Appendix A.

Figures 11.3, 11.4 and 11.5 give some of the results for different values of the indicated parameters. As one might expect, the curves for BETAV and BETAH are similar under the condition that ABETAV and ABETAH are the same (compare Figures 11.3 and 11.4), while some differences are to be noted because of the different reaction times. In particular, BETAH shows a higher terminal value when there is no starting delay, and there is a late correction for BETAV when there is no delay in response to initial data. It is clear, too, that there is a better approximation of actual velocities to the standard profile when the delays are reduced. These phenomena are doubtless due to the peculiar nature of the mechanism which simulates the player's responses, but they are significant in that appropriate responses in the simulator can reflect on the validity of the simulation and the quality of the mechanisms used to do the job.

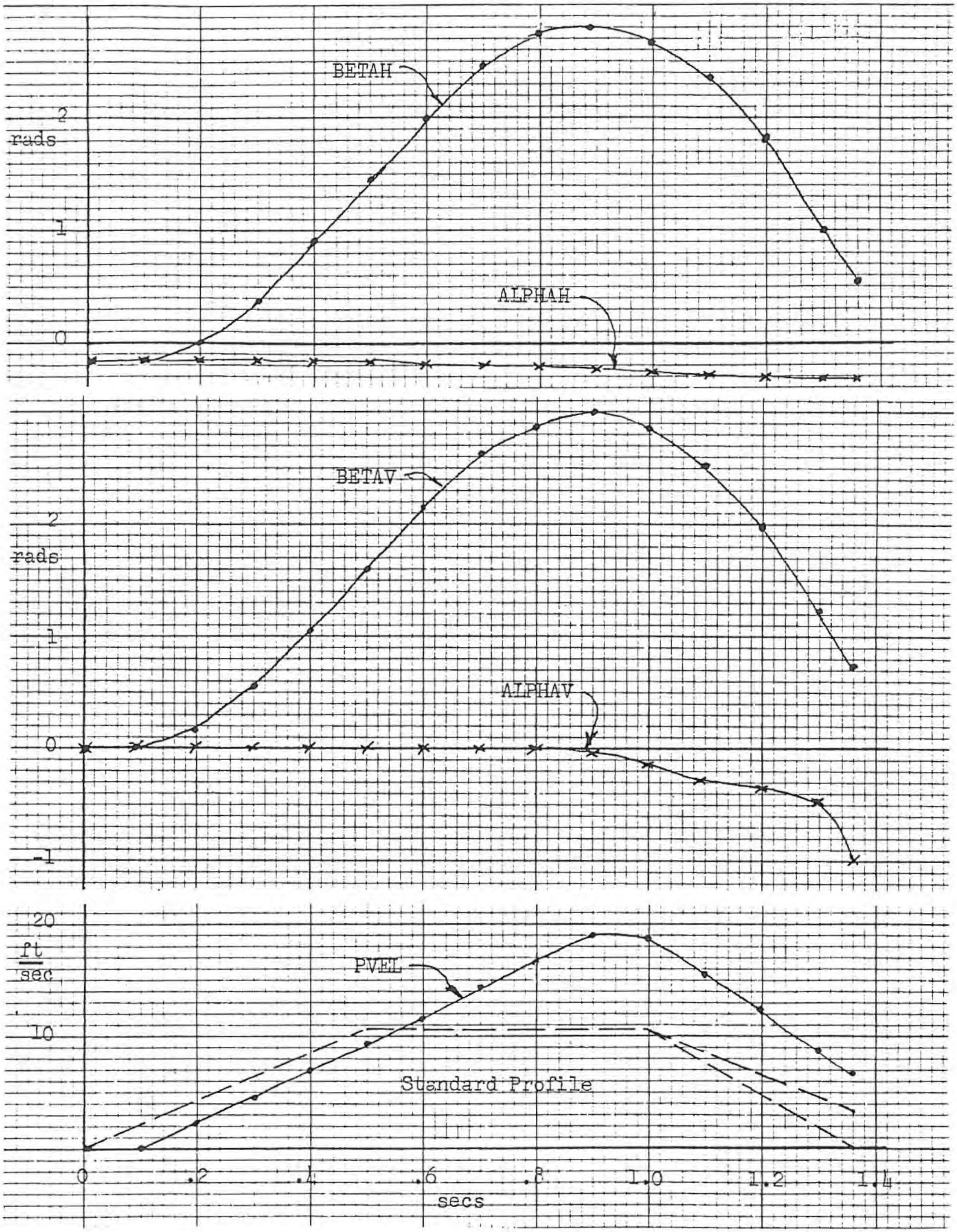


Figure 11.2. Functional relationships between a) ALPHAH and BETAH, b) ALPHAV and BETAV, and c) PVEL and standard velocity profile, for (NDELYIN, NDELPIN, ABETAH, ABETAV, PACCEL) = (7, 11, 20.0, 20.0, 24.0)

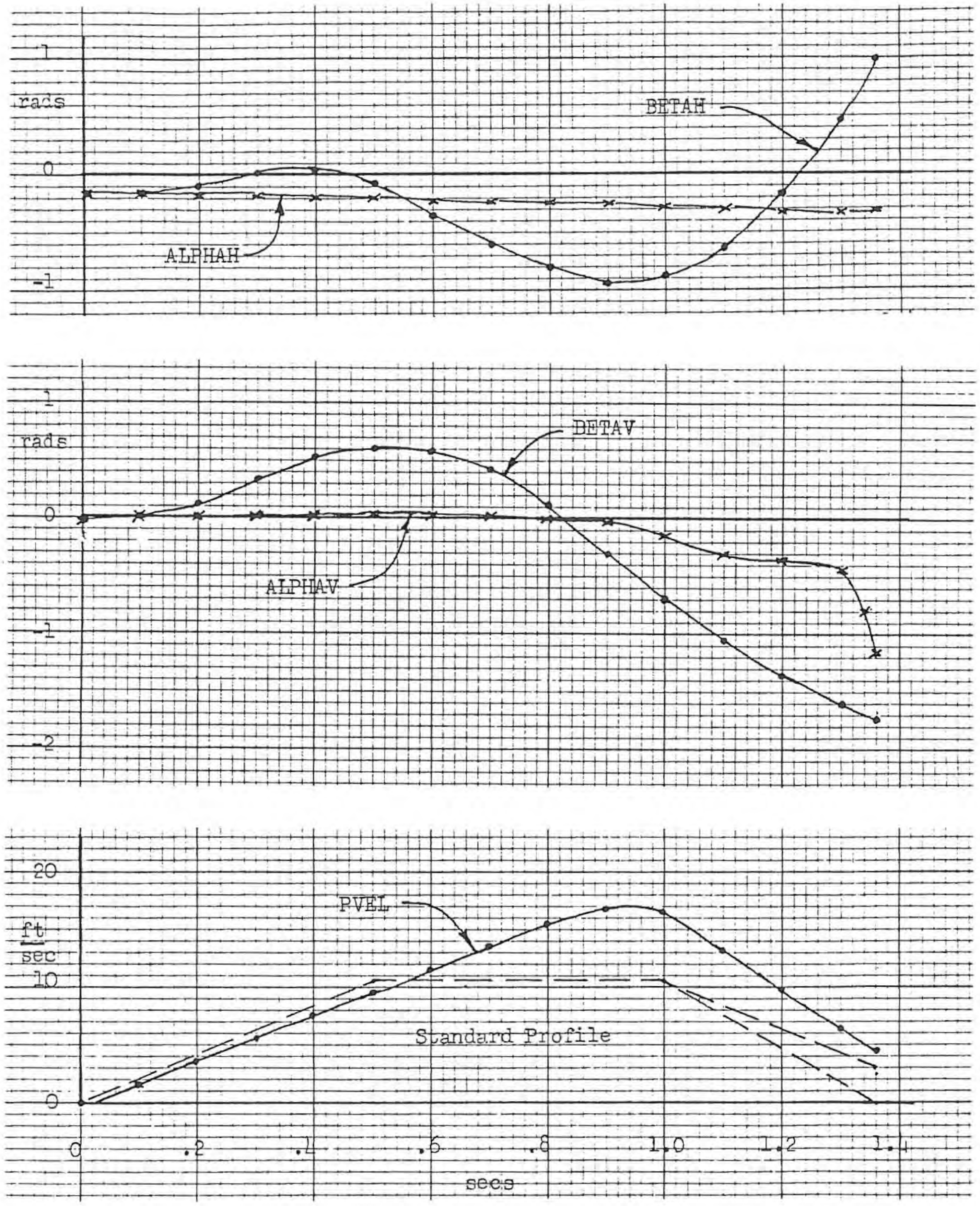


Figure 11.3. Functional relationship between a) ALPAH and BETAH, b) ALPHAV and BETAV, and c) PVEL and standard velocity profile, for (NDELYIN, NDELPIN, ABETAH, ABETAV, PACCELL) = (4, 2, 5, 10, 20.0).

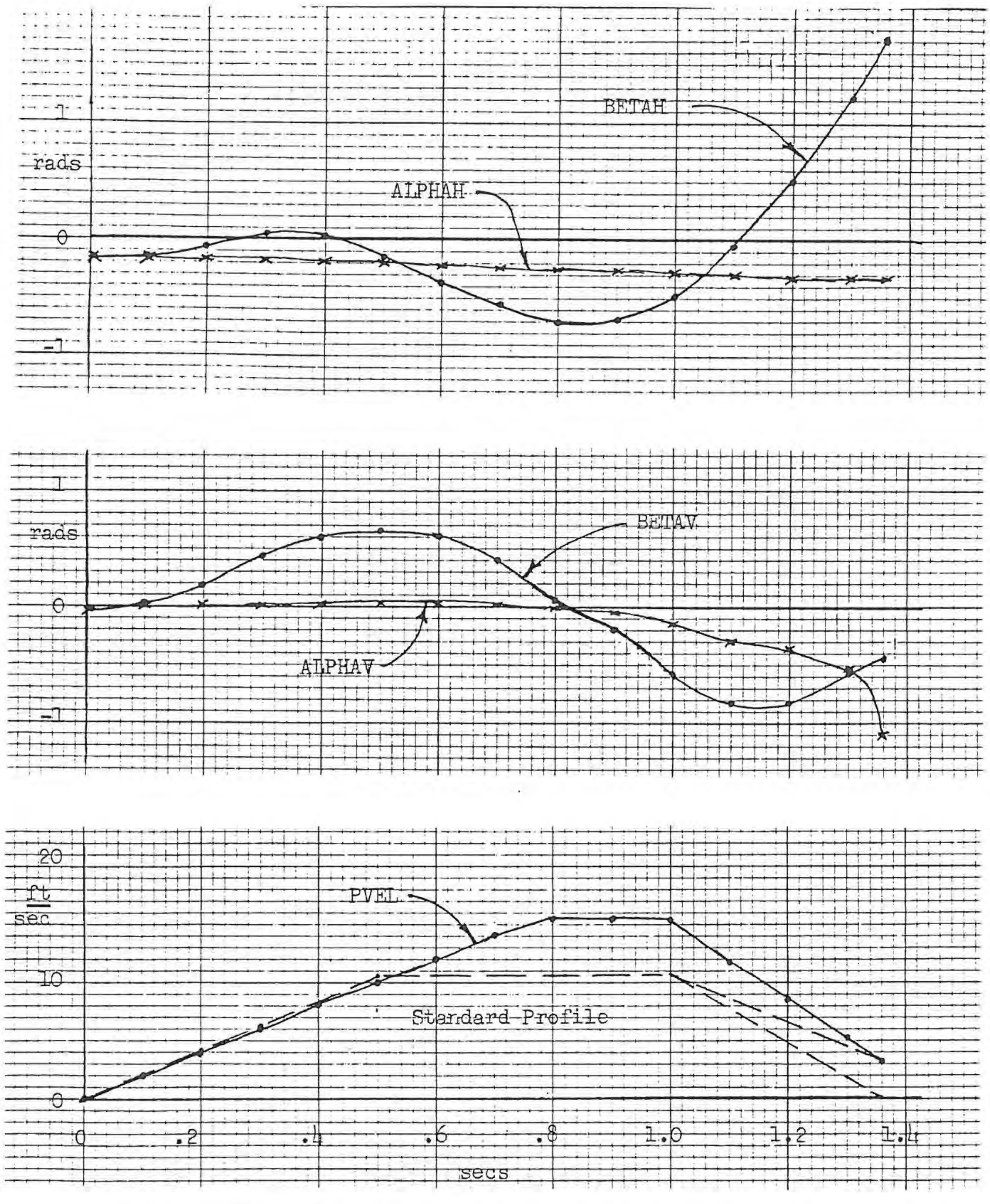


Figure 11.4. Functional relationship between a) ALPHAH and BETAH, b) ALPHAV and BETAV, and c) PVEL and standard velocity profile, for (NDELYIN, NDELPIN, ABETAH, ABETAV, PACCEL) = (0, 0, 5.0, 10.0, 20.0).

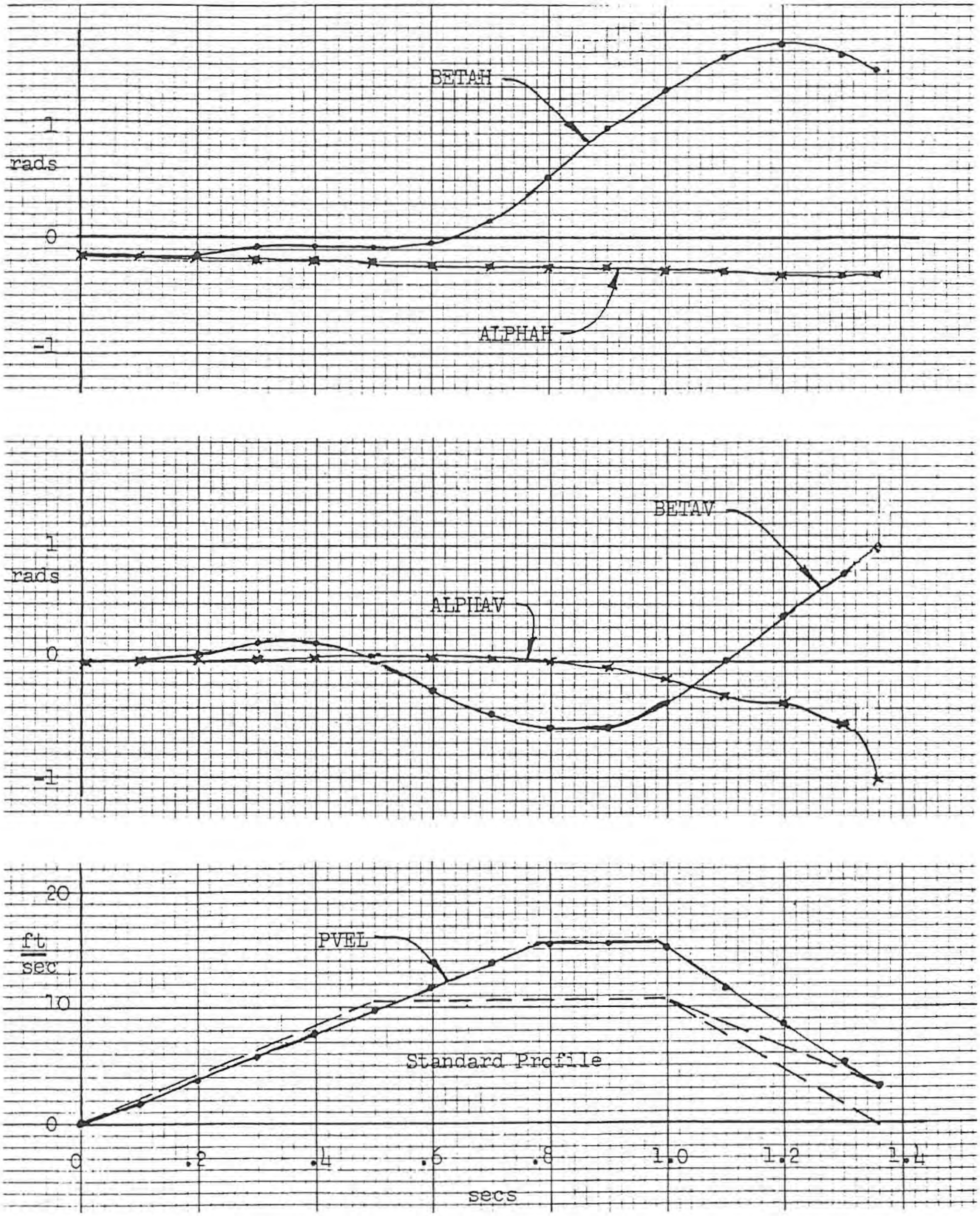


Figure 11.5. Functional relationships between a) ALPHAH and BETAH, b) ALPHAV and BETAV, and c) PVEL and standard velocity profile, for (NDELYIN, NDELPIN, ABETAH, ABETAV, PACCEL) = (1, 1, 2.0, 5.0, 20.0).

CHAPTER 12

THREE EXTENSIONS OF THE MODEL

The prototype simulator in its present form, we have seen, is very restricted in its capability. For one thing it can only handle designated cross-court trajectories. But it also performs no more than just a few of the many possible perceptual-motor functions. For example, detection and identification were not mechanized. As a consequence, it was pointless to simulate the stimulus inputs that are required for detection or identification -- namely the patterns of incident energy. Without this input, furthermore, there was no need to configure the eyes or the visual neural network. Hence, receptive fields were superfluous also.

Player orientation and stability, also, were not part of the prototype model. Indeed, most of the bio-mechanical details of movement were left unstructured, as were the psychological factors such as intentional fields, attitudes and interests, not to mention the extremely complex physiological aspects of the motor function.

In this respect, then, our player cannot be said to play interesting tennis. However, I believe the fact that he can do anything at all is in itself a significant step, and the model does suggest a wide range of possible extensions. Some of these extensions can be obtained merely by relaxing the prototype constraints. One might then generalize the program so that, for example, the receiving player may be allowed more than a center-baseline starting position from which to launch his interception. This and other similar changes can be made without yielding the simplification gained by treating the ball and the players as mere points. Three such extensions are developed below.

FIRST EXTENSION

In the first extension of the prototype model, the input mechanism is generalized to accommodate starting data for any forehand cross-court trajectory. It can also accept receiver starting position data for any intercept to the right. The assigned values for these parameters determine the time and distance to the point of interception, inasmuch as the ball is moving with a well defined horizontal velocity and known direction and the direction of the player's path is specified by his intercept strategy.

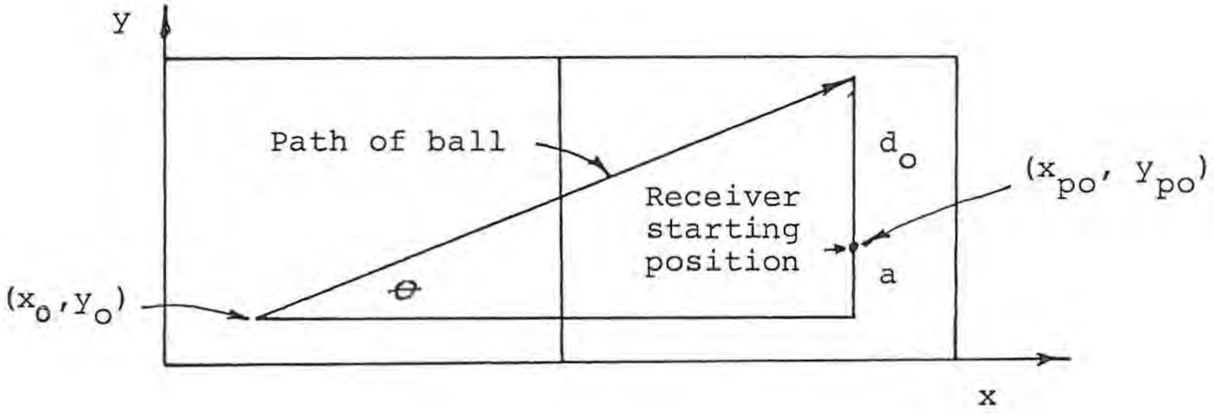


Figure 12.1. Intercept geometry.

Figure 12.1 shows the geometry for this more generalized intercept. The ball is hit from an arbitrary starting point from the opponent's court with some angle, θ. The receiver, too, can be in any position in his own court, but he is restricted to intercepts to his right. The computations for time-to-go and distance-to-go are as follows:

$$d_o = (x_{po} - x_o)\tan\theta - a$$

$$= (x_{po} - x_o)\tan\theta - (y_{po} - y_o + 3),$$

and

$$t_o = (x_{po} - x_o)/(v_{bo}\cos\theta),$$

where d_o and t_o are distance-to-go and time-to-go at the start, x_{po} and y_{po} are the initial coordinates of the receiving player, x_o and y_o are the initial coordinates of the ball (or opponent), θ is the angle at which the ball is hit, and the number 3 accounts for the receiver's racquet extension.

In the prototype model, these quantities were hand computed and specified as the inputs, TTGO and DTGO, initial time- and distance-to-go. In the first extension they are identified by the Fortran expressions:

```
DTGO = (PX - X0)*tan(THETA) - PY + YO - 3
```

and

```
TTGOO = (PX - X0)/(BVELHO*cosTHETA).
```

Similarly, both the time-slice control counter and the shape of the velocity profile were pre-set in the prototype verson. However, it is more convenient to let the computer do this work, and in fact, the first extension does compute its own running time and the specific shape of the velocity profile. It also computes the trajectory properties that are needed to choose the appropriate equation set to be used to determine the position and velocity of the ball.

For program running time, a conditional logic test is used. Since there are 100 time slices per second, and TTGOO is measured in seconds, the control counter is compared with the quantity TTGOO*100. If the counter equals or exceeds this number, the program terminates; otherwise it continues. The Fortran expression for this conditional is

```
IF(I .LT. TTGOO*100) GO TO 101.
  If not, STOP
```

For shaping the velocity profile, another conditional logic test is used. The velocity profile is presumed to be shaped by the player. In the prototype model the player ends his acceleration phase as soon as he has estimated that he has reached the .5 second mark of his running time, a point that defines a "standard" turning point for an interception path of this type, arbitrarily stated.

The conditional logic test is also used in the first extension, but in this case the test quantity is more generally, but still somewhat arbitrarily, stated as a third of the initial estimate of time-to-go. As expressed in Fortran, the test quantity is TTGOO/3.0.

Similarly, to select the appropriate form of the equation to compute the position and velocity (vertical) of the ball, still another conditional logic test is used. The test determines the time relative to the time at which the ball reaches its maximum height and to the time at which it reaches the ground for the first bounce. In the prototype model the time quantities are hand computed and set into the program. In the first extension, however, the computations are made internally as a function of the starting values of the trajectory selected for simulator operations. These computations initiate the subroutine COMPUTE. For details see the program listing in Appendix B.

Figure 12.2 gives a summary of the follow (tracking) and intercept movements for the indicated parameters for the first extension of the prototype. For low starting accelerations for both vertical and horizontal components of the movements of the line-of-sight, the eye follows the line of the ball reasonably well, lagging only slightly. The actual velocity profile doesn't match the profile standard too badly and the terminal velocity is within the specified limits. However, the player ends slightly short of the ball position.

Figure 12.3 shows what happens to the actual profile for velocity as the player's starting acceleration, PACCEL, is varied about the standard acceleration. The worst situation occurs with the value of PACCEL only slightly less than the standard acceleration, i.e., PACCEL = 30. This is due mostly to the

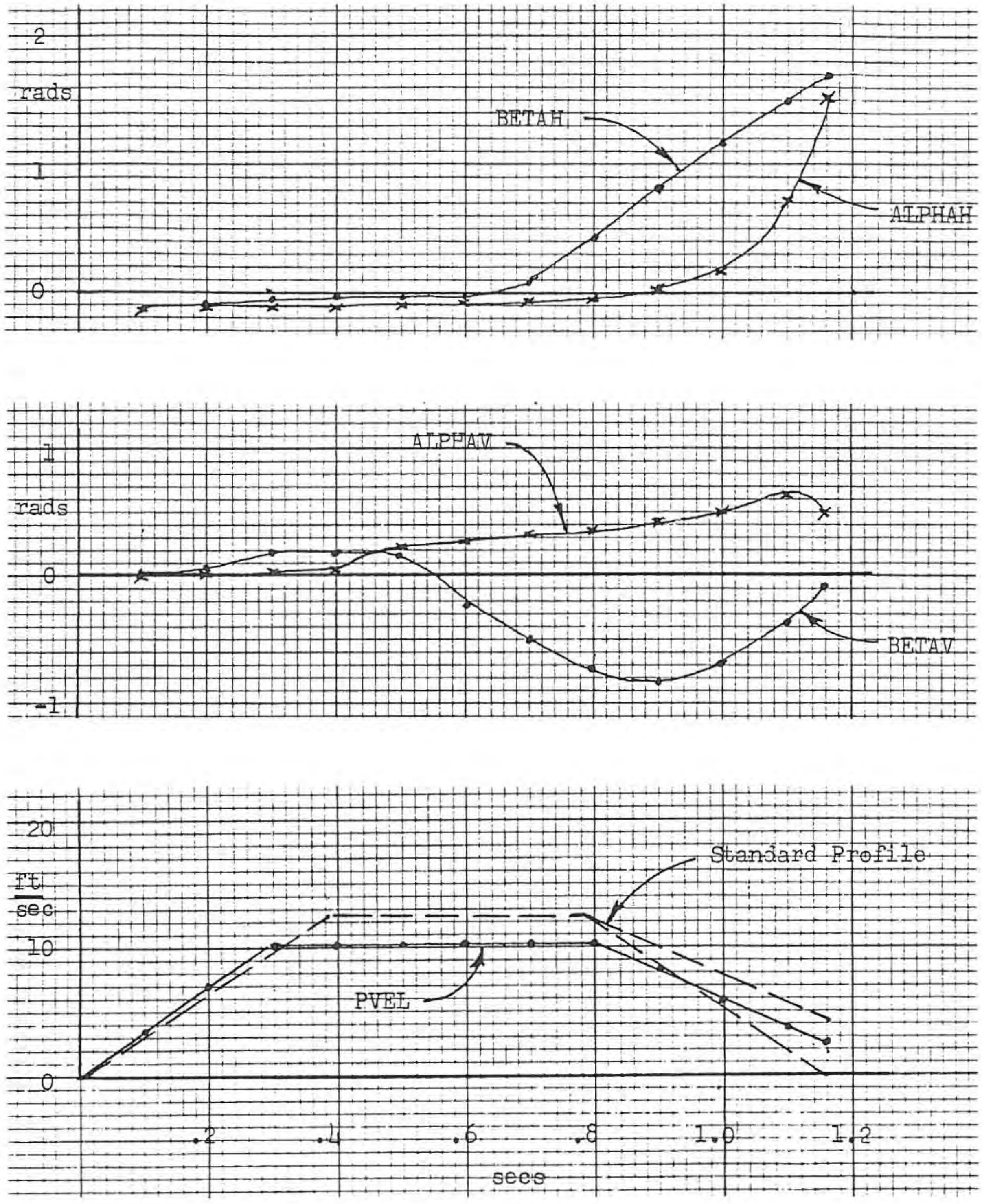


Figure 12.2 Functional relationship between a) ALPHAH and BETAH, b) ALPHAV and BETAV, and c) PVEL and Standard Velocity Profile, for (NDELYIN, NDELPIN, ABETAH, ABETAV, PACCEL) (0, 0, 2.0, 5.0, 20.0).

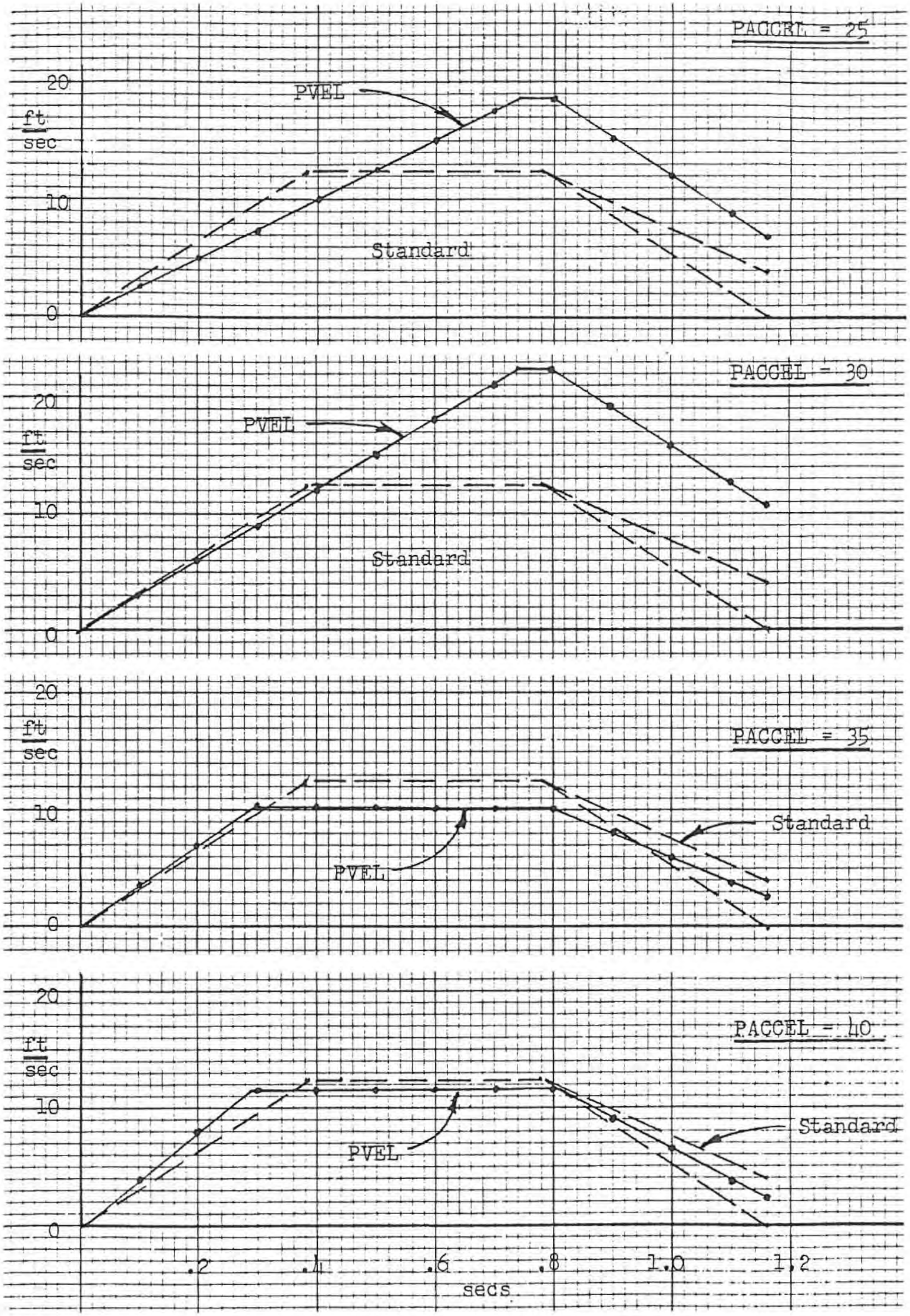


Figure 12.3. Actual vs desired velocity profile for Paccel equal to 25, 30, 35, and 40 ft/sec/sec, respectively, as a starting acceleration for the player.

the structural properties of the velocity profile and the method of correction. The actual velocity is always slightly enough less than the desired velocity that no acceleration cutoff occurs at the start of the constant velocity phase. But the refractory nature of the player also contributes to the large error because another 250 ms must pass before another correction is possible. By this time the player has far exceeded the required velocity.

SECOND EXTENSION

The second extension of the simulator generalizes the trajectory selection procedure to include down-the-line shots. The ball may thus be hit to the left of the receiver or to his right, and the player has to determine both the direction and magnitude of his starting acceleration. At the same time the player estimates the vertical and horizontal accelerations for his eyes. The program performs these tasks by evaluating a sign for the direction of acceleration and uses multipliers to evaluate magnitudes of acceleration, as follows.

On the first pass, for I = 1, the vertical and horizontal angular positions of the eyes are set. These positions change as the eye follows the ball, and on the tenth pass, for I = 10, the differences between the current positions and the "remembered" starting positions are computed. These are the values ALPHAVD and ALPHAHD. If ALPHAHD is less than 0.0, the sign, JSIGN, is set to -1; otherwise it is set to +1. On this same pass, the acceleration magnitudes are computed. That is,

```
PACCEL = ABS(MULTI*ALPHAHD)
ABETAV = ABS(MULT2*ALPHAVD)
ABETAH = ABS(MULT3*ALPHAHD)
```

As before, PACCEL is the body acceleration, and ABETAV and ABETAH are the vertical and horizontal accelerations, respectively, of the eyes. The details of this logic are shown in Appendix C.

If the ball is hit too far or too wide, the program detects it and outputs an "out of bounds" message. If the ball is hit too low, an "in the net" message is issued. It is assumed that the player is an expert in judging the ball in this respect, so he never interferes with a shot that is going out. In later models he will have to be made to "take" an occasional bad ball, but at this time the added complexity is unnecessary.

In this program the track and intercept logics are inhibited for a longer time than was the case in the previous versions. The reason is that the first refractory interval is designed to overlap the opponent's ball contact time. The time interval for the refractory period is taken to be the same as before, viz., 250 ms. But now a period of 150 ms is allocated to permit the player to "gain information" about the angle of the racquet face at the ball at the moment of contact. During the remaining 100 ms of the receiver's "immobility," he is gaining additional information from the change in the angular position of the ball as he views it. Based on this data he decides which way to run and how fast he must go.

The sureness and precision of his response are determined by the competence level set for him in this regard. In this extension of the program the player's competence is established by the above-mentioned multipliers, viz., MULT1, MULT2, and MULT3. They reflect the information gained about the ball during the full 250 ms of the refractory period. This information is converted into the starting accelerations PACCEL, ABETAV, and ABETAH using the equations above.

Considerably more analysis of the regulatory cues in the display during the time just prior to the release of the ball from the opponent's racquet is needed before a detailed simulation can be made of that information source. This is a particularly critical area for the player, so later programs will have to come to serious terms with the matter.

Some of the results of this program are presented in Figure 12.4. The player has chosen starting accelerations according to the

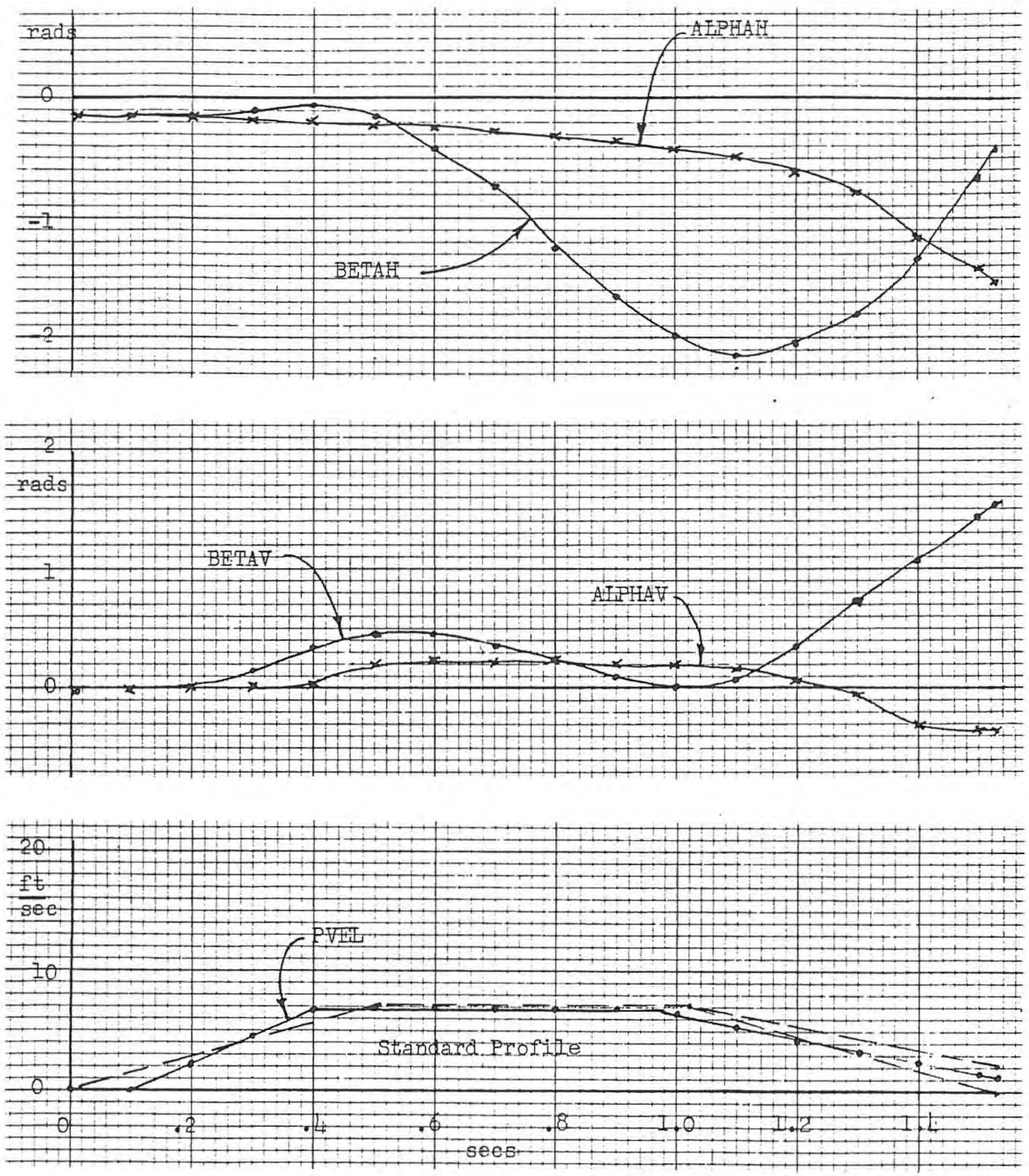


Figure 12.4. Functional relationship between a) ALPHAH and BETAH, b) ALPHAV and BETAV, and c) PVEL and standard velocity profile, for (NDELYPIN, NDELPIN, ABETAH, ABETAV, PACCEL) (2, 3, 2.4, 8.5, 23.9).

magnitude of the change of the angle of the line to the ball and they lead to fairly good track and intercept results after additional corrections made during the course of the trajectory. The relationship between the actual velocity profile and the standard profile is very close and the player intercepts the ball easily.

THIRD EXTENSION

The third extension incorporates a mechanism that allows the opponent to use a strategy for ball placement. The player chooses either a cross-court or a down-the-line shot, depending on the relative magnitude of the space in the court to the left of the receiver and to his right. He directs his shot to the midpoint of the larger of these two areas, according to the principle that he should, first, hit to where the opponent isn't, and second, take the conservative shot. The program requires as a starting condition that the position of each player on the court is specified. The height of each player must also be known, since this determines the player's perceptual perspective. The ball is presumed to be hit out of hand initially. The hitter must therefore choose the starting height as well as the speed and direction of the ball for the first trajectory.

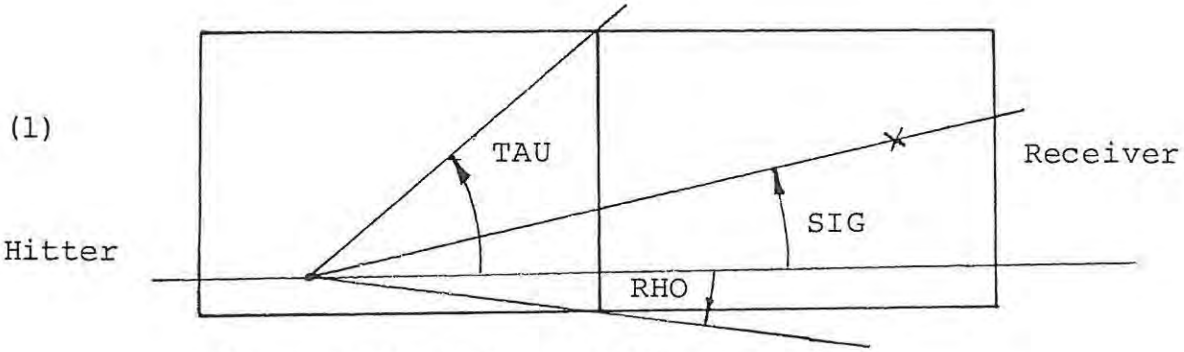
In the hitter's decision procedure, four geometric situations can be configured, as shown in Figure 12.5. In each of the four cases the hitter is at the apex of the projected angles. TAU, RHO, and SIG represent, respectively, the angles to the left court edge, the right court edge, and the receiver. LANG and RANG thus define the areas to the left and to the right of the receiver, from the hitter's point of view. From these four cases it can be seen that, in general,

$$\text{LANG} = \text{TAU} + \text{SIG}$$

and

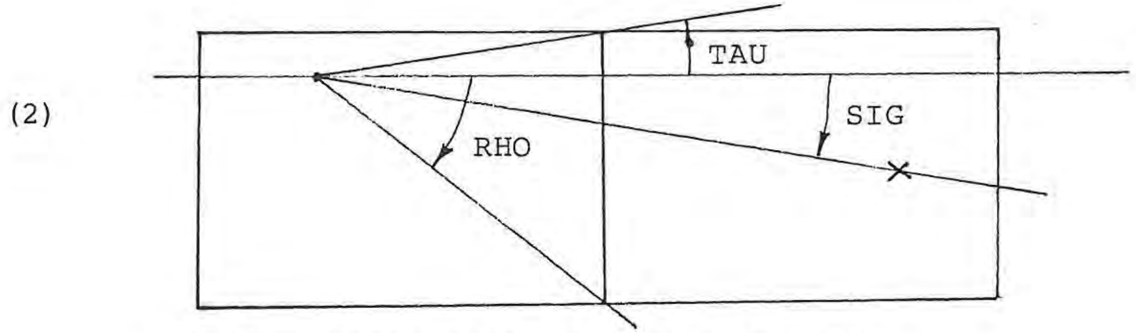
$$\text{RANG} = \text{RHO} + \text{SIG}.$$

The angle of trajectory, THETA, is then either (TAU + SIG)/2 if LANG is the larger, or (RHO + SIG)/2 if RANG is the larger.



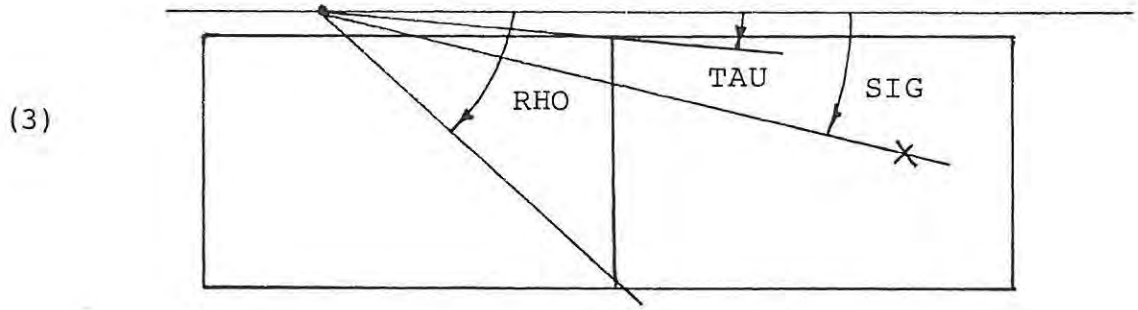
LANG = ATAN ((25-yo)/(39-x_o) - SIG

RANG = ATAN ((yo)/(39-xo) + SIG



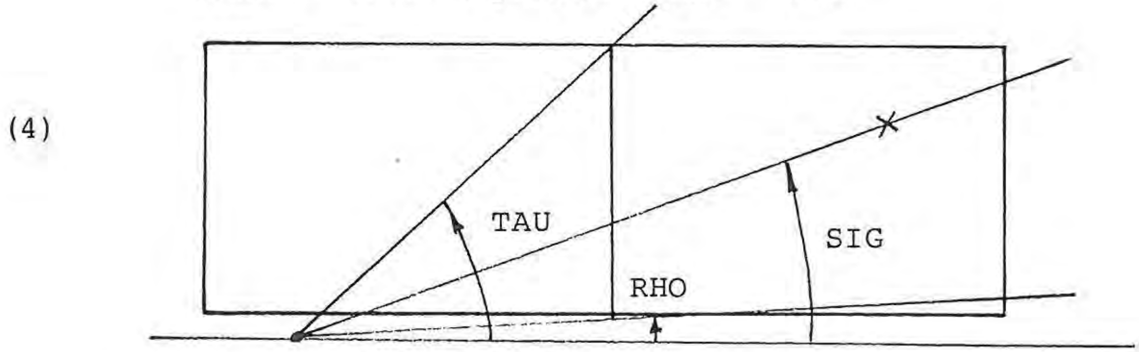
LANG = ATAN ((27-yo)/(39-xo)) + SIG

RANG = ATAN ((yo)/(39-xo)) - SIG



LANG = - ATAN ((y_o-27)/(39-xo)) + SIG

RANG = ATAN ((yo)/(39-xo)) - SIG



LANG = ATAN ((27+yo)/(39-xo)) - SIG

RANG = -ATAN ((yo)/(39-xo)) + SIG

Figure 12.5 Geometry for hitting area test; four cases.

To see that this is so, note the change in the sign of the angles.

Later versions of the simulator will incorporate mechanisms to deal in depth with forehand and backhand shots. At that time the hitter's decision-making process will have to be examined in more depth. The strategy of hitting to the weaker side will have to be considered in conjunction with other strategies. The current version simplifies the decision problem while yet demonstrating that mechanisation of the more complex process is feasible.

This extension proceeds with the tracking and intercept functions as in the previous version, but now the program lets the receiver, himself, be a hitter as well. Like the first hitter, he can choose either a cross-court or down-the-line shot, using the same principle of selection as his opponent. The height of the ball at contact is not under his control, of course; he must take what he gets. He can, however, select the speed and direction of the return shot.

In this program the first hitter is turned into a receiver, who must react to the ball hit to him. This is handled by repeating the appropriate segments of the program with new parameter values to accomodate the characteristics of the new receiver. So his effective height is specified, as are the multipliers which determine his competences, or accelerations initiating the track and intercept movements. In effect, the court is "turned around" so that the origin is at the opposite corner. The status indicator, SWITCH, is used to determine the route through the program for the respective player. If the first receiver fails to intercept the ball, there is of course no follow-on shot. In this event the program issues a 'missed intercept' message.

For any arbitrary shot, the value of the tag, ISIGN, is set in accordance with logic that tests the relative lateral position of the receiver to the hitter, the angle of the oncoming ball and whether it will pass to the right or to the left of the receiver. The boundary conditions of the trajectory are also determined using this data, and the appropriate message is issued if the shot is bad. The proper conditions for the receiver are thereby established as well.

The program list and output are given in Appendix D. Some results are shown in Figure 12.6, which depicts the movement of the first receiver, and Figure 12.7, which gives the movement of the second receiver. The agreement between actual and desired values is generally quite good. The only anomaly is with BETAH, in which a divergence occurred after a correction point and continued during the whole of the refractory period, as shown in Figure 12.6 for the first receiver. By the time the next correction began to have an effect, the divergence had extended to more than three radians. A less severe divergence began late in the second trajectory, but this was already into the last refractory interval and could not have affected the player's action at the ball. The receiver would already have been committed to his shot and could not have altered his movement to adjust to the visual divergence that was occuring.

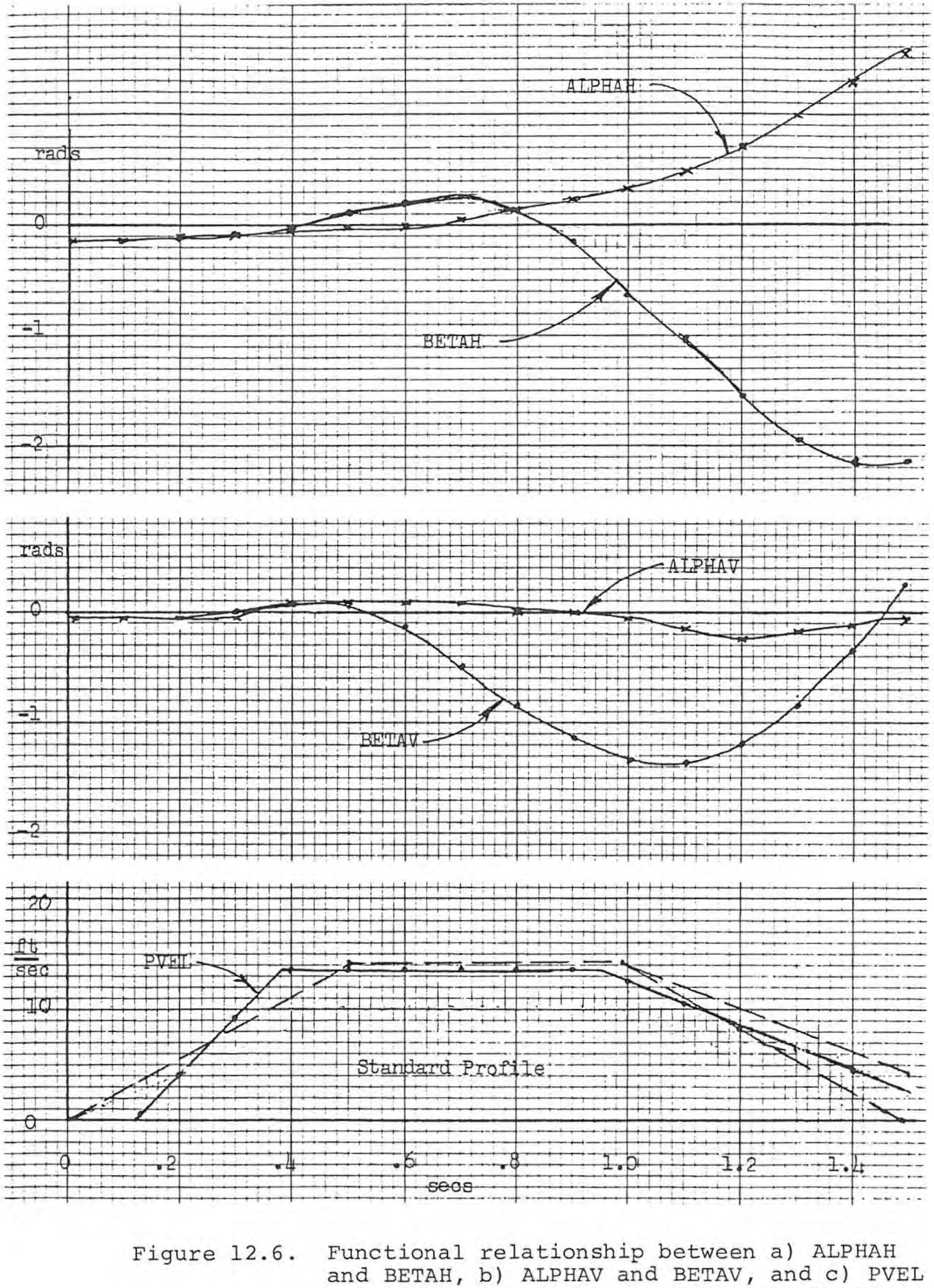


Figure 12.6. Functional relationship between a) ALPHAH and BETAH, b) ALPHAV and BETAV, and c) PVEL and Standard velocity profile for the first of a trajectory sequence, for (NDELYIN, NDELPIN, X0, and YO) = (2, 3, 5.8, and 3.5).

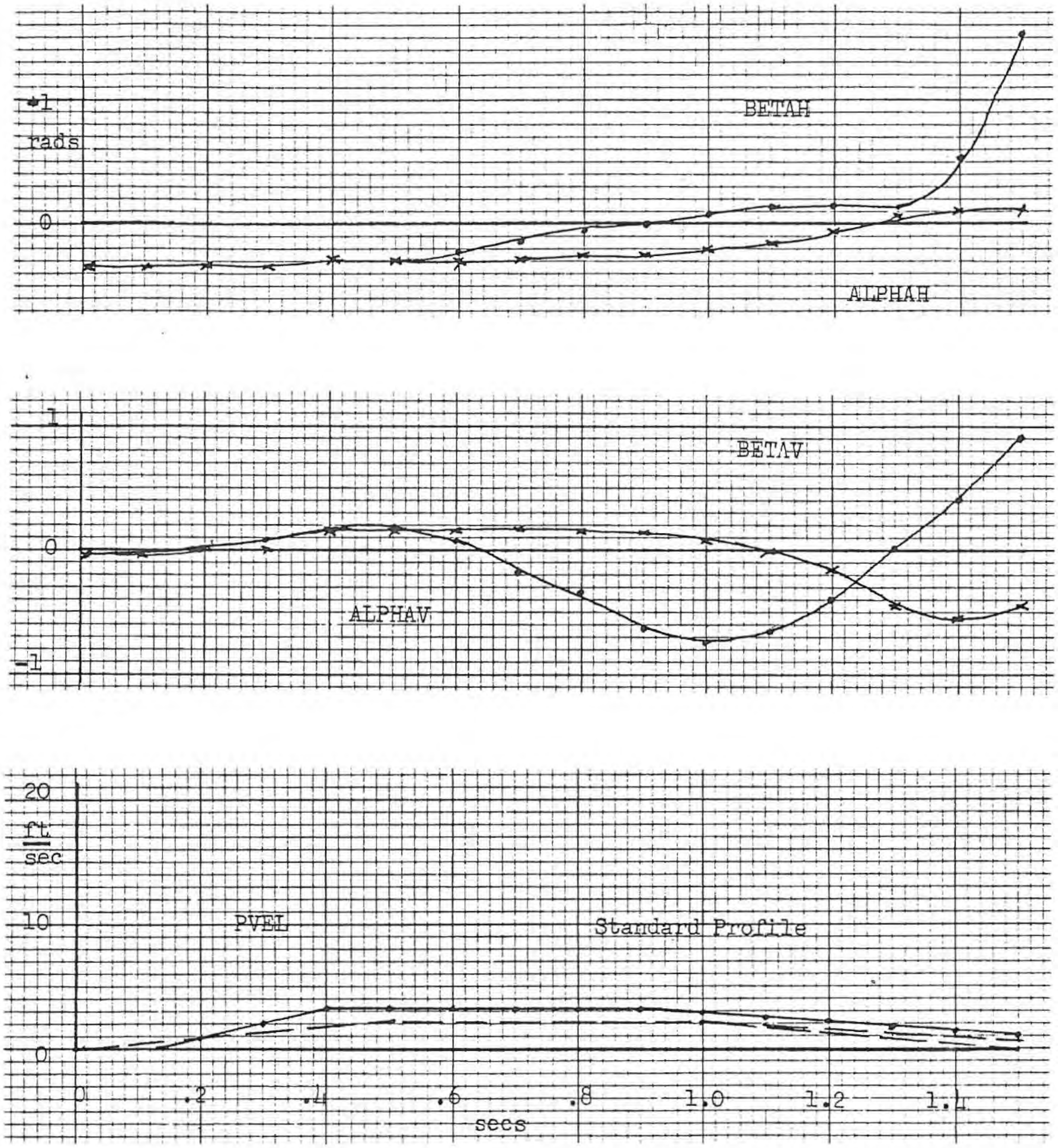


Figure 12.7. Functional relationship between a) ALPHAH and BETAH, b) ALPHAV and BETAV, and c) PVEL and Standard velocity profile for second of a trajectory sequence, for (NDELYIN, NDELPIN, PX, and PY) = (2, 3, 75.0, and 14.2).

SUMMARY AND PROSPECT

This work aims at the development of a full-fledged computer program to simulate the visuo-motor processes of the tennis athlete in the context of his playing or behavioral environment. The plan is to provide a way to examine and test the effectiveness of behavioral skills without subjecting him to possibly long and harmful, or at least wasteful, training. Support for such an idea comes from the successful use of simulation in the Aerospace industry to test new aircraft, spacecraft, or missile designs prior to the production of hardware. Simulated flight facilitates design and avoids many costly errors.

Simulation of the athlete is clearly a long-term effort fraught with difficulties. The athlete is an extremely complex system. Like him, the computer model has to "experience" its playing arena as well as move around in it; it has to be a self-starting, perceiving, self-directing, and self-regulating entity; it has to be able to act on its own, make its own decisions, and maneuver through the environment. This means that many physical, physiological, and psychological factors have to be considered. On the side of automation, analysis and formulation requires the development of many logical, mathematical, and programming mechanisms of simulation.

The work here is only a first step, the tip of a large pyramid of construction. But it is a new development in simulation. It interprets the player's perceptual-motor skills in terms of standards of behavior, strategies to be employed when behavior falls short of those standards, and competence levels. It provides a procedure for dealing with the player's subjective experience while at the same time representing his physical side. And it offers a precise formulation for the interaction of the subjective with the objective realm and the perceptual with the motor skills.

The player's skills are thus given a dual representation, one from the player's point of view and the other as considered by the public. There is an interplay between the two realms in that what the player sees, interprets and decides to do affects the way he moves, and the path of his motion affects what he sees, interprets and decides. In the program this interaction is handled by an information loop in which objective counterparts of personal behavior are feedback components.

The work deals basically with ball skills, or perceptual-motor skills related to the tracking and interception of a moving ball. It simulates these skills and thereby provides a vehicle for studying their dynamics for various combinations of competence levels on the skills. For example, one can run a series of trials for various trajectories to determine the velocity requirements for given intercept strategies and specific success rates. Or one can test the ability of players with specified movement and/or reaction-time limits to intercept certain classes of trajectories. (The data lists in the Appendices give some measure of such results.) Further, decision stresses can be imposed on the simulated player to evaluate the intercept results for given information processing capabilities. The procedure could possibly test the validity of different channel hypotheses.

As already noted, the prototype simulator is very specialized in the nature of the trajectory with which it deals and is highly restricted in the class of perceptual-motor functions which can be performed. For practical reasons, many aspects of the ultimate product had to be set aside for inclusion in later models. These include: simulation of the incident radiant energy, structuring the binocular system, use of parallax, representing receptive fields, modeling detailed movements of the eyes and the body, and simulating such psycho-sociological factors as intentional fields, attitudes and interests. The wide array of related subjects simply generates too much design material to be incorporated into a prototype or first working model.

In this respect, our player cannot be said to play particularly interesting or instructive tennis. But the model does provide a basis for further development, three examples of which were given in the previous chapter. Those variations were obtained merely by relaxing constraints on the prototype model, so that, for instance, the player was allowed to receive more than a single pre-designed cross-court trajectory and could move to his left as well as to his right to effect an interception. Other similar changes might be made as well without relinquishing the simplification gained by treating the ball and the players as points.

With expansion of the program to include more classes of trajectories or different kinds of shots, as well as more player functions, the range of tests can be expanded also. Thus it would be possible in principle to query the effects of various kinds of tactics on the success rate of play. The different tactics need to be simulated only with sufficient realism to give a reasonable approximation to the results that would occur in a real game context.

In the expansion of the program to include such functions as striking the ball, the "smoothed" behavioral field employed in the prototype model could be retained, but it would be necessary to drop the "point" representation in order to simulate the player's arm and racquet. A "line" representation might be used instead. This line could then be rotated by the player and applied as a racquet according to the conditions of the trajectory.

The problem is by no means trivial. The refractory nature of the player creates the situation that the racquet has to be brought into coincidence with the ball on the strength of information that could be at least .250 seconds old. In these last moments the ball could be rising rapidly and spinning away. If good ball contact is to be made, the changes in trajectory state must be predicted with considerable precision. A displacement of just a few inches one way or another could be enough to turn a good hit into a bad one. The action calls for considerable accuracy because the ball could easily travel thirty feet in the quarter-second refractory period. The velocity need only be 80 mph, which is 30% to 40% below the top speeds attained in the game. At higher ball speeds the difficulty in prediction increases dramatically, creating a great gulf between the novice and the player of championship caliber.

Without adding new functions, an extension of the prototype model could be made merely by enhancing the capability of the players. For example, a quadratic rather than a linear dead-reckoning procedure might be used to simulate the receiver's prediction of the state of the trajectory. The player might be allowed to adopt his choice of different intercept paths. Or his velocity profile could be made more sophisticated. These changes would add to the flexibility of the program, but they also add greatly to program complexity, because a variety of new tactics have to be incorporated and a decision procedure has to be established for the player's choice of action.

Retaining the "smoothed" level of simulation, the program might still incorporate certain ancillary functions, such as keeping tabs on the position and velocity of the opponent or the relative location of the net or boundary lines. The player has to be able to navigate. While "keeping his eye on the ball," he must be able to orient himself and know where he is at all times. This calls for a complex set of organizing and decision-making principles.

A major step in the development of a full-fledged simulator is to give spatial extension to the receiving player's visual field. This can be done without discarding either the point/line representation for the receiver or the smoothed nature of his experience. Initially, however, only the simplest formulation of the objects of his field would be feasible. For example, the ball and his opponent might still be shown as points. The net, court surface and surrounding screens could be simplified to be opaque rectangles, and the painted lines of the court boundary could be presented as dimensionless lines. The receiver would have to be one-eyed under these circumstances; principles of perspective could then portray, in physical space, the shapes of the proximal images of these surfaces as the player moved to intercept the ball. The rudiments of detection and identification might then be incorporated as components of the processing by means of which he constructs his behavioral environment. But this could entail only a functional representation of the physiological processes; structural details, such as feature detectors and receptive fields, would have to be omitted.

Another major step would be to represent the receiver, himself, as a 3-dimensional figure. At first this should involve no more than a simplified anatomical model for the 3-d representation, possibly using mechanical linkages to tie the bones together and 3rd class levers for the muscle system. Some relatively simple movements could then be simulated. Extensions on this simulator could yield more detailed structures and increasingly complex movement groups, possibly allowing movements of the head to control line-of-sight positioning for purposes of tracking.

Eventually, the eye, too, has to be simulated. As we have seen, the eye is a complex structure, involving a great deal of anatomical and neurophysiological details, so the modeling must begin simply, as with the structure of the rest of the body. For instance, it can be treated as a sphere having three degrees of freedom and a uniform index of refraction. The retina may be presumed to consist only of cones, since rods are not used in daylight, when tennis is normally played.

Binocular vision has also to be simulated. This clearly requires two proximal images, one for each eye, and some kind of mechanism by means of which a single, unified patterned response is effected to represent the player's behavioral environment.

Cones, neural nets, or receptive fields may or may not be designed as part of the process. The representation may be functional rather than structural, at least to begin with. If parallax is to be simulated, representation of the visual field for each eye has to be sufficiently detailed to reflect the subtle differences in perspective which produce the parallax.

We have seen that the eyes are in constant motion, so that the proximal images are constantly shifting. To simulate this process, saccadic and microsaccadic movements have to be represented. This adds greatly to the complexity of the program because now a mechanism has to be used to smooth the action to generate the stable, relatively unchanging world of normal experience.

These and other extensions of the basic program are projected. It is evident that a great deal of work remains to be done. The prototype model is only a beginning. It is a first essential step in a long process of refinement to characterize the action of the player with realism. If progress is to be made toward this goal, more detailed explorations are required in many directions.

For example, if the movement of the ball is to be presented more realistically, account would have to be taken of spin, aerodynamic drag and wind factors. This could change the trajectory characteristics drastically and thus alter both the equations of motion of the ball and the techniques used to mechanize its interception.

Incorporation of a "striking" capability for the hitter requires a more detailed study of the movements involved in the swing. And guiding geometry has to be formulated. The servo loops controlling the processes have to be designed and the role of afferent and efferent signals in these control loops has to be clarified. Do the signals directly affect the muscles, and if so, how? And how are the biases on the control loops produced? These and other aspects of the problem have to be examined in depth.

When the transition is made in the simulation to an iconic representation of the physical and experiential fields, a wide range of topics has to be re-examined. This includes a study of the properties of surfaces and their boundaries and the manner in which light interacts with them. The question of the nature of the information content of light has to be reopened. It is necessary to ask again how the proximal image is converted to a 3-d representation of the world. What cues does the player use to identify the ball and other aspects of his environment? What regulatory cues does he use to direct his actions? Which regulatory cues would be more efficient? How can he code his information to maximize his information processing rate? What coding techniques would minimize his reaction times?

These and many other physical, psychological and physiological ideas have to be considered in depth before they can be applied to construct a full-fledged simulation of the tennis athlete. A start has now been made, and it is reasonable to believe that better and better approximations are possible. But a lot more work and a great deal of determination will be required to carry on with the job.

I think it is fair to say that the need for simulation in sports is increasing. Athletes across the board are reaching new heights in physical ability and skills. A great deal of money is being spent: in player salaries, new and better equipment, bigger facilities, and improved sports medicine. In short, winning at sports has become very big business, and competition is getting very keen. To stay in the game it is becoming increasingly more important to find ways to examine and improve athletic technique. Simulation is one of these ways.

Appendix A

Prototype Program List

```
JOB QFORTRAN,CSHP ,PAPPO
MINIMOP CSHP
FORTRANCOMP FXXX
VOLUME 40000
EXECUTE
****
```

```
RUN BY GEORGE 2/MK9F

FORTRAN COMPILATION BY #XFAT MK 6B

DATE 06/09/79  TIME 09/30/52
```

```
LIST
PROGRAM (TENN)
OUTPUT 6=LP0
COMPRESS INTEGER AND LOGICAL
COMPACT
TRACE 2
END
```

```
                MASTER TENNIS

      COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, NDELPIN, PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
     * NDELYCOR

C  SET INITIAL CONDITIONS FOR THE CROSS-COURT TRACK AND
C  INTERCEPT FUNCTIONS

      I = 0
      TIME = 0.0
      BHEIGHT = 4.0
      BVELV = 14.0
      BVELH = 60.0
      BDIST = 79.1
      ALPHAV = -0.0126
      ALPHAH = -0.1714
      VALPHAV = 0.18
      VALPHAH = 0.13
      THETA = 0.3330
      PHI = 0.1714
      BVELR = 10.2
      BETAV = -0.0126
      BETAH = -0.1714
      VBETAV = 0.0
      VBETAH = 0.0
      ABETAV = 20.0
      ABETAH = 20.0
      PX = 78.0
      PY = 13.5
      PVEL = 0.0
      PACCEL = 24.0
      PHEIGHT = 5.0
      PDIST = 0.0
      PACCSTD = 24.0
      PACCEL36 = -24.0
      X = 0.0
      Y = 0.0
      R = 0.0
      ALPHAV25 = 0.0
      ALPHAH25 = 0.0
      PDIST250 = 0.0
      BDIST250 = 0.0
      VALPHAV2 = 0.0
      VALPHAH2 = 0.0
      PVEL250 = 0.0
      N5CTR = -1
      N25CTR = -1
      N100CTR = -1
      DTGO = 10.5
      TTGO = 1.36
      BETAV250 = 0.0
      BETAH250 = 0.0
      ABETAV25 = 0.0
      ABETAH25 = 0.0
      VBETAV25 = 0.0
      VBETAH25 = 0.0
      DTG250 = 0.0
      TTG250 = 0.0

C  SET STATUS INDICATORS AND DELAY COUNTERS

      IFOLLOW = 0
      INTERCEPT = 0
      NDELYIN = 7
      NDELPIN = 11
      NDELYCOR = -1
      NDELPCOR = -1
      IFLAG = 0
```

```
C SET INCREMENTAL CONSTANTS

       DELTAT1 = 0.01
        DELTAT2 = 0.25

       WRITE (6,6000)
6000   FORMAT (1H1/////////////////////////////, 56X, '- TENNIS -')
       WRITE (6,6001)
6001   FORMAT (////1H ,41X,'SIMULATION OF THE VISUO-MOTOR PROCESSES')
       WRITE (6,6002)
6002   FORMAT (////1H ,52X,'A PROTOTYPE MODEL')
       WRITE (6,6003)
6003   FORMAT (//////////1H ,55X,'H. A. PAPPO')
       WRITE (6,6004)
6004   FORMAT (1H ,52X,'RHODES UNIVERSITY')
       WRITE (6,6005)
6005   FORMAT (1H ,58X,'1979')


C   AFTER PRINTING TITLE PAGE, GO TO NEXT PAGE AND PRINT ARRAY
C   OF PARAMETER NAMES.  SKIP SIX LINES AND PRINT CORRES-
C   PONDING ARRAY OF INITIAL VALUES OF THOSE PARAMETERS.
C   AFTER PASS THROUGH FIRST TIME-SLICE, CONTROL RETURNS TO
C   LINE 100 AND PARAMETER VALUES ARE PRINTED OUT ON NEXT
C   PAGE.  SKIP THREE LINES AND PRINT SECOND PASS RESULTS.
C   SKIP THREE MORE AND PRINT THIRD TIME-SLICE SLICE RESULTS.
C   REPEAT ON NEXT PAGE.

       WRITE (6,6008)

       WRITE (6,6010)
       WRITE (6,6011)
       WRITE (6,6012)
       WRITE (6,6013)
       WRITE (6,6014)
       WRITE (6,6015)
       WRITE (6,6016)
       WRITE (6,6017)


6008   FORMAT(1H1,40X,'DATA BLOCK AND STARTING VALUES')

6010   FORMAT(//////////1H ,34X,'I',7X,'TIME',4X,'BHEIGHT',5X,
     *   'ALPHAV',5X,'ALPHAH',6X,'PDIST')
6011   FORMAT(1H ,28X,'IFOLLOW',2X,'INTERCEPT',6X,
     *   'BDIST',3X,'ALPHAV25',3X,'ALPHAH25',3X,'PDIST250')
6012   FORMAT(1H ,28X,'NDELYIN',4X,'NDELPIN',3X,
     *   'BDIST250',4X,'VALPHAV',4X,'VALPHAH',7X,'PVEL')
6013   FORMAT(1H ,27X,'NDELYCOR',3X,'NDELPCOR',6X,
     *   'BVELV',3X,'VALPHAV2',3X,'VALPHAH2',4X,'PVEL250')
6014   FORMAT(/1H ,30X,'N5CTR',5X,'N25CTR',10X,'R',6X,
     *   'BETAV',6X,'BETAH',5X,'PACCEL')
6015   FORMAT(1H ,28X,'N100CTR',6X,'IFLAG',8X,'PHI',5X,
     *   'VBETAV',5X,'VBETAH',4X,'PACCSTD')
6016   FORMAT(1H ,31X,'DTGO',7X,'TTGO',3X,'BETAV250',5X,
     *   'ABETAV',5X,'ABETAH',3X,'VBETAV25')
6017   FORMAT(1H ,29X,'DTG250',5X,'TTG250',3X,'BETAH250',
     *   3X,'ABETAV25',3X,'ABETAH25',3X,'VBETAH25')

       WRITE (6,6160) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
                    K = 0
                GO TO 103
100       IF(I .LT. 137) GO TO 101
C   END OF RUN
          STOP

101       IF(K .NE. 1) GO TO 102

       WRITE (6,6444) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
                    K = -5
                GO TO 103
102    WRITE (6,6130) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
103    WRITE (6,6100) IFOLLOW,INTERCEPT,PDIST,ALPHAV25,ALPHAH25,PDIST250
       WRITE (6,6100) NDELYIN,NDELPIN,BDIST250,VALPHAV,VALPHAH,PVEL
       WRITE (6,6100) NDELYCOR,NDELPCOR,BVELV,VALPHAV2,VALPHAH2,PVEL250
       WRITE (6,6110) N5CTR,N25CTR,R,BETAV,BETAH,PACCEL
       WRITE (6,6100) N100CTR,IFLAG,PHI,VBFTAV,VBETAH,PACCSTD
       WRITE (6,6120) DTGO,TTGO,BETAV250,ABETAV,ABETAH,VBETAV25
       WRITE (6,6120) DTG250,TTG250,BETAH250,ABETAV25,ABETAH25,VBETAH25
```

```
                K = K + 1

6100    FORMAT (1H ,24X,2I11,4F11.4)
6110    FORMAT (/1H ,24X,2I11,4F11.4)
6120    FORMAT (1H ,24X,6F11.4)
6150    FORMAT (/////1H ,24X,I11,5F11.4)
6160    FORMAT (//////1H ,24X, I11,5F11.4)
6444    FORMAT (1H1,24X,I11,5F11.4)

C   UPDATE TIME-SLICE AND TIME FROM PROGRAM START.  TEST TIME FOR
C   PLAYER TO BEGIN HIS DECELERATION.  INITIATE PROCESSING OF
C   GENERAL FOLLOW AND INTERCEPT LOOP.

105                  I = I + 1
                  TIME = TIME + 0.01
                TTGO = 1.36 - TIME
                DTGO = 10.5 - PDIST
               IF (TIME .LT. 1.0) GO TO 110
                IF (IFLAG .NE. 1) GO TO 110
                    PACCEL = PACCEL36

C   POSITION AND VELOCITY OF BALL ARE COMPUTED IN COURT COORDINATES

110               CALL COMPUTE

C   UPDATE COUNTERS
                 N5CTR = N5CTR - 1
               N25CTR = N25CTR - 1
             N100CTR = N100CTR - 1
             NDELYIN = NDELYIN - 1
             NDELPIN = NDELPIN - 1
            NDELYCOR = NDFLYCOR - 1
            NDELPCOR = NDELPCOR - 1

C   STATUS CHECKS ARE REQUIRED TO DETERMINE CONDITION OF CORRECTION
C   DELAY COUNTERS BEFORE INTERCEPT AND/OR FOLLOW LOGICS CAN BE
C   PROCESSED.

                  IF(NDELPCOR) 200, 210, 220
200            IF(NDELYCOR) 300, 250, 260

C   CORRECT FOLLOW MOVEMENT ONLY
250               ABETAV = ABETAVT
                     ABETAH = ABETAHT
                     GO TO 820
C   NO CORRECTION.  DELAY STILL OPERATIVE.
260               GO TO 830

210            IF(NDELYCOR) 230, 270, 280

C   CORRECT INTERCEPT MOVEMENT ONLY
230            IF(TIME .GE. 1.0) GO TO 232
                    PACCEL = PACCSTD
                     GO TO 820
232             PACCEL = PACCEL36
                    GO TO 820

C   CORRECT BOTH FOLLOW AND INTERCEPT MOVEMENTS.
270             ABETAV = ABETAVT
                  ABETAH = ABETAHT
                   GO TO 230

C   CORRECT INTERCEPT MOVEMENT ONLY.  FOLLOW CORRECTION DELAY
C   STILL OPERATIVE.
280            IF(TIME .GE. 1.0) GO TO 282

                    PACCEL = PACCSTD
                     GO TO 820
282              PACCEL = PACCEL36
                     GO TO 820

220            IF(NDELYCOR) 240, 290, 299

C   NO CORRECTION.  DELAY STILL OPERATIVE.
240               GO TO 830

C   CORRECT FOLLOW MOVEMENT ONLY.  INTERCEPT CORRECTION DELAY
```

```
C  STILL OPERATIVE.
290            ABETAV = ABETAVT
                 ABETAH = ABETAHT
                  GO TO 820

C  NO CORRECTION.  BOTH DELAYS STILL OPERATIVE.
299              GO TO 100


C  CHECK CONDITION OF DELAYS ON FOLLOW AND INTERCEPT MOVEMENTS

300          IF(NDELYIN .GT. 0) GO TO 320
                IF(NDELPIN .GT. 0) GO TO 400

C  STARTING DELAYS NO LONGER OPERATIVE, SO CHECK STATUS OF
C  THE FOLLOW AND/OR INTERCEPT LOGIC TO ESTABLISH PROGRAM
C  SEQUENCE.

                IF(IFOLLOW .EQ. 1) GO TO 500
                IF(INTERCEPT .EQ. 1) GO TO 600

C  OTHERWISE ACTIVATE BOTH FOLLOW AND INTERCEPT LOGIC.
310               IFOLLOW = 1
                    INTERCEPT = 1

C  ENTER INFORMATION PROCESSING LOOP FOR FOLLOW AND INTERCEPT
                    GO TO 820

C  FOLLOW LOGIC STILL NOT ACTIVE.  STARTING DELAY STILL OPERATIVE

320          IF(NDELPIN .GT. 0) GO TO 350

C  INTERCEPT LOGIC DELAY NO LONGER OPERATIVE, SO CHECK STATUS
C  OF INTERCEPT LOGIC TO ESTABLISH PROGRAM SEQUENCE.

                IF(INTERCEPT .EQ. 1) GO TO 600

C  INTERCEPT LOGIC NOT ACTIVE, SO ACTIVATE AND BEGIN PROCESSING.
                    INTERCEPT = 1

C  ENTER INFORMATION PROCESSING LOOP FOR INTERCEPT AND
C  POSSIBLY FOLLOW LOGIC.
                    GO TO 820

C  BOTH FOLLOW AND INTERCEPT LOGIC DELAYS STILL OPERATIVE,
C  SO NO PLAYER ACTION.
350               GO TO 100

C  INTERCEPT LOGIC DELAY STILL OPERATIVE, SO TEST FOLLOW LOGIC
C  STATUS.
400          IF(IFOLLOW .EQ. 1) GO TO 450
                  IFOLLOW = 1

C  ENTER INFORMATION PROCESSING LOOP FOR FOLLOW AND POSSIBLY
C  INTERCEPT LOGIC.
                    GO TO 820

C  FOLLOW LOGIC ACTIVE, SO ENTER INFORMATION PROCESSING LOOP
C  AS IF INTERCEPT ALSO ACTIVE.
450          IF(N100CTR .LE. 0) GO TO 700
                    GO TO 830

C  FOLLOW LOGIC ACTIVE, SO TEST INTERCEPT LOGIC.
500          IF(INTERCEPT .EQ. 1) GO TO 550
                IF(N100CTR .LE. 0) GO TO 700
                  INTERCEPT = 1

C  ENTER INFORMATION LOOP TO PROCESS FOLLOW AND INTERCEPT LOGIC
                    GO TO 830

C  BOTH FOLLOW AND INTERCEPT LOGICS ACTIVE.
550               GO TO 830

C  INTERCEPT LOGIC ACTIVE, SO TEST 100 MS COUNTER.
600          IF(N100CTR .GT. 0) GO TO 650
                  IFOLLOW = -1

C  ENTER INFORMATION LOOP TO PROCESS ONLY INTERCEPT LOGIC.
                    GO TO 830
```

```
C  100 MS COUNTER STILL OPERATIVE, SO ENTER INFORMATION LOOP
C  TO PROCESS INTERCEPT AND   FOLLOW LOGIC.
650             IFOLLOW = 1
                    GO TO 830

C  FOLLOW LOGIC ACTIVE AND 100 MS DELAY TIME PASSED, SO
C  PROCESS ONLY FOLLOW LOGIC.
700            INTERCEPT = -1
                    GO TO 830


C  INITIALIZE TRAJECTORY VELOCITY COUNTERS AND BEGIN VELOCITY
C  AVERAGING.

820                 N5CTR = 5
                     N25CTR = 25
                   N100CTR = 10
                      BVSUMV = 0
                      BVSUMH = 0
                      TOTALV = 0
                      TOTALH = 0
C  INITIALIZE FEEDFORWARD COMPUTATION USING CURRENT VALUESOF POSITION
C  AND VELOCITY OF PLAYER AND LINE OF SIGHT AND LINE TO BALL
         BETAVST = BETAV
         BETAHST = BETAH
        VBETAVST = VBETAV
        VBETAHST = VBETAH
       GAMMAVST = ALPHAV - BETAV
       GAMMAHST = ALPHAH - BETAH
      VGAMAVST = VALPHAV - VBETAV
      VGAMAHST = VALPHAH - VBETAH
       PDISTST = PDIST
        PVELST = PVEL
      PACCELST = PACCEL
           RST = R
      BHEIGTST = BHEIGHT
        TIMEST = TIME
        ABETAVST = ABETAV
        ABETAHST = ABETAH
         IST = I
C  BEGIN PROCESSING FOLLOW AND/OR INTERCEPT LOGIC.  FIRST
C  OBTAIN AVERAGE OF VERTICAL COMPONENTS OF TRAJECTORY
C  VELOCITY AND AVERAGE OF HORIZONTAL COMPONENTS.

830       IF(TTGO .LE. 0.25) GO TO 100

          BVSUMV = BVSUMV + BVELV
          BVSUMH = BVSUMH + BVELH

        IF(N5CTR .GT. 1) GO TO 835
           BVAVE1V = BVSUMV/5.0
           BVAVE1H = BVSUMH/5.0
            BVSUMV = 0.0
            BVSUMH = 0.0

              N5CTR = 6

         TOTALV = TOTALV + BVAVE1V
         TOTALH = TOTALH + BVAVE1H

835    IF(N25CTR .NE. 1) GO TO 100

C  COMPUTE PLAYER'S ESTIMATE OF TRAJECTORY VELOCITY
C  COMPONENTS USING AVERAGE VELOCITY

         BVAVE2V = TOTALV/5.0
         BVAVE2H = TOTALH/5.0

C  COMPUTE ESTIMATED VALUES OF PLAYER'S DISTANCE ATTAINED
C  IN 250 MS AND PLAYER VELOCITY AT 250 MS.  DATA USED
C  FOR BOTH FOLLOW AND INTERCEPT LOGICS./

        PDIST250=PDISTST+PVELST*DELTAT2+PACCELST*DELTAT2**2
       PVEL250=PVELST+PACCELST*DELTAT2


C  TEST STATUS OF FOLLOW LOGIC FOR INFO PROCESSING.

              IF(IFOLLOW .EQ. -1) GO TO 970
```

```
C   PROCESS FOLLOW LOGIC USING ESTIMATED PLAYER POSITION
C   AND VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                          CALL FOLLOW

C   TEST STATUS OF INTERCEPT LOGIC FOR INFO PROCESSING.

970               IF(INTERCEPT .EQ. -1) GO TO 988

C   PROCESS INTERCEPT LOGIC USING ESTIMATED PLAYER POSITION
C   AND VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                  IF(TIMEST .GT. 0.5) GO TO 972
              DTG250 = 1.15*(10.5 - PDIST250)
                       GO TO 973

972             IF(TIMEST .GT. 1.0) GO TO 974
              DTG250 = 1.10*(10.5 - PDIST250)
                       GO TO 973

974         DTG250 = 1.05*(10.5 - PDIST250)

973             TTG250 = 1.36 - TIMEST - 0.25

C   PLAYER COMPARES ESTIMATED ACTUAL WITH ESTIMATED DESIRED VELOCITY
C   AT THE 250 MARK

                  IF(TIMEST .GT. 0.5) GO TO 980
                 PVSTDST = PACCSTD * TIMEST
              PVSTD250 = PVSTDST + PACCSTD * DELTAT2
        IF(ABS(PVSTD250 - PVEL250) .LE. 0.05*(PVSTD250+PVEL250))GO TO 987
             IF(PVSTD250 - PVEL250 .GT. 0.0) GO TO 987
                        PACCSTD = 0.0

C   PACCEL MUST BE SET TO ZERO ALSO, BUT THIS CAN'T BE DONE
C   UNTIL THE DELAY, NDELPCOR, FOR PLAYER CORRECTION HAS
C   COUNTED DOWN

                         NDELPCOR = 4
                          GO TO 987

980             IF(TIMEST .GT. 1.0) GO TO 987
                        PVSTD250 = 11.6

                         PACCSTD = 0.0
                         NDELPCOR = 4

        IF(ABS(PVSTD250 - PVEL250) .LE. 0.05*(PVSTD250+PVEL250))GO TO 985
                IF(PVSTD250 - PVEL250 .LT. 0.0) GO TO 981
                        PACCEL36 = -22.4

C   PACCEL IS ALSO SET TO -22.4, BUT NOT UNTIL TIME = 1.0.

                          GO TO 986

981                    PACCEL36 = -33.5
                          GO TO 986
985                    PACCEL36 = -24.0
986                       IFLAG = 1
987                     INTERCEPT = 0
                         IFOLLOW = 0
                          GO TO 100

988             IF(IFOLLOW .EQ. 1) GO TO 100
                       INTERCEPT = 0
                        IFOLLOW = 0
                          GO TO 100
          END

END OF SEGMENT, LENGTH  1600, NAME  TENNIS
```

```
                    SUBROUTINE COMPUTE

      COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, NDELPIN, PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
     * NDELYCOR

C   COMPUTE POSITION AND VELOCITY OF BALL IN COURT COORDS.

                   R = BVELH*TIME
               IF(TIME .LE. 0.44) GO TO 130
               IF(TIME .LE. 1.10) GO TO 120

         BHEIGHT = 16.0*(TIME - 1.10)*(2.10 - TIME)
          BVELV = 16.0 - 32.0*(TIME - 1.10)
                 GO TO 140

120     BHEIGHT = 7.06 - 16.0*(TIME - 0.44)**2
            BVELV = 32.0*(TIME - 0.44)
                 GO TO 140

130     BHEIGHT = 14.0*TIME - 16.0*TIME**2 + 4.0
            BVELV = 14.0 - 32.0*TIME

C   COMPUTE DISTANCE AND ANGULAR POSITION AND VELOCITY OF BALL

140     BDIST = SQRT((78.0-R*COS(THETA))**2+(13.5+PDIST-R*SIN(THETA))**2)
                ALPHAV = ATAN((BHEIGHT - 5.0)/BDIST)
              ALPHAH = ATAN((Y - 13.5 - PDIST)/(78.0 - X))
                VALPHAV = BVELV/BDIST
          W = (13.5 + PDIST - R*SIN(THETA))/(78.0 - R*COS(THETA))
                  PHI = ATAN(W)
        VALPHAH = (BVELH*SIN(THETA - PHI) - PVEL*COS(PHI))/BDIST

C   MOVEMENT OF PLAYER'S LINE OF SIGHT (LOS) IS DELAYED BY AN
C   AMOUNT EQUAL TO THE PLAYER'S REACTION TIME TO OPPONENT'S
C   STRIKING THE BALL.

              IF(NDELYIN .GT. 0) GO TO 180

C   AFTER THE DELAY, ANGULAR POSITION AND VELOCITY OF LOS ARE
C   COMPUTED.

          BETAV = BETAV + VBETAV*DELTAT1 + ABETAV*DELTAT1**2
          BETAH = BETAH + VBETAH*DELTAT1 + ABETAH*DELTAT1**2
            VBETAV = VBETAV + ABETAV*DELTAT1
            VBETAH = VBETAH + ABETAH*DELTAT1

C   MOVEMENT OF PLAYER IS DELAYED BY AN AMOUNT EQUAL TO HIS
C   REACTION TIME TO OPPONENT'S STRIKING THE BALL.

180       IF(NDELPIN .GT. 0) GO TO 190

C   THE NEW POSITION AND VELOCITY OF PLAYER IN HIS INTERCEPT
C   PATH ARE COMPUTED AS SOON AS THE DELAY HAS COUNTED DOWN.

          PDIST = PDIST + PVEL*DELTAT1 + PACCEL*DELTAT1**2
            PVEL = PVEL + PACCEL*DELTAT1

190         RETURN
               END

END OF SEGMENT, LENGTH   333, NAME  COMPUTE
```

```
                   SUBROUTINE FOLLOW

      COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, HDELPIN, PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
     * HDELYCOR

C   PROCESS FOLLOW LOGIC USING ESTIMATED PLAYER POSITION AND
C   VELOCITY AND PREPARE CORRECTION IF NECESSARY.

              IF(TIMEST .LE. 0.44) GO TO 841
              IF(TIMEST .LE. 1.10) GO TO 842

841       BHEIT250 = BHEIGTST + BVAVE2V*DELTAT2
                GO TO 843

842       BHEIT250 = BHEIGTST - BVAVE2V*DELTAT2
843          R250 = RST + BVAVE2H*DELTAT2
       BDIST250 = SQRT((78.0 - R250*COS(THETA))**2
     *            + (13.5 + PDIST250 - R250*SIN(THETA))**2)

C   FIND ANGULAR POSITION AND VELOCITY OF LINE TO BALL

              ALPHAV25 = ATAN((BHEIT250 - 5.0)/BDIST250)
      ALPHAH25=ATAN((R250*SIN(THETA)-PDIST250)/(78.0-R250*COS(THETA)))
          VALPHAV2 = BVAVE2V/BDIST250
         W250 = (13.5+PDIST250-R250*SIN(THETA))/(78.0-R250*COS(THETA))
       VALPHAH2=(BVAVE2H*SIN(THETA-ATAN(W250))-PVEL250*COS(ATAN(W250)))/
     *                   BDIST250

C   FIND ANGULAR POSITION AND VELOCITY OF LOS AND FORM DIFFERENCES

         BETAV250 = BETAVST + VBETAVST*DELTAT2 + ABETAVST*DELTAT2**2
         BETAH250 = BETAHST + VBETAHST*DELTAT2 + ABETAHST*DELTAT2**2
             VBETAV25 = VBETAVST + ABETAVST*DELTAT2
             VBETAH25 = VBETAHST + ABETAHST*DELTAT2
               GAMAV250 = ALPHAV25 - BETAV250
               GAMAH250 = ALPHAH25 - BETAH250

             VGAMAV25 = VALPHAV2 - VBETAV25
             VGAMAH25 = VALPHAH2 - VBETAH25

C   THE ANGULAR DIFFERENCES AND ANGULAR VELOCITY DIFFERENCES MUST
C   NOW BE COMPARED AGAINST THE PLAYER'S STANDARDS OF MAGNITUDE

       IF(ABS(GAMAV250).LE.0.05*(ALPHAV25 + BETAV250)) GO TO 844
            IF(GAMAV250 .LT. 0.0) GO TO 845
          IF(ABS(GAMAV250) .LE. 0.18) GO TO 846
          IF(ABS(GAMAV250) .LE. 0.9) GO TO 847

C   VERTICAL ANGULAR DIFF IS LARGE POSITIVE
                 VANGDIFF = 3
                    GO TO 851
846             VANGDIFF = 1
                    GO TO 851
847             VANGDIFF = 2

                    GO TO 851

C VERTICAL ANG DIFF IS NEGATIVE

845       IF(ABS(GAMAV250) .LE. 0.18) GO TO 848
            IF(ABS(GAMAV250) .LE. 0.9) GO TO 849

                 VANGDIFF = -3
                    GO TO 851
848             VANGDIFF = -1
                    GO TO 851
849             VANGDIFF = -2
```

```
                  GO TO 851
844           VANGDIFF = 0
851      IF(ABS(GAMAH250) .LE. 0.05*(ALPHAH25 + BETAH250)) GO TO 854
                 IF(GAMAH250 .LT. 0.0) GO TO 855
              IF(ABS(GAMAH250) .LE. 0.18) GO TO 856
              IF(ABS(GAMAH250) .LE. 0.9) GO TO 857
C  HORIZONTAL ANGULAR DIFF IS LARGE POSITIVE
                HANGDIFF = 3
                  GO TO 861
856           HANGDIFF = 1
                  GO TO 861
857           HANGDIFF = 2
                  GO TO 861
C  HORIZONTAL ANG DIFF IS NEGATIVE
855        IF(ABS(GAMAH250) .LE. 0.18) GO TO 858
              IF(ABS(GAMAH250) .LE. 0.9) GO TO 859
                HANGDIFF = -3
                  GO TO 861
858           HANGDIFF = -1
                  GO TO 861
859           HANGDIFF = -2
                  GO TO 861
854            HANGDIFF = 0
861      IF(ABS(VGAMAV25) .LE. 0.05*(VALPHAV2+VBETAV25)) GO TO 864
              IF(VGAMAV25 .LT. 0.0) GO TO 865
              IF(ABS(VGAMAV25) .LE. 0.18) GO TO 866
              IF(ABS(VGAMAV25) .LE. 0.9) GO TO 867
C  VERTICAL ANGULAR VELOCITY DIFF IS LARGE POSITIVE
                  VANVDIFF = 3
                    GO TO 871
866             VANVDIFF = 1
                    GO TO 871
867             VANVDIFF = 2
                    GO TO 871
C  HORIZONTAL ANGULAR VELOCITY DIFF IS NEGATIVE
865         IF(ABS(VGAMAV25) .LE. 0.18) GO TO 868
               IF(ABS(VGAMAV25) .LE. 0.9) GO TO 869
                  VANVDIFF = -3
                    GO TO 871
868             VANVDIFF = -1
                    GO TO 871
869             VANVDIFF = -2
                    GO TO 871
864             VANVDIFF = 0
871     IF(ABS(VGAMAH25) .LE. 0.05*(VALPHAH2 + VBETAH25)) GO TO 874
                 IF(VGAMAH25 .LT. 0.0) GO TO 875
              IF(ABS(VGAMAH25) .LE. 0.18) GO TO 876
              IF(ABS(VGAMAH25) .LE. 0.9) GO TO 877
C  HORIZONTAL ANGULAR VELOCITY DIFF IS LARGE POSITIVE
                  HANVDIFF = 3
                    GO TO 881
876             HANVDIFF = 1
                    GO TO 881
877             HANVDIFF = 2
                    GO TO 881
C  HORIZONTAL ANGULAR VELOCITY DIFF IS NEGATIVE
875         IF(ABS(VGAMAH25) .LE. 0.18) GO TO 878
               IF(ABS(VGAMAH25) .LE. 0.9) GO TO 879
                  HANVDIFF = -3
```

```
                     GO TO 881
878              HANVDIFF = -1
                     GO TO 881
879              HANVDIFF = -2
                     GO TO 881

874              HANVDIFF = 0

881              L1 = VANGDIFF + VANVDIFF
                    L2 = HANGDIFF + HANVDIFF

                IF(L1 .LT. 0) GO TO 884
                IF(L1 .EQ. 0) GO TO 885
                IF(L1 .EQ. 1) GO TO 886
                IF(L1 .EQ. 2) GO TO 887

C  VERTICAL DRIVING ACCELERATION IS LARGE POSITIVE.

                     ABETAV25 = 20.0
                         GO TO 891
885                ABETAV25 = 0.0
                         GO TO 891
886                ABETAV25 = 5.0
                         GO TO 891
887                ABETAV25 = 10.0
                         GO TO 891

884           IF(L1 .EQ. -1) GO TO 888
                IF(L1 .EQ. -2) GO TO 889

C  VERTICAL DRIVING ACCELERATION IS LARGE NEGATIVE.

                     ABETAV25 = -20.0
                         GO TO 891
888                ABETAV25 = -5.0
                         GO TO 891
889                ABETAV25 = -10

891            IF(L2 .LT. 0) GO TO 894
                  IF(L2 .EQ. 0) GO TO 895
                  IF(L2 .EQ. 1) GO TO 896
                  IF(L2 .EQ. 2) GO TO 897

C  HORIZONTAL DRIVING ACCELERATION IS LARGE POSITIVE.

                     ABETAH25 = 20.0
                         GO TO 900
895                ABETAH25 = 0.0
                         GO TO 900
896                ABETAH25 = 5.0
                         GO TO 900
897                ABETAH25 = 10.0
                         GO TO 900

894           IF(L2 .EQ. -1) GO TO 898
                IF(L2 .EQ. -2) GO TO 899

C  HORIZONTAL DRIVING ACCELERATION IS LARGE NEGATIVE.

                     ABETAH25 = -20.0
                         GO TO 900
898                ABETAH25 = -5.0
                         GO TO 900
899                ABETAH25 = -10.0

C  DETERMINE VALUE OF PLAYER'S CORRECTION TO EYE MOVEMENT.

900       IF(ABS(ABETAV + ABETAV25) .LE. 20.0) GO TO 920
            IF(ABETAV + ABETAV25 .LT. 0.0) GO TO 930

C  PLAYER APPLIES MAXIMUM VERTICAL ACCELERATION.
                         ABETAVT = 20.0
                           GO TO 940

C  PLAYER APPLIES MAXIMUM VERTICAL DECELERATION.
930                      ABETAVT = -20.0
                           GO TO 940
```

```
C  CORRECTIVE ADDITION DOESN'T EXCEED MAXIMUM ACCELERATION.
920             ABETAVT = ABETAV + ABETAV25
940       IF(ABS(ABETAH + ABETAH25) .LE. 20.0) GO TO 950
              IF(ABETAH + ABETAH25 .LT. 0.0) GO TO 960
C  PLAYER APPLIES MAXIMUM HORIZONTAL ACCELERATION.
                      ABETAHT = 20.0
                        GO TO 965
C  PLAYER APPLIES MAXIMUM HORIZONTAL DECELERATION.
960                 ABETAHT = -20.0
                        GO TO 965
C  CORRECTIVE ADDITION DOESN'T EXCEED MAXIMUM DECELERATION.
950             ABETAHT = ABETAH + ABETAH25
965                  NDELYCOR = 3
                     IFOLLOW = 0
          RETURN
           END

END OF SEGMENT, LENGTH  1230, NAME  FOLLOW
```

```
                         FINISH
END OF COMPILATION -  NO ERRORS

S/C SUBFILE:                  74 BUCKETS USED


CONSOLIDATED BY XPCK 12K    DATE    06/09/79   TIME 09/14/53

PROGRAM TENN
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE               7488

                SEG     TENNIS
                CUV     BALL
                SEG     COMPUTE
                SEG     FOLLOW
                SEG     ABS
                SEG     SQRT
                SEG     COS
                SEG     SIN
                SEG     ATAN
                CLV     SPFIL
```

Appendix B

First Extension of the Prototype Model

```
JOB QFORTRAN,CSHP ,PAPPO
MINIMOP CSHP
FORTRANCOMP FXXX
VOLUME 40000
EXECUTE
****
```

```
RUN BY GEORGE 2/MK9F

FORTRAN COMPILATION BY #XFAT MK 6B

DATE  22/10/79  TIME  09/55/55
```

```
LIST
PROGRAM (TENN)
OUTPUT 6=LPO
COMPRESS INTEGER AND LOGICAL
COMPACT
TRACE 2
END
```

```
            MASTER TENNIS

      COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, NDELPIN, PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
     * NDELYCOR, TM1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
     * X0, Y0, PX, PY, BVELVGR

C  SELECT CROSS-COURT TRAJECTORY STARTING CONDITIONS,
C  RECEIVER STARTING POSITION, AND LINE-OF-SIGHT
C  STARTING CONDITIONS

      I = 0
      TIME = 0.0
      X0 = 5.8
      Y0 = 3.5
      BHEIGHT0 = 3.5
      BVELV0 = 15.0
      BVELH0 = 63.0
      THETA = 0.3330
      BETAV = -0.020
      BETAH = -0.136
      VBETAV = 0.0
      VBETAH = 0.0
      ABETAV = 5.0
      ABETAH = 2.0
      PX = 75.0
      PY = 14.2
      PVEL = 0.0
      PACCEL = 35.0
      PHEIGHT = 5.0

C  SET STATUS INDICATORS AND COUNTERS

      IFOLLOW = 0
      INTERCEPT = 0
      NDELYIN = 0
      NDELPIN = 0
      NDELYCOR = -1
      NDELPCOR = -1
      IFLAG = 0
      N5CTR = -1
      N25CTR = -1
      N100CTR = -1

C SET INCREMENTAL CONSTANTS

      DELTAT1 = 0.01
       DELTAT2 = 0.25

C  SET FEEDFORWARD COMPUTATION PARAMATERS TO ZERO

      ALPHAV25 = 0.0
      ALPHAH25 = 0.0
      PDIST250 = 0.0
      BDIST250 = 0.0
      VALPHAV2 = 0.0
      VALPHAH2 = 0.0
      PVEL250 = 0.0
      BETAV250 = 0.0
      BETAH250 = 0.0
      ABETAV25 = 0.0
      ABETAH25 = 0.0
      VBETAV25 = 0.0
      VBETAH25 = 0.0
      DTG250 = 0.0
      TTG250 = 0.0

      WRITE (6,6000)
 6000 FORMAT (1H1///////////////////////////////, 56X, '- TENNIS -')
```

```
      WRITE (6,6001)
6001  FORMAT (////1H ,41X,'SIMULATION OF THE VISUO-MOTOR PROCESSES')
      WRITE (6,6002)
6002  FORMAT (////1H ,52X,'A PROTOTYPE MODEL')
      WRITE (6,6003)
6003  FORMAT (//////////1H ,55X,'H. A. PAPPO')
      WRITE (6,6004)
6004  FORMAT (1H ,52X,'RHODES UNIVERSITY')
      WRITE (6,6005)
6005  FORMAT (1H ,58X,'1979')

C   AFTER PRINTING TITLE PAGE, GO TO NEXT PAGE AND PRINT ARRAY
C   OF PARAMETER NAMES. AFTER FIRST TIME-SLICE PASS, SKIP
C   FIVE LINES AND PRINT PARAMETER VALUES.  SKIP FIVE MORE
C   LINES AND PRINT SECOND PASS RESULTS.  ETC.  REPEAT ON
C   NEXT PAGE.

      WRITE (6,6008)

      WRITE (6,6010)
      WRITE (6,6011)
      WRITE (6,6012)
      WRITE (6,6013)
      WRITE (6,6014)
      WRITE (6,6015)
      WRITE (6,6016)
      WRITE (6,6017)


6008  FORMAT(1H1,46X,'TIME-SLICE DATA BLOCK')

6010  FORMAT(/////////////1H ,34X,'I',7X,'TIME',4X,'BHEIGHT',5X,
     *   'ALPHAV',5X,'ALPHAH',6X,'PDIST')
6011  FORMAT(1H ,28X,'IFOLLOW',2X,'INTERCEPT',6X,
     *   'BDIST',3X,'ALPHAV25',3X,'ALPHAH25',3X,'PDIST250')
6012  FORMAT(1H ,28X,'NDELYIN',4X,'NDELPIN',3X,
     *   'BDIST250',4X,'VALPHAV',4X,'VALPHAH',7X,'PVEL')
6013  FORMAT(1H ,27X,'NDELYCOR',3X,'NDELPCOR',6X,
     *   'BVELV',3X,'VALPHAV2',3X,'VALPHAH2',4X,'PVEL250')
6014  FORMAT(/1H ,30X,'N5CTR',5X,'N25CTR',10X,'R',6X,
     *   'BETAV',6X,'BETAH',5X,'PACCEL')
6015  FORMAT(1H ,28X,'N100CTR',6X,'IFLAG',8X,'PHI',5X,
     *   'VBETAV',5X,'VBETAH',4X,'PACCSTD')
6016  FORMAT(1H ,31X,'DTGO',7X,'TTGO',3X,'BETAV250',5X,
     *   'ABETAV',5X,'ABETAH',3X,'VBETAV25')
6017  FORMAT(1H ,29X,'DTG250',5X,'TTG250',3X,'BETAH250',
     *   3X,'ABETAV25',3X,'ABETAH25',3X,'VBETAH25')

         DTGO0 = (PX - XO)*TAN(THETA) - PY + YO - 3
         TTGO0 = (PX - XO)/(BVELHO*COS(THETA))
                K = -4
            GO TO 104
100     IF(I .LT. TTGO0*100) GO TO 101
C   END OF RUN
          STOP

101     IF(K .NE. 1) GO TO 102

      WRITE (6,6444) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
               K = -5
            GO TO 103
102   WRITE (6,6130) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
103   WRITE (6,6100) IFOLLOW,INTERCEPT,BDIST,ALPHAV25,ALPHAH25,PDIST250
      WRITE (6,6100) NDELYIN,NDFLPIN,BDIST250,VALPHAV,VALPHAH,PVEL
      WRITE (6,6100) NDELYCOR,NDELPCOR,BVELV,VALPHAV2,VALPHAH2,PVEL250
      WRITE (6,6110) N5CTR,N25CTR,R,BETAV,BETAH,PACCEL
      WRITE (6,6100) N100CTR,IFLAG,PHI,VBETAV,VBETAH,PACCSTD
      WRITE (6,6120) DTGO,TTGO,BETAV250,ABETAV,ABETAH,VBETAV25
      WRITE (6,6120) DTG250,TTG250,BETAH250,ABETAV25,ABETAH25,VBETAH25


104          K = K + 1
        BVELH = BVELHO

6100  FORMAT (1H ,24X,2I11,4F11.4)
6110  FORMAT (/1H ,24X,2I11,4F11.4)
6120  FORMAT (1H ,24X,6F11.4)
6130  FORMAT (/////1H ,24X,I11,5F11.4)
6444  FORMAT (1H1,24X,I11,5F11.4)
```

```
C  UPDATE TIME-SLICE AND TIME FROM PROGRAM START.  TEST TIME FOR
C  PLAYER TO BEGIN HIS DECELERATION.  INITIATE PROCESSING OF
C  GENERAL FOLLOW AND INTERCEPT LOOP.

105                I = I + 1
                TIME = TIME + 0.01
              TTGO = TTGOO - TIME
              DTGO = DTGOO - PDIST
             IF (TIME .LT. 2.0*TTGOO/3.0) GO TO 110
              IF (IFLAG .NE. 1) GO TO 110
                 PACCEL = PACCEL36

C  POSITION AND VELOCITY OF BALL ARE COMPUTED IN COURT COORDINATES

110             CALL COMPUTE

C  UPDATE COUNTERS
                N5CTR = N5CTR - 1
              N25CTR = N25CTR - 1
             N100CTR = N100CTR - 1
             NDELYIN = NDELYIN - 1
             NDELPIN = NDELPIN - 1
            NDELYCOR = NDELYCOR - 1
            NDELPCOR = NDELPCOR - 1

C  STATUS CHECKS ARE REQUIRED TO DETERMINE CONDITION OF CORRECTION
C  DELAY COUNTERS BEFORE INTERCEPT AND/OR FOLLOW LOGICS CAN BE
C  PROCESSED.

                IF(NDELPCOR) 200, 210, 220
200           IF(NDELYCOR) 300, 250, 260

C  CORRECT FOLLOW MOVEMENT ONLY
250             ABETAV = ABETAVT
                  ABETAH = ABETAHT
                   GO TO 820
C  NO CORRECTION.  DELAY STILL OPERATIVE.
260             GO TO 830

210           IF(NDELYCOR) 230, 270, 280

C  CORRECT INTERCEPT MOVEMENT ONLY
230           IF(TIME .GE. 2.0*TTGOO/3.0) GO TO 232
                  PACCEL = PACCSTD
                   GO TO 820
232            PACCEL = PACCEL36
                  GO TO 820

C  CORRECT BOTH FOLLOW AND INTERCEPT MOVEMENTS.
270            ABETAV = ABETAVT
                 ABETAH = ABETAHT
                  GO TO 230

C  CORRECT INTERCEPT MOVEMENT ONLY.  FOLLOW CORRECTION DELAY
C  STILL OPERATIVE.
280           IF(TIME .GE. 2.0*TTGOO/3.0) GO TO 282

                  PACCEL = PACCSTD
                   GO TO 820
282             PACCEL = PACCEL36
                   GO TO 820

220           IF(NDELYCOR) 240, 290, 299

C  NO CORRECTION.  DELAY STILL OPERATIVE.
240             GO TO 830

C  CORRECT FOLLOW MOVEMENT ONLY.  INTERCEPT CORRECTION DELAY
C  STILL OPERATIVE.
290             ABETAV = ABETAVT
                  ABETAH = ABETAHT
                   GO TO 820

C  NO CORRECTION.  BOTH DELAYS STILL OPERATIVE.
299             GO TO 100

C  CHECK CONDITION OF DELAYS ON FOLLOW AND INTERCEPT MOVEMENTS
```

```
300          IF(NDELYIN .GT. 0) GO TO 320
                IF(NDELPIN .GT. 0) GO TO 400

C   STARTING DELAYS NO LONGER OPERATIVE, SO CHECK STATUS OF
C   THE FOLLOW AND/OR INTERCEPT LOGIC TO ESTABLISH PROGRAM
C   SEQUENCE.

                IF(IFOLLOW .EQ. 1) GO TO 500
                IF(INTERCEPT .EQ. 1) GO TO 600

C   OTHERWISE ACTIVATE BOTH FOLLOW AND INTERCEPT LOGIC.
310                IFOLLOW = 1
                     INTERCEPT = 1

C   ENTER INFORMATION PROCESSING LOOP FOR FOLLOW AND INTERCEPT
                     GO TO 820

C   FOLLOW LOGIC STILL NOT ACTIVE.  STARTING DELAY STILL OPERATIVE

320          IF(NDELPIN .GT. 0) GO TO 350

C   INTERCEPT LOGIC DELAY NO LONGER OPERATIVE, SO CHECK STATUS
C   OF INTERCEPT LOGIC TO ESTABLISH PROGRAM SEQUENCE.

                IF(INTERCEPT .EQ. 1) GO TO 600

C   INTERCEPT LOGIC NOT ACTIVE, SO ACTIVATE AND BEGIN PROCESSING.
                     INTERCEPT = 1

C   ENTER INFORMATION PROCESSING LOOP FOR INTERCEPT AND
C   POSSIBLY FOLLOW LOGIC.
                     GO TO 820

C   BOTH FOLLOW AND INTERCEPT LOGIC DELAYS STILL OPERATIVE,
C   SO NO PLAYER ACTION.
350               GO TO 100

C   INTERCEPT LOGIC DELAY STILL OPERATIVE, SO TEST FOLLOW LOGIC
C   STATUS.
400          IF(IFOLLOW .EQ. 1) GO TO 450
                   IFOLLOW = 1

C   ENTER INFORMATION PROCESSING LOOP FOR FOLLOW AND POSSIBLY
C   INTERCEPT LOGIC.
                     GO TO 820

C   FOLLOW LOGIC ACTIVE, SO ENTER INFORMATION PROCESSING LOOP
C   AS IF INTERCEPT ALSO ACTIVE.
450          IF(N100CTR .LE. 0) GO TO 700
                     GO TO 830

C   FOLLOW LOGIC ACTIVE, SO TEST INTERCEPT LOGIC.
500          IF(INTERCEPT .EQ. 1) GO TO 550
                IF(N100CTR .LE. 0) GO TO 700
                   INTERCEPT = 1

C   ENTER INFORMATION LOOP TO PROCESS FOLLOW AND INTERCEPT LOGIC
                     GO TO 830

C   BOTH FOLLOW AND INTERCEPT LOGICS ACTIVE.
550               GO TO 830

C   INTERCEPT LOGIC ACTIVE, SO TEST 100 MS COUNTER.
600          IF(N100CTR .GT. 0) GO TO 650
                    IFOLLOW = -1

C   ENTER INFORMATION LOOP TO PROCESS ONLY INTERCEPT LOGIC.
                     GO TO 830

C   100 MS COUNTER STILL OPERATIVE, SO ENTER INFORMATION LOOP
C   TO PROCESS INTERCEPT AND   FOLLOW LOGIC.
650             IFOLLOW = 1
                     GO TO 830

C   FOLLOW LOGIC ACTIVE AND 100 MS DELAY TIME PASSED, SO
C   PROCESS ONLY FOLLOW LOGIC.
700            INTERCEPT = -1
                     GO TO 830
```

```
C  INITIALIZE TRAJECTORY VELOCITY COUNTERS AND BEGIN VELOCITY
C  AVERAGING.

820               N5CTR = 5
                   N25CTR = 25
                 N100CTR = 10
                    BVSUMV = 0
                    BVSUMH = 0
                    TOTALV = 0
                    TOTALH = 0
C  INITIALIZE FEEDFORWARD COMPUTATION USING CURRENT VALUESOF POSITION
C  AND VELOCITY OF PLAYER AND LINE OF SIGHT AND LINE TO BALL
         BETAVST = BETAV
         BETAHST = BETAH
        VBETAVST = VBETAV
        VBETAHST = VBETAH
       GAMMAVST = ALPHAV - BETAV
       GAMMAHST = ALPHAH - BETAH
      VGAMAVST = VALPHAV - VBETAV
      VGAMAHST = VALPHAH - VBETAH
       PDISTST = PDIST
        PVELST = PVEL
      PACCELST = PACCEL
           RST = R
      BHEIGTST = BHEIGHT
        TIMEST = TIME
        ABETAVST = ABETAV
        ABETAHST = ABETAH
         IST = I
C  BEGIN PROCESSING FOLLOW AND/OR INTERCEPT LOGIC.  FIRST
C  OBTAIN AVERAGE OF VERTICAL COMPONENTS OF TRAJECTORY
C  VELOCITY AND AVERAGE OF HORIZONTAL COMPONENTS.

830       IF(TTGO .LE. 0.25) GO TO 100

          BVSUMV = BVSUMV + BVELV
          BVSUMH = BVSUMH + BVELH

        IF(N5CTR .GT. 1) GO TO 835
          BVAVE1V = BVSUMV/5.0
           BVAVE1H = BVSUMH/5.0
            BVSUMV = 0.0
            BVSUMH = 0.0

              N5CTR = 6

         TOTALV = TOTALV + BVAVE1V
         TOTALH = TOTALH + BVAVE1H

835    IF(N25CTR .NE. 1) GO TO 100

C  COMPUTE PLAYER'S ESTIMATE OF TRAJECTORY VELOCITY
C  COMPONENTS USING AVERAGE VELOCITY

         BVAVE2V = TOTALV/5.0
         BVAVE2H = TOTALH/5.0

C  COMPUTE ESTIMATED VALUES OF PLAYER'S DISTANCE ATTAINED
C  IN 250 MS AND PLAYER VELOCITY AT 250 MS.  DATA USED
C  FOR BOTH FOLLOW AND INTERCEPT LOGICS./

        PDIST250=PDISTST+PVELST*DELTAT2+PACCELST*DELTAT2**2
       PVEL250=PVELST+PACCELST*DELTAT2


C  TEST STATUS OF FOLLOW LOGIC FOR INFO PROCESSING.

              IF(IFOLLOW .EQ. -1) GO TO 970

C  PROCESS FOLLOW LOGIC USING ESTIMATED PLAYER POSITION
C  AND VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                    CALL FOLLOW

C  TEST STATUS OF INTERCEPT LOGIC FOR INFO PROCESSING.

970        IF(INTERCEPT .EQ. -1) GO TO 988

C  PROCESS INTERCEPT LOGIC USING ESTIMATED PLAYER POSITION
```

```
C   AND VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                 IF(TIMEST .GT. TTG00/3) GO TO 972
            DTG250 = 1.15*(DTG00 - PDIST250)
                    GO TO 973

972           IF(TIMEST .GT. 2.0*TTG00/3.0) GO TO 974
            DTG250 = 1.10*(DTG00 - PDIST250)
                    GO TO 973

974       DTG250 = 1.05*(DTG00 - PDIST250)

973         TTG250 = TTG00 - TIMEST - 0.25

C   PLAYER COMPARES ESTIMATED ACTUAL WITH ESTIMATED DESIRED VELOCITY
C   AT THE 250 MARK

             PVMSTD = 18.0*DTG00/(13.0*TTG00)

                 IF(TIMEST .GT. TTG00/3) GO TO 980
              PACCSTD = 3.0*PVMSTD/TTG00
                PVSTDST = PACCSTD * TIMEST
             PVSTD250 = PVSTDST + PACCSTD * DELTATZ
        IF(ABS(PVSTD250 - PVEL250) .LE. 0.05*(PVSTD250+PVEL250))GO TO 987
            IF(PVSTD250 - PVEL250 .GT. 0.0) GO TO 987
                   PACCSTD = 0.0

C   PACCEL MUST BE SET TO ZERO ALSO, BUT THIS CAN'T BE DONE
C   UNTIL THE DELAY, NDELPCOR, FOR PLAYER CORRECTION HAS
C   COUNTED DOWN

                   NDELPCOR = 4
                    GO TO 987

980           IF(TIMEST .GT. 2.0*TTG00/3.0) GO TO 987
                    PVSTD250 = PVMSTD

                     PACCSTD = 0.0
                    NDELPCOR = 1

        IF(ABS(PVSTD250 - PVEL250) .LE. 0.05*(PVSTD250+PVEL250))GO TO 985
                 IF(PVSTD250 - PVEL250 .LT. 0.0) GO TO 981

          PACCEL36 = -(2.0*PVMSTD/3)/(TTG00 - 2*TTG00/3)

C   PACCEL IS ALSO SET TO  THIS VALUE, BUT NOT UNTIL TIME .
C   EQUALS 2*TTG00/3,

                      GO TO 986

981                PACCEL36 = -PVMSTD/(TTG00 -2*TTG00/3)
                      GO TO 986
985                PACCEL36 = -(5.0*PVMSTD/6.0)/(TTG00 -2.0*TTG00/3.0)
986                    IFLAG = 1
987                 INTERCEPT = 0
                     IFOLLOW = 0
                      GO TO 100

988          IF(IFOLLOW .EQ. 1) GO TO 100
                  INTERCEPT = 0
                    IFOLLOW = 0
                      GO TO 100
            END

     END OF SEGMENT, LENGTH  1610, NAME  TENNIS
```

```
                SUBROUTINE COMPUTE
      COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, NDELPIN, PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
     * NDELYCOR, TM1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
     * X0, Y0, PX, PY, BVELVGR

C  COMPUTE POSITION AND VELOCITY OF BALL IN COURT COORDS.

                R = BVELH*TIME
            TM1 = BVELV0/32.0
        BHEIGHT1 = BVELV0 - 16.0*TM1*TM1 + BHEIGHT0
            TGR = SQRT(BHEIGHT1/16.0)
             TG = TGR + TM1
          BVELVGR = 32.0*TGR
             IF(TIME .LE. TM1) GO TO 130
             IF(TIME .LE. TG) GO TO 120

        BHEIGHT = 16.0*(TIME - TG) - 16.0*(TIME - TG)**2
          BVELV = 16.0 - 32.0*(TIME - TG)
                GO TO 140

120     BHEIGHT = BHEIGHT1 - 16.0*(TIME - TM1)**2
          BVELV = 32.0*(TIME - TM1)
                GO TO 140

130     BHEIGHT = BVELV0*TIME - 16.0*TIME**2 + BHEIGHT0
          BVELV = BVELV0 - 32.0*TIME

C  COMPUTE DISTANCE AND ANGULAR POSITION AND VELOCITY OF BALL

140           X = R*COS(THETA) + X0
              Y = R*SIN(THETA) + Y0
        BDIST = SQRT((PX - X)**2 + (PY + PDIST - Y)**2)
             ALPHAV = ATAN((BHEIGHT - 5.0)/BDIST)
          ALPHAH = ATAN((Y - PY - PDIST)/(PX - X))
              VALPHAV = BVELV/BDIST
           W = (PY + PDIST - Y)/(PX - X)
                PHI = ATAN(W)
        VALPHAH = (BVELH*SIN(THETA - PHI) - PVEL*COS(PHI))/BDIST

C  MOVEMENT OF PLAYER'S LINE OF SIGHT (LOS) IS DELAYED BY AN
C  AMOUNT EQUAL TO THE PLAYER'S REACTION TIME TO OPPONENT'S
C  STRIKING THE BALL.

             IF(NDELYIN .GT. 0) GO TO 180

C  AFTER THE DELAY, ANGULAR POSITION AND VELOCITY OF LOS ARE
C  COMPUTED.

        BETAV = BETAV + VBETAV*DELTAT1 + ABETAV*DELTAT1**2
        BETAH = BETAH + VBETAH*DELTAT1 + ABETAH*DELTAT1**2
           VBETAV = VBETAV + ABETAV*DELTAT1
           VBETAH = VBETAH + ABETAH*DELTAT1

C  MOVEMENT OF PLAYER IS DELAYED BY AN AMOUNT EQUAL TO HIS
C  REACTION TIME TO OPPONENT'S STRIKING THE BALL.

180         IF(NDELPIN .GT. 0) GO TO 190

C  THE NEW POSITION AND VELOCITY OF PLAYER IN HIS INTERCEPT
C  PATH ARE COMPUTED AS SOON AS THE DELAY HAS COUNTED DOWN.

        PDIST = PDIST + PVEL*DELTAT1 + PACCEL*DELTAT1**2
           PVEL = PVEL + PACCEL*DELTAT1

190          RETURN
                 END
```

```
END OF SEGMENT, LENGTH   410, NAME  COMPUTE


                        SUBROUTINE FOLLOW

        COMMON/BALL/ R, BVELV, PVELH, TIME, BHEIGHT,BDIST,
       *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
       *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
       * BETAH, VBETAH,  NDELPIN, PVEL, PACCEL,
       * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
       * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
       * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
       * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
       * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
       * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
       * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
       * NDELYCOR, TM1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
       * X0, Y0, PX, PY, BVELVGR

C   PROCESS FOLLOW LOGIC USING ESTIMATED PLAYER POSITION AND
C   VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                  IF(TIMEST .LE. TM1) GO TO 841
                  IF(TIMEST .LE. TG) GO TO 842

841       BHEIT250 = BHEIGTST + BVAVE2V*DELTAT2
                   GO TO 843

842       BHEIT250 = BHEIGTST - BVAVE2V*DELTAT2
843           R250 = RST + BVAVE2H*DELTAT2
        BDIST250 = SQRT((PX - R250*COS(THETA))**2
       *          + (PY + PDIST250 - R250*SIN(THETA))**2)

C   FIND ANGULAR POSITION AND VELOCITY OF LINE TO BALL

                 ALPHAV25 = ATAN((BHEIT250 - 5.0)/BDIST250)
        ALPHAH25=ATAN((R250*SIN(THETA)-PDIST250)/(PX-R250*COS(THETA)))
             VALPHAV2 = BVAVE2V/BDIST250
           W250 = (PY+PDIST250-R250*SIN(THETA))/(PX-R250*COS(THETA))
         VALPHAH2=(BVAVE2H*SIN(THETA-ATAN(W250))-PVEL250*COS(ATAN(W250)))/
       *                         BDIST250

C   FIND ANGULAR POSITION AND VELOCITY OF LOS AND FORM DIFFERENCES

           BETAV250 = BETAVST + VBETAVST*DELTAT2 + ABETAVST*DELTAT2**2
           BETAH250 = BETAHST + VBETAHST*DELTAT2 + ABETAHST*DELTAT2**2
                VBETAV25 = VBETAVST + ABETAVST*DELTAT2
                VBETAH25 = VBETAHST + ABETAHST*DELTAT2
                  GAMAV250 = ALPHAV25 - BETAV250
                  GAMAH250 = ALPHAH25 - BETAH250


                VGAMAV25 = VALPHAV2 - VBETAV25
                VGAMAH25 = VALPHAH2 - VBETAH25

C   THE ANGULAR DIFFERENCES AND ANGULAR VELOCITY DIFFERENCES MUST
C   NOW BE COMPARED AGAINST THE PLAYER'S STANDARDS OF MAGNITUDE

        IF(ABS(GAMAV250).LE.0.05*(ALPHAV25 + BETAV250)) GO TO 844
             IF(GAMAV250 .LT. 0.0) GO TO 845
           IF(ABS(GAMAV250) .LE. 0.18) GO TO 846
           IF(ABS(GAMAV250) .LE. 0.9) GO TO 847

C   VERTICAL ANGULAR DIFF IS LARGE POSITIVE
                     VANGDIFF = 3
                       GO TO 851
846              VANGDIFF = 1
                       GO TO 851
847              VANGDIFF = 2

                       GO TO 851

C VERTICAL ANG DIFF IS NEGATIVE

845       IF(ABS(GAMAV250) .LE. 0.18) GO TO 848
               IF(ABS(GAMAV250) .LE. 0.9) GO TO 849

                    VANGDIFF = -3
                       GO TO 851
```

```
848          VANGDIFF = -1
                 GO TO 851
849          VANGDIFF = -2
                 GO TO 851

844          VANGDIFF = 0

851    IF(ABS(GAMAH250) .LE. 0.05*(ALPHAH25 + BETAH250)) GO TO 854
               IF(GAMAH250 .LT. 0.0) GO TO 855
             IF(ABS(GAMAH250) .LE. 0.18) GO TO 856
             IF(ABS(GAMAH250) .LE. 0.9) GO TO 857

C  HORIZONTAL ANGULAR DIFF IS LARGE POSITIVE

                HANGDIFF = 3
                 GO TO 861
856          HANGDIFF = 1
                 GO TO 861
857          HANGDIFF = 2
                 GO TO 861

C  HORIZONTAL ANG DIFF IS NEGATIVE

855        IF(ABS(GAMAH250) .LE. 0.18) GO TO 858
              IF(ABS(GAMAH250) .LE. 0.9) GO TO 859

                HANGDIFF = -3
                 GO TO 861
858          HANGDIFF = -1
                 GO TO 861
859          HANGDIFF = -2
                 GO TO 861

854           HANGDIFF = 0

861    IF(ABS(VGAMAV25) .LE. 0.05*(VALPHAV2+VBETAV25)) GO TO 864
              IF(VGAMAV25 .LT. 0.0) GO TO 865
              IF(ABS(VGAMAV25) .LE. 0.18) GO TO 866
              IF(ABS(VGAMAV25) .LE. 0.9) GO TO 867

C  VERTICAL ANGULAR VELOCITY DIFF IS LARGE POSITIVE

                   VANVDIFF = 3
                     GO TO 871
866             VANVDIFF = 1
                     GO TO 871
867             VANVDIFF = 2
                     GO TO 871

C  HORIZONTAL ANGULAR VELOCITY DIFF IS NEGATIVE

865         IF(ABS(VGAMAV25) .LE. 0.18) GO TO 868
              IF(ABS(VGAMAV25) .LE. 0.9) GO TO 869

                   VANVDIFF = -3
                     GO TO 871
868             VANVDIFF = -1
                     GO TO 871
869             VANVDIFF = -2
                     GO TO 871

864             VANVDIFF = 0

871   IF(ABS(VGAMAH25) .LE. 0.05*(VALPHAH2 + VBETAH25)) GO TO 874
               IF(VGAMAH25 .LT. 0.0) GO TO 875
             IF(ABS(VGAMAH25) .LE. 0.18) GO TO 876
             IF(ABS(VGAMAH25) .LE. 0.9) GO TO 877

C  HORIZONTAL ANGULAR VELOCITY DIFF IS LARGE POSITIVE

                   HANVDIFF = 3
                    GO TO 881
876             HANVDIFF = 1
                    GO TO 881
877             HANVDIFF = 2
                    GO TO 881

C  HORIZONTAL ANGULAR VELOCITY DIFF IS NEGATIVE

875         IF(ABS(VGAMAH25) .LE. 0.18) GO TO 878
```

```
                 IF(ABS(VGAMAH25) .LE. 0.9) GO TO 879

                      HANVDIFF = -3
                       GO TO 881
878                 HANVDIFF = -1
                       GO TO 881
879                 HANVDIFF = -2
                       GO TO 881

874                 HANVDIFF = 0

881                 L1 = VANGDIFF + VANVDIFF
                       L2 = HANGDIFF + HANVDIFF

                 IF(L1 .LT. 0) GO TO 884
                 IF(L1 .EQ. 0) GO TO 885
                 IF(L1 .EQ. 1) GO TO 886
                 IF(L1 .EQ. 2) GO TO 887

C  VERTICAL DRIVING ACCELERATION IS LARGE POSITIVE.

                        ABETAV25 = 20.0
                           GO TO 891
885                   ABETAV25 = 0.0
                           GO TO 891
886                   ABETAV25 = 5.0
                           GO TO 891
887                   ABETAV25 = 10.0
                           GO TO 891

884             IF(L1 .EQ. -1) GO TO 888
                   IF(L1 .EQ. -2) GO TO 889

C  VERTICAL DRIVING ACCELERATION IS LARGE NEGATIVE.

                        ABETAV25 = -20.0
                           GO TO 891
888                   ABETAV25 = -5.0
                           GO TO 891
889                   ABETAV25 = -10

891              IF(L2 .LT. 0) GO TO 894
                    IF(L2 .EQ. 0) GO TO 895
                    IF(L2 .EQ. 1) GO TO 896
                    IF(L2 .EQ. 2) GO TO 897

C  HORIZONTAL DRIVING ACCELERATION IS LARGE POSITIVE.

                        ABETAH25 = 20.0
                           GO TO 900
895                   ABETAH25 = 0.0
                           GO TO 900
896                   ABETAH25 = 5.0
                           GO TO 900
897                   ABETAH25 = 10.0
                           GO TO 900

894              IF(L2 .EQ. -1) GO TO 898
                    IF(L2 .EQ. -2) GO TO 899

C  HORIZONTAL DRIVING ACCELERATION IS LARGE NEGATIVE.

                        ABETAH25 = -20.0
                           GO TO 900
898                   ABETAH25 = -5.0
                           GO TO 900
899                   ABETAH25 = -10.0

C  DETERMINE VALUE OF PLAYER'S CORRECTION TO EYE MOVEMENT.

900           IF(ABS(ABETAV + ABETAV25) .LE. 20.0) GO TO 920
                 IF(ABETAV + ABETAV25 .LT. 0.0) GO TO 930

C  PLAYER APPLIES MAXIMUM VERTICAL ACCELERATION.
                           ABETAVT = 20.0
                            GO TO 940

C  PLAYER APPLIES MAXIMUM VERTICAL DECELERATION.
```

```
930                     ABETAVT = -20.0
                          GO TO 940
C  CORRECTIVE ADDITION DOESN'T EXCEED MAXIMUM ACCELERATION.
920              ABETAVT = ABETAV + ABETAV25
940        IF(ABS(ABETAH + ABETAH25) .LE. 20.0) GO TO 950
                IF(ABETAH + ABETAH25 .LT. 0.0) GO TO 960
C  PLAYER APPLIES MAXIMUM HORIZONTAL ACCELERATION.
                        ABETAHT = 20.0
                          GO TO 965
C  PLAYER APPLIES MAXIMUM HORIZONTAL DECELERATION.
960                   ABETAHT = -20.0
                          GO TO 965
C  CORRECTIVE ADDITION DOESN'T EXCEED MAXIMUM DECELERATION.
950              ABETAHT = ABETAH + ABETAH25
965                   NDELYCOR = 1
                      IFOLLOW = 0
            RETURN
             END

   END OF SEGMENT, LENGTH  1237, NAME  FOLLOW .
```

```
                              FINISH
END OF COMPILATION -   NO ERRORS

S/C SUBFILE:                74 BUCKETS USED


CONSOLIDATED BY XPCK 12K     DATE     22/10/79    TIME 09/57/09

PROGRAM TENN
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE              7680

                 SEG       TENNIS
                 CUV       BALL
                 SEG       TAN
                 SEG       COS
                 SEG       COMPUTE
                 SEG       FOLLOW
                 SEG       ABS
                 SEG       SQRT
                 SEG       SIN
                 SEG       ATAN
                 CLV       SPFIL
```

Appendix C

Second Extension of the Prototype Model

```
JOB QFORTRAN,CSHP ,PAPPO
MINIMOP CSHP
FORTRANCOMP FXXX
VOLUME 40000
EXECUTE
****


    RUN BY GEORGE 2/MK9F


    FORTRAN COMPILATION BY #XFAT MK. 6B


    DATE  26/10/79  TIME  19/07/16
```

```
LIST
PROGRAM (TEMN)
OUTPUT 6=LP0
COMPRESS INTEGER AND LOGICAL
COMPACT
TRACE 2
END
```

```
              MASTER TENNIS

      COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, NDELPIN, PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
     * NDELYCOR, TM1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
     * X0, Y0, PX, PY, BVELVGR

C   SELECT CROSS-COURT TRAJECTORY STARTING CONDITIONS,
C   RECEIVER STARTING POSITION, AND LINE-OF-SIGHT
C   STARTING CONDITIONS

      I = 0
      TIME = 0.0
      X0 = 5.8
      Y0 = 3.5
      BHEIGHT0 = 3.5
      BVELV0 = 15.0
      BVELH0 = 45.0
      THETA = 0.0
      VBETAV = 0.0
      VBETAH = 0.0
      ABETAV = 0.0
      ABETAH = 0.0
      PX = 75.0
      PY = 14.2
      PVEL = 0.0
      PACCEL = 0.0
      PHEIGHT = 5.0
      VCON = 3.0

C   SET STATUS INDICATORS AND COUNTERS

      IFOLLOW = 1
      INTERCEPT = 1
      NDELYIN = -1
      NDELPIN = -1
      NDELYCOR = -1
      NDELPCOR = -1
      IFLAG = 0
      N5CTR = 5
      N25CTR = 10
      N100CTR = -1
      ISIGN = -1

C SET INCREMENTAL CONSTANTS

      DELTAT1 = 0.01
      DELTAT2 = 0.25

      MULT1 = 2700.0
      MULT2 = 500.0
      MULT3 = 250.0

C   SET FEEDFORWARD COMPUTATION PARAMETERS TO ZERO

      ALPHAV25 = 0.0
      ALPHAH25 = 0.0
      PDIST250 = 0.0
      BDIST250 = 0.0
      VALPHAV2 = 0.0
      VALPHAH2 = 0.0
      PVEL250 = 0.0
      BETAV250 = 0.0
      BETAH250 = 0.0
      ABETAV25 = 0.0
      ABETAH25 = 0.0
      VBETAV25 = 0.0
      VBETAH25 = 0.0
      DTG250 = 0.0
```

```
      TTG250 = 0.0

      WRITE (6,6000)
6000  FORMAT (1H1//////////////////////////////, 56X, '- TENNIS -')
      WRITE (6,6001)
6001  FORMAT (////1H ,41X,'SIMULATION OF THE VISUO-MOTOR PROCESSES')
      WRITE (6,6002)
6002  FORMAT (/////1H ,52X,'A PROTOTYPE MODEL')
      WRITE (6,6003)
6003  FORMAT (///////////1H ,55X,'H. A. PAPPO')
      WRITE (6,6004)
6004  FORMAT (1H ,52X,'RHODES UNIVERSITY')
      WRITE (6,6005)
6005  FORMAT (1H ,58X,'1979')

C   AFTER PRINTING TITLE PAGE, GO TO NEXT PAGE AND PRINT ARRAY
C   OF PARAMETER NAMES. AFTER FIRST TIME-SLICE PASS, SKIP
C   FIVE LINES AND PRINT PARAMETER VALUES.  SKIP FIVE MORE
C   LINES AND PRINT SECOND PASS RESULTS.  ETC.  REPEAT ON
C   NEXT PAGE.

      WRITE (6,6008)

      WRITE (6,6010)
      WRITE (6,6011)
      WRITE (6,6012)
      WRITE (6,6013)
      WRITE (6,6014)
      WRITE (6,6015)
      WRITE (6,6016)
      WRITE (6,6017)


6008  FORMAT(1H1,46X,'TIME-SLICE DATA BLOCK')

6010  FORMAT(/////////////1H ,34X,'I',7X,'TIME',4X,'BHEIGHT',5X,
     *   'ALPHAV',5X,'ALPHAH',6X,'PDIST')
6011  FORMAT(1H ,28X,'IFOLLOW',2X,'INTERCEPT',6X,
     *   'BDIST',3X,'ALPHAV25',3X,'ALPHAH25',3X,'PDIST250')
6012  FORMAT(1H ,28X,'NDELYIN',4X,'NDELPIN',3X,
     *   'BDIST250',4X,'VALPHAV',4X,'VALPHAH',7X,'PVEL')
6013  FORMAT(1H ,27X,'NDELYCOR',3X,'NDELPCOR',6X,
     *   'BVELV',3X,'VALPHAV2',3X,'VALPHAH2',4X,'PVEL250')
6014  FORMAT(/1H ,30X,'N5CTR',5X,'N25CTR',10X,'R',6X,
     *   'BETAV',6X,'BETAH',5X,'PACCEL')
6015  FORMAT(1H ,28X,'N100CTR',6X,'IFLAG',8X,'PHI',5X,
     *   'VBETAV',5X,'VBETAH',4X,'PACCSTD')
6016  FORMAT(1H ,31X,'DTG0',7X,'TTG0',3X,'BETAV250',5X,
     *   'ABETAV',5X,'ABETAH',5X,'VBETAV25')
6017  FORMAT(1H ,29X,'DTG250',5X,'TTG250',3X,'BETAH250',
     *   3X,'ABETAV25',3X,'ABETAH25',3X,'VBETAH25')

C   CHECK BOUNDARY CONDITIONS ON TRAJECTORY, USING ISIGN FOR CONTROL.

          DTG00 = ISIGN*((PX - X0)*TAN(THETA) - PY + Y0) - 3
          TTG00 = (PX - X0)/(BVELH0*COS(THETA))
            TM1 = BVELV0/32.0
          BHEIGHT1 = BVELV0 - 16.0*TM1*TM1 + BHEIGHT0
            TGR = SQRT(BHEIGHT1/16.0)
               TG = TGR + TM1

           IF(BVELH0*TG*COS(THETA) + X0 .GT. 78.0) GO TO 50
           IF(BVELH0*TG*SIN(THETA) + Y0 .GE. 0.0) GO TO 60
50          WRITE(6,6500)
6500     FORMAT(/////1H ,50X,'BALL OUT OF BOUNDS')
               STOP

60        TN = (39.0 - X0)/(BVELH0*COS(THETA))
             IF(TN .LE. TM1) GO TO 70
             IF(TN .LT. TG) GO TO 68
68        IF(BHEIGHT1-16.0*(TN-TM1)**2 .LT. 3.0) GO TO 71
                GO TO 90
70       IF(BVELV0*TN-16.0*TN**2+BHEIGHT0 .GT. 3.0) GO TO 90
71              WRITE(6,6600)
6600      FORMAT(/////1H , 53X, 'BALL IN NET')
                  STOP

90                 K = -4
               GO TO 104
```

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100       IF(I .LT. TTG00*100) GO TO 101
C   END OF RUN
          STOP

101       IF(K .NE. 1) GO TO 102

      WRITE (6,6444) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
                   K = -5
              GO TO 103
102   WRITE (6,6130) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
103   WRITE (6,6100) IFOLLOW,INTERCEPT,BDIST,ALPHAV25,ALPHAH25,PDIST250
      WRITE (6,6100) NDELYIN,NDELPIN,BDIST250,VALPHAV,VALPHAH,PVEL
      WRITE (6,6100) NDELYCOR,NDELPCOR,BVELV,VALPHAV2,VALPHAH2,PVEL250
      WRITE (6,6110) N5CTR,N25CTR,R,BETAV,BETAH,PACCEL
      WRITE (6,6100) N100CTR,IFLAG,PHI,VBETAV,VBETAH,PACCSTD
      WRITE (6,6120) DTGO,TTGO,BETAV250,ABETAV,ABETAH,VBETAV25
      WRITE (6,6120) DTG250,TTG250,BETAH250,ABETAV25,ABETAH25,VBETAH25


104             K = K + 1
            BVELH = BVELH0

6100  FORMAT (1H ,24X,2I11,4F11.4)
6110  FORMAT (/1H ,24X,2I11,4F11.4)
6120  FORMAT (1H ,24X,6F11.4)
6130  FORMAT (/////1H ,24X,I11,5F11.4)
6444  FORMAT (1H1,24X,I11,5F11.4)

C   UPDATE TIME-SLICE AND TIME FROM PROGRAM START.  TEST TIME FOR
C   PLAYER TO BEGIN HIS DECELERATION.  INITIATE PROCESSING OF
C   GENERAL FOLLOW AND INTERCEPT LOOP.

105                  I = I + 1
                  TIME = TIME + 0.01
                TTGO = TTG00 - TIME
                DTGO = DTG00 - PDIST
               IF (TIME .LT. 2.0*TTG00/3.0) GO TO 110
                IF (IFLAG .NE. 1) GO TO 110
                    PACCEL = PACCSTD

C   POSITION AND VELOCITY OF BALL ARE COMPUTED IN COURT COORDINATES

110               CALL COMPUTE

                IF(I .NE. 1) GO TO 112

C   SET STARTING ANGULAR POSITION FOR EYES

                  BETAV = ALPHAV
                  BETAH = ALPHAH

C   PLAYER ESTIMATES DIRECTION OF MOTION AND STARTING
C   ACCELERATIONS FOR BODY AND EYE MOVEMENTS.

                ALPHAV1 = ALPHAV
                ALPHAH1 = ALPHAH
112           IF(I .NE. 10) GO TO 116
               ALPHAVD = ALPHAV - ALPHAV1
               ALPHAHD = ALPHAH - ALPHAH1

              IF(ALPHAHD .LT. 0.0) GO TO 113
                    JSIGN = 1
                   GO TO 114
113                 JSIGN = -1

114            PACCEL = ABS(MULT1*ALPHAHD)
               ABETAV = ABS(MULT2*ALPHAVD)
               ABETAH = ABS(MULT3*ALPHAHD)

               IFOLLOW = 0
              INTERCEPT = 0
               N100CTR = 10

                 NDELYIN = 2
                 NDELPIN = 3

116           IF(I .EQ. 1) GO TO 821

C   UPDATE COUNTERS
                 N5CTR = N5CTR - 1
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             N25CTR = N25CTR - 1
            N100CTR = N100CTR - 1
            NDELYIN = NDELYIN - 1
            NDELPIN = NDELPIN - 1
           NDELYCOR = NDELYCOR - 1
           NDELPCOR = NDELPCOR - 1


C   STATUS CHECKS ARE REQUIRED TO DETERMINE CONDITION OF CORRECTION
C   DELAY COUNTERS BEFORE INTERCEPT AND/OR FOLLOW LOGICS CAN BE
C   PROCESSED.

                 IF(NDELPCOR) 200, 210, 220
200           IF(NDELYCOR) 300, 250, 260

C   CORRECT FOLLOW MOVEMENT ONLY
250              ABETAV = ABETAVT
                    ABETAH = ABETAHT
                    GO TO 820
C   NO CORRECTION.  DELAY STILL OPERATIVE.
260              GO TO 830

210           IF(NDELYCOR) 230, 270, 280

C   CORRECT INTERCEPT MOVEMENT ONLY
230                 PACCEL = PACCSTD
                    GO TO 820

C   CORRECT BOTH FOLLOW AND INTERCEPT MOVEMENTS.
270             ABETAV = ABETAVT
                  ABETAH = ABETAHT
                   GO TO 230

C   CORRECT INTERCEPT MOVEMENT ONLY.  FOLLOW CORRECTION DELAY
C   STILL OPERATIVE.

280                 PACCEL = PACCSTD
                    GO TO 820

220           IF(NDELYCOR) 240, 290, 299

C   NO CORRECTION.  DELAY STILL OPERATIVE.
240              GO TO 830

C   CORRECT FOLLOW MOVEMENT ONLY.  INTERCEPT CORRECTION DELAY
C   STILL OPERATIVE.
290             ABETAV = ABETAVT
                   ABETAH = ABETAHT
                    GO TO 820

C   NO CORRECTION.  BOTH DELAYS STILL OPERATIVE.
299              GO TO 100


C   CHECK CONDITION OF DELAYS ON FOLLOW AND INTERCEPT MOVEMENTS

300           IF(NDELYIN .GT. 0) GO TO 320
                 IF(NDELPIN .GT. 0) GO TO 400

C   STARTING DELAYS NO LONGER OPERATIVE, SO CHECK STATUS OF
C   THE FOLLOW AND/OR INTERCEPT LOGIC TO ESTABLISH PROGRAM
C   SEQUENCE.

                 IF(IFOLLOW .EQ. 1) GO TO 500
                 IF(INTERCEPT .EQ. 1) GO TO 600

C   OTHERWISE ACTIVATE BOTH FOLLOW AND INTERCEPT LOGIC.
310                IFOLLOW = 1
                     INTERCEPT = 1

C   ENTER INFORMATION PROCESSING LOOP FOR FOLLOW AND INTERCEPT
                     GO TO 820

C   FOLLOW LOGIC STILL NOT ACTIVE.  STARTING DELAY STILL OPERATIVE

320           IF(NDELPIN .GT. 0) GO TO 350

C   INTERCEPT LOGIC DELAY NO LONGER OPERATIVE, SO CHECK STATUS
C   OF INTERCEPT LOGIC TO ESTABLISH PROGRAM SEQUENCE.
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              IF(INTERCEPT .EQ. 1) GO TO 600
C  INTERCEPT LOGIC NOT ACTIVE, SO ACTIVATE AND BEGIN PROCESSING.
                  INTERCEPT = 1

C  ENTER INFORMATION PROCESSING LOOP FOR INTERCEPT AND
C  POSSIBLY FOLLOW LOGIC.
                  GO TO 820

C  BOTH FOLLOW AND INTERCEPT LOGIC DELAYS STILL OPERATIVE,
C  SO NO PLAYER ACTION.
350            GO TO 100

C  INTERCEPT LOGIC DELAY STILL OPERATIVE, SO TEST FOLLOW LOGIC
C  STATUS.
400        IF(IFOLLOW .EQ. 1) GO TO 450
                IFOLLOW = 1

C  ENTER INFORMATION PROCESSING LOOP FOR FOLLOW AND POSSIBLY
C  INTERCEPT LOGIC.
                  GO TO 820

C  FOLLOW LOGIC ACTIVE, SO ENTER INFORMATION PROCESSING LOOP
C  AS IF INTERCEPT ALSO ACTIVE.
450        IF(N100CTR .LE. 0) GO TO 700
                  GO TO 830

C  FOLLOW LOGIC ACTIVE, SO TEST INTERCEPT LOGIC.
500        IF(INTERCEPT .EQ. 1) GO TO 550
              IF(N100CTR .LE. 0) GO TO 700
                INTERCEPT = 1

C  ENTER INFORMATION LOOP TO PROCESS FOLLOW AND INTERCEPT LOGIC
                  GO TO 830

C  BOTH FOLLOW AND INTERCEPT LOGICS ACTIVE.
550            GO TO 830

C  INTERCEPT LOGIC ACTIVE, SO TEST 100 MS COUNTER.
600        IF(N100CTR .GT. 0) GO TO 650
                 IFOLLOW = -1

C  ENTER INFORMATION LOOP TO PROCESS ONLY INTERCEPT LOGIC.
                  GO TO 830

C  100 MS COUNTER STILL OPERATIVE, SO ENTER INFORMATION LOOP
C  TO PROCESS INTERCEPT AND   FOLLOW LOGIC.
650           IFOLLOW = 1
                  GO TO 830

C  FOLLOW LOGIC ACTIVE AND 100 MS DELAY TIME PASSED, SO
C  PROCESS ONLY FOLLOW LOGIC.
700          INTERCEPT = -1
                  GO TO 830


C  INITIALIZE TRAJECTORY VELOCITY COUNTERS AND BEGIN VELOCITY
C  AVERAGING.

820               N5CTR = 5
                   N25CTR = 25
                 N100CTR = 10
821                 BVSUMV = 0
                    BVSUMH = 0
                    TOTALV = 0
                    TOTALH = 0
C  INITIALIZE FEEDFORWARD COMPUTATION USING CURRENT VALUES OF POSITION
C  AND VELOCITY OF PLAYER AND LINE OF SIGHT AND LINE TO BALL.
           BETAVST = BETAV
             BETAHST = BETAH
          VBETAVST = VBETAV
          VBETAHST = VBETAH
          GAMMAVST = ALPHAV - BETAV
          GAMMAHST = ALPHAH - BETAH
          VGAMAVST = VALPHAV - VBETAV
          VGAMAHST = VALPHAH - VBETAH
          PDISTST = PDIST
            PVELST = PVEL
          PACCELST = PACCEL
               RST = R
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            BHEIGTST = BHEIGHT
              TIMEST = TIME
              ABETAVST = ABETAV
              ABETAHST = ABETAH
               IST = 1

C   BEGIN PROCESSING FOLLOW AND/OR INTERCEPT LOGIC.  FIRST
C   OBTAIN AVERAGE OF VERTICAL COMPONENTS OF TRAJECTORY
C   VELOCITY AND AVERAGE OF HORIZONTAL COMPONENTS.

830          IF(TTGO .LE. 0.25) GO TO 100

             BVSUMV = BVSUMV + BVELV
             BVSUMH = BVSUMH + BVELH

           IF(N5CTR .GT. 1) GO TO 835
              BVAVE1V = BVSUMV/5.0
              BVAVE1H = BVSUMH/5.0
               BVSUMV = 0.0
               BVSUMH = 0.0

                N5CTR = 6

            TOTALV = TOTALV + BVAVE1V
            TOTALH = TOTALH + BVAVE1H

835      IF(N25CTR .NE. 1) GO TO 100

C   COMPUTE PLAYER'S ESTIMATE OF TRAJECTORY VELOCITY
C   COMPONENTS USING AVERAGE VELOCITY.  VCON IS A CONSTANT THAT
C   ALLOWS FOR VARIABLE STARTING CONDITIONS.

            BVAVE2V = TOTALV/(5.0 - VCON)
            BVAVE2H = TOTALH/(5.0 - VCON)

              VCON = 0.0

C   COMPUTE ESTIMATED VALUES OF PLAYER'S DISTANCE ATTAINED
C   IN 250 MS AND PLAYER VELOCITY AT 250 MS.  DATA USED
C   FOR BOTH FOLLOW AND INTERCEPT LOGICS.

          PDIST250=PDISTST+PVELST*DELTAT2+PACCELST*DELTAT2**2
         PVEL250=PVELST+PACCELST*DELTAT2


C   TEST STATUS OF FOLLOW LOGIC FOR INFO PROCESSING.

                IF(IFOLLOW .EQ. -1) GO TO 970

C   PROCESS FOLLOW LOGIC USING ESTIMATED PLAYER POSITION
C   AND VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                         CALL FOLLOW

C   TEST STATUS OF INTERCEPT LOGIC FOR INFO PROCESSING.

970           IF(INTERCEPT .EQ. -1) GO TO 998

C   PROCESS INTERCEPT LOGIC USING ESTIMATED PLAYER POSITION
C   AND VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                  IF(TIMEST .GT. TTG00/3) GO TO 972
              DTG250 = 1.15*(DTG00 - PDIST250)
                         GO TO 973

972               IF(TIMEST .GT. 2.0*TTG00/3.0) GO TO 974
              DTG250 = 1.10*(DTG00 - PDIST250)
                         GO TO 973

974        DTG250 = 1.05*(DTG00 - PDIST250)

973          TTG250 = TTG00 - TIMEST - 0.25

C   PLAYER COMPARES ESTIMATED ACTUAL WITH ESTIMATED DESIRED VELOCITY
C   AT THE 250 MARK

               PVMSTD = 18.0*DTG00/(13.0*TTG00)

                  IF(TIMEST .GT. TTG00/3) GO TO 980
             PACCSTD = 3.0*PVMSTD/TTG00
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              PVSTDST = PACCSTD * TIMEST
           PVSTD250 = PVSTDST + PACCSTD * DELTAT2
      IF(ABS(PVSTD250 - PVEL250) .LE. 0.05*(PVSTD250+PVEL250))GO TO 987
         IF(PVSTD250 - PVEL250 .GT. 0.0) GO TO 987
                 PACCSTD = 0.0

C  PACCEL MUST BE SET TO ZERO ALSO, BUT THIS CAN'T BE DONE
C  UNTIL THE DELAY, NDELPCOR, FOR PLAYER CORRECTION HAS
C  COUNTED DOWN

                 NDELPCOR = 4
                  GO TO 987

980         IF(TIMEST .GT. 2.0*TTGOO/3.0) GO TO 987
                  PVSTD250 = PVMSTD

                   PACCSTD = 0.0
                  NDELPCOR = 4

      IF(ABS(PVSTD250 - PVEL250) .LE. 0.05*(PVSTD250+PVEL250))GO TO 985
              IF(PVSTD250 - PVEL250 .LT. 0.0) GO TO 981

        PACCSTD = -(2.0*PVMSTD/3)/(TTGOO - 2*TTGOO/3)

C  PACCEL IS ALSO SET TO  THIS VALUE, BUT NOT UNTIL TIME
C  EQUALS 2*TTGOO/3.

                     GO TO 986

981              PACCSTD = -PVMSTD/(TTGOO -2*TTGOO/3)
                     GO TO 986
985           PACCSTD = -(5.0*PVMSTD/6.0)/(TTGOO -2.0*TTGOO/3.0)
986                IFLAG = 1
987              INTERCEPT = 0
                  IFOLLOW = 0
                    GO TO 100

998        IF(IFOLLOW .EQ. 1) GO TO 100
                 INTERCEPT = 0
                  IFOLLOW = 0
                    GO TO 100
          END

  END OF SEGMENT, LENGTH  1899, NAME  TENNIS
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                  SUBROUTINE COMPUTE

       COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *   PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *   X, Y, NDFLYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, NDELPIN, PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGIST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ADETAV, ABETAVT, ABETAH, ABETAHT,
     * NDELYCOR, TM1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
     * X0, Y0, PX, PY, BVELVGR

C   COMPUTE POSITION AND VELOCITY OF BALL IN COURT COORDS.

                       R = BVELH*TIME
                     BVELVGR = 32.0*TGR
                   IF(TIME .LE. TM1) GO TO 130
                   IF(TIME .LE. TG) GO TO 120

          BHEIGHT = 16.0*(TIME - TG) - 16.0*(TIME - TG)**2
             BVELV = 16.0 - 32.0*(TIME - TG)
                 GO TO 140

120      BHEIGHT = BHEIGHT1 - 16.0*(TIME - TM1)**2
             BVELV = 32.0*(TIME - TM1)
                 GO TO 140

130      BHEIGHT = BVELV0*TIME - 16.0*TIME**2 + BHEIGHT0
             BVELV = BVELV0 - 32.0*TIME

C   COMPUTE DISTANCE AND ANGULAR POSITION AND VELOCITY OF BALL

140          X = R*COS(THETA) + X0
             Y = R*SIN(THETA) + Y0
       BDIST = SQRT((PX - X)**2 + (PY + JSIGN*PDIST - Y)**2)
                ALPHAV = ATAN((BHEIGHT - 5.0)/BDIST)
            ALPHAH = ATAN((Y - PY - JSIGN*PDIST)/(PX - X))
                VALPHAV = BVELV/BDIST
            W = (PY + JSIGN*PDIST - Y)/(PX - X)
                 PHI = ATAN(W)
        VALPHAH = (BVELH*SIN(THETA - PHI) - PVEL*COS(PHI))/BDIST

C   MOVEMENT OF PLAYER'S LINE OF SIGHT (LOS) IS DELAYED BY AN
C   AMOUNT EQUAL TO THE PLAYER'S REACTION TIME TO OPPONENT'S
C   STRIKING THE BALL.

                IF(NDFLYIN .GT. 0) GO TO 180

C   AFTER THE DELAY, ANGULAR POSITION AND VELOCITY OF LOS ARE
C   COMPUTED.

          BETAV = BETAV + VBETAV*DELTAT1 + ABETAV*DELTAT1**2
          BETAH = BETAH + VBETAH*DELTAT1 + ABETAH*DELTAT1**2
             VBETAV = VBETAV + ABETAV*DELTAT1
             VBETAH = VBETAH + ABETAH*DELTAT1

C   MOVEMENT OF PLAYER IS DELAYED BY AN AMOUNT EQUAL TO HIS
C   REACTION TIME TO OPPONENT'S STRIKING THE BALL.

180          IF(NDELPIN .GT. 0) GO TO 190

C   THE NEW POSITION AND VELOCITY OF PLAYER IN HIS INTERCEPT
C   PATH ARE COMPUTED AS SOON AS THE DELAY HAS COUNTED DOWN.

          PDIST = PDIST + PVEL*DELTAT1 + PACCEL*DELTAT1**2
             PVEL = PVEL + PACCEL*DELTAT1

190            RETURN
                   END

END OF SEGMENT, LENGTH   383, NAME  COMPUTE
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                SUBROUTINE FOLLOW

      COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, NDELPIN, PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
     * NDELYCOR, TM1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
     * X0, Y0, PX, PY, BVELVGR

C   PROCESS FOLLOW LOGIC USING ESTIMATED PLAYER POSITION AND
C   VELOCITY AND PREPARE CORRECTION IF NECESSARY.

              IF(TIMEST .LE. TM1) GO TO 841
              IF(TIMEST .LE. TG) GO TO 842

841        BHEIT250 = BHEIGTST + BVAVE2V*DELTAT2
                  GO TO 843

842        BHEIT250 = BHEIGTST - BVAVE2V*DELTAT2
843            R250 = RST + BVAVE2H*DELTAT2
        BDIST250 = SQRT((PX - R250*COS(THETA))**2
     *                + (PY + PDIST250 - R250*SIN(THETA))**2)

C   FIND ANGULAR POSITION AND VELOCITY OF LINE TO BALL

            ALPHAV25 = ATAN((BHEIT250 - 5.0)/BDIST250)
        ALPHAH25=ATAN((R250*SIN(THETA)-PDIST250)/(PX-R250*COS(THETA)))
           VALPHAV2 = BVAVE2V/BDIST250
          W250 = (PY+PDIST250-R250*SIN(THETA))/(PX-R250*COS(THETA))
        VALPHAH2=(BVAVE2H*SIN(THETA-ATAN(W250))-PVEL250*COS(ATAN(W250)))/
     *                          BDIST250

C   FIND ANGULAR POSITION AND VELOCITY OF LOS AND FORM DIFFERENCES

          BETAV250 = BETAVST + VBETAVST*DELTAT2 + ABETAVST*DELTAT2**2
          BETAH250 = BETAHST + VBETAHST*DELTAT2 + ABETAHST*DELTAT2**2
              VBETAV25 = VBETAVST + ABETAVST*DELTAT2
              VBETAH25 = VBETAHST + ABETAHST*DELTAT2
                GAMAV250 = ALPHAV25 - BETAV250
                GAMAH250 = ALPHAH25 - BETAH250


              VGAMAV25 = VALPHAV2 - VBETAV25
              VGAMAH25 = VALPHAH2 - VBETAH25

C   THE ANGULAR DIFFERENCES AND ANGULAR VELOCITY DIFFERENCES MUST
C   NOW BE COMPARED AGAINST THE PLAYER'S STANDARDS OF MAGNITUDE

        IF(ABS(GAMAV250).LE.0.05*(ALPHAV25 + BETAV250)) GO TO 844
            IF(GAMAV250 .LT. 0.0) GO TO 845
          IF(ABS(GAMAV250) .LE. 0.18) GO TO 846
          IF(ABS(GAMAV250) .LE. 0.9) GO TO 847

C   VERTICAL ANGULAR DIFF IS LARGE POSITIVE
                VANGDIFF = 3
                    GO TO 851
846           VANGDIFF = 1
                    GO TO 851
847           VANGDIFF = 2

                    GO TO 851

C VERTICAL ANG DIFF IS NEGATIVE

845       IF(ABS(GAMAV250) .LE. 0.18) GO TO 848
              IF(ABS(GAMAV250) .LE. 0.9) GO TO 849

                VANGDIFF = -3
                    GO TO 851
848           VANGDIFF = -1
                    GO TO 851
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849           VANGDIFF = -2
                 GO TO 851

844           VANGDIFF = 0

851      IF(ABS(GAMAH250) .LE. 0.05*(ALPHAH25 + BETAH250)) GO TO 854
               IF(GAMAH250 .LT. 0.0) GO TO 855
              IF(ABS(GAMAH250) .LE. 0.18) GO TO 856
              IF(ABS(GAMAH250) .LE. 0.9) GO TO 857

C  HORIZONTAL ANGULAR DIFF IS LARGE POSITIVE

                HANGDIFF = 3
                 GO TO 861
856           HANGDIFF = 1
                 GO TO 861
857           HANGDIFF = 2
                 GO TO 861

C  HORIZONTAL ANG DIFF IS NEGATIVE

855        IF(ABS(GAMAH250) .LE. 0.18) GO TO 858
              IF(ABS(GAMAH250) .LE. 0.9) GO TO 859

                HANGDIFF = -3
                 GO TO 861
858           HANGDIFF = -1
                 GO TO 861
859           HANGDIFF = -2
                 GO TO 861

854            HANGDIFF = 0

861      IF(ABS(VGAMAV25) .LE. 0.05*(VALPHAV2+VBETAV25)) GO TO 864
               IF(VGAMAV25 .LT. 0.0) GO TO 865
               IF(ABS(VGAMAV25) .LE. 0.18) GO TO 866
               IF(ABS(VGAMAV25) .LE. 0.9) GO TO 867

C  VERTICAL ANGULAR VELOCITY DIFF IS LARGE POSITIVE

                 VANVDIFF = 3
                  GO TO 871
866             VANVDIFF = 1
                  GO TO 871
867             VANVDIFF = 2
                  GO TO 871

C  HORIZONTAL ANGULAR VELOCITY DIFF IS NEGATIVE

865         IF(ABS(VGAMAV25) .LE. 0.18) GO TO 868
              IF(ABS(VGAMAV25) .LE. 0.9) GO TO 869

                 VANVDIFF = -3
                  GO TO 871
868             VANVDIFF = -1
                  GO TO 871
869             VANVDIFF = -2
                  GO TO 871

864             VANVDIFF = 0

871     IF(ABS(VGAMAH25) .LE. 0.05*(VALPHAH2 + VBETAH25)) GO TO 874
               IF(VGAMAH25 .LT. 0.0) GO TO 875
             IF(ABS(VGAMAH25) .LE. 0.18) GO TO 876
             IF(ABS(VGAMAH25) .LE. 0.9) GO TO 877

C  HORIZONTAL ANGULAR VELOCITY DIFF IS LARGE POSITIVE

                 HANVDIFF = 3
                  GO TO 881
876             HANVDIFF = 1
                  GO TO 881
877             HANVDIFF = 2
                  GO TO 881

C  HORIZONTAL ANGULAR VELOCITY DIFF IS NEGATIVE

875         IF(ABS(VGAMAH25) .LE. 0.18) GO TO 878
              IF(ABS(VGAMAH25) .LE. 0.9) GO TO 879
```

```
                  HANVDIFF = -3
                     GO TO 881
878             HANVDIFF = -1
                   GO TO 881
879             HANVDIFF = -2
                   GO TO 881


874             HANVDIFF = 0

881             L1 = VANGDIFF + VANVDIFF
                   L2 = HANGDIFF + HANVDIFF

               IF(L1 .LT. 0) GO TO 884
               IF(L1 .EQ. 0) GO TO 885
               IF(L1 .EQ. 1) GO TO 886
               IF(L1 .EQ. 2) GO TO 887

C  VERTICAL DRIVING ACCELERATION IS LARGE POSITIVE.

                    ABETAV25 = 20.0
                       GO TO 891
885               ABETAV25 = 0.0
                       GO TO 891
886               ABETAV25 = 5.0
                       GO TO 891
887               ABETAV25 = 10.0
                       GO TO 891

884          IF(L1 .EQ. -1) GO TO 888
               IF(L1 .EQ. -2) GO TO 889

C  VERTICAL DRIVING ACCELERATION IS LARGE NEGATIVE.

                    ABETAV25 = -20.0
                       GO TO 891
888               ABETAV25 = -5.0
                       GO TO 891
889               ABETAV25 = -10

891           IF(L2 .LT. 0) GO TO 894
                 IF(L2 .EQ. 0) GO TO 895
                 IF(L2 .EQ. 1) GO TO 896
                 IF(L2 .EQ. 2) GO TO 897

C  HORIZONTAL DRIVING ACCELERATION IS LARGE POSITIVE.

                    ABETAH25 = 20.0
                      GO TO 900
895               ABETAH25 = 0.0
                      GO TO 900
896               ABETAH25 = 5.0
                      GO TO 900
897               ABETAH25 = 10.0
                      GO TO 900

894           IF(L2 .EQ. -1) GO TO 898
                IF(L2 .EQ. -2) GO TO 899

C  HORIZONTAL DRIVING ACCELERATION IS LARGE NEGATIVE.

                    ABETAH25 = -20.0
                      GO TO 900
898               ABETAH25 = -5.0
                      GO TO 900
899               ABETAH25 = -10.0

C  DETERMINE VALUE OF PLAYER'S CORRECTION TO EYE MOVEMENT.

900         IF(ABS(ABETAV + ABETAV25) .LE. 20.0) GO TO 920
                IF(ABETAV + ABETAV25 .LT. 0.0) GO TO 930

C  PLAYER APPLIES MAXIMUM VERTICAL ACCELERATION.
                      ABETAVT = 20.0
                        GO TO 940

C  PLAYER APPLIES MAXIMUM VERTICAL DECELERATION.
930                   ABETAVT = -20.0
                        GO TO 940
```

```
C  CORRECTIVE ADDITION DOESN'T EXCEED MAXIMUM ACCELERATION.

920                ABETAVT = ABETAV + ABETAV25

940       IF(ABS(ABETAH + ABETAH25) .LE. 20.0) GO TO 950
              IF(ABETAH + ABETAH25 .LT. 0.0) GO TO 960

C  PLAYER APPLIES MAXIMUM HORIZONTAL ACCELERATION.

                          ABETAHT = 20.0
                           GO TO 965

C  PLAYER APPLIES MAXIMUM HORIZONTAL DECELERATION.

960                    ABETAHT = -20.0
                           GO TO 965

C  CORRECTIVE ADDITION DOESN'T EXCEED MAXIMUM DECELERATION.

950                ABETAHT = ABETAH + ABETAH25

965                     NDELYCOR = 2
                        IFOLLOW = 0

          RETURN
           END

END OF SEGMENT, LENGTH  1237, NAME  FOLLOW
```

```
                       FINISH
END OF COMPILATION -  NO ERRORS

S/C SUBFILE:             00 BUCKETS USED


CONSOLIDATED BY XPCK 12A    DATE    26/10/79   TIME 19/07/57

PROGRAM TENN
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE            8000

                 SEG     TENNIS
                 CUV     BALL
                 SEG     TAN
                 SEG     COS
                 SEG     SQRT
                 SEG     SIN
                 SEG     COMPUTE
                 SEG     ABS
                 SEG     FOLLOW
                 SEG     ATAN
                 CLV     SPFIL
```

Appendix D

Third Extension of the Prototype Model

```
JOB OFORTRAN,CSHP ,PAPPO
MINIMOP CSHP
FORTRANCOMP FXXX
VOLUME 40000
EXECUTE
****

       RUN BY GEORGE 2/MK9F

       FORTRAN COMPILATION BY #XFAT MK 6B

       DATE  30/10/79  TIME  23/32/54
```

```
LIST
PROGRAM (TENN)
OUTPUT 6=LP0
COMPRESS INTEGER AND LOGICAL
COMPACT
TRACE 2
END
```

```
              MASTER TENNIS

       COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
      *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
      *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
      * BETAH, VBETAH, NDELPIN, PVEL, PACCEL,
      * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
      * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
      * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
      * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
      * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
      * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
      * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
      * NDELYCOR, TH1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
      * X0, Y0, PX, PY, BVELVGR .

C   SET STARTING CONDITIONS FOR HITTER

       X0 = 5.8
       Y0 = 3.5

          SWITCH = 0

C   SET STARTING CONDITIONS FOR RECEIVER

          PX = 75.0
          PY = 14.2
          PHEIGHT = 5.0

          MULT1 = 3200
          MULT2 = 400
          MULT3 = 250

20        PVEL = 0.0
          PACCEL = 0.0
          VBETAV = 0.0
          VBETAH = 0.0
          ABETAV = 0.0
          ABETAH = 0.0

          VCON = 3.0

C   SET STATUS INDICATORS AND COUNTERS FOR RECEIVER

       I = 0
       TIME = 0.0
       IFOLLOW = 1
       INTERCEPT = 1
       NDELYIN = -1
       NDELPIN = -1
       NDELYCOR = -1
       NDELPCOR = -1
       IFLAG = 0
       N5CTR = 5
       N25CTR = 10
       N100CTR = -1

C SET INCREMENTAL CONSTANTS FOR RECEIVER

       DELTAT1 = 0.01
       DELTAT2 = 0.25

C   SET FEEDFORWARD COMPUTATION PARAMETERS TO ZERO

       ALPHAV25 = 0.0
       ALPHAH25 = 0.0
       PDIST250 = 0.0
       BDIST250 = 0.0
       VALPHAV2 = 0.0
       VALPHAH2 = 0.0
       PVEL250 = 0.0
       BETAV250 = 0.0
       BETAH250 = 0.0
       ABETAV25 = 0.0
       ABETAH25 = 0.0
       VBETAV25 = 0.0
       VBETAH25 = 0.0
       DTG250 = 0.0
```

```
      TTG250 = 0.0
        IF(SWITCH .EQ. 1) GO TO 25
C  PRINT TITLE PAGE ON FIRST PASS ONLY
      WRITE (6,6000)
6000  FORMAT (1H1,////////////////////////, 56X, '- TENNIS -')
      WRITE (6,6001)
6001  FORMAT (////1H ,41X,'SIMULATION OF THE VISUO-MOTOR PROCESSES')
      WRITE (6,6002)
6002  FORMAT (////1H ,44X,'THIRD EXTENSION OF PROTOTYPE MODEL')
      WRITE (6,6003)
6003  FORMAT (//////////1H ,55X,'H. A. PAPPO')
      WRITE (6,6004)
6004  FORMAT (1H ,52X,'RHODES UNIVERSITY')
      WRITE (6,6005)
6005  FORMAT (1H ,58X,'1979')
C  AFTER PRINTING TITLE PAGE, GO TO NEXT PAGE AND PRINT ARRAY
C  OF PARAMETER NAMES. AFTER FIRST TIME-SLICE PASS, SKIP
C  FIVE LINES AND PRINT PARAMETER VALUES.  SKIP FIVE MORE
C  LINES AND PRINT SECOND PASS RESULTS.  ETC.  REPEAT ON
C  NEXT PAGE.
25    WRITE (6,6008)
      WRITE (6,6010)
      WRITE (6,6011)
      WRITE (6,6012)
      WRITE (6,6013)
      WRITE (6,6014)
      WRITE (6,6015)
      WRITE (6,6016)
      WRITE (6,6017)
6008  FORMAT(1H1,46X,'TIME-SLICE DATA BLOCK')
6010  FORMAT(//////////////1H ,34X,'I',7X,'TIME',4X,'BHEIGHT',5X,
     *  'ALPHAV',5X,'ALPHAH',6X,'PDIST')
6011  FORMAT(1H ,28X,'IFOLLOW',2X,'INTERCEPT',6X,
     *  'BDIST',3X,'ALPHAV25',3X,'ALPHAH25',3X,'PDIST250')
6012  FORMAT(1H ,28X,'NDELYIN',4X,'NDELPIN',3X,
     *  'BDIST250',4X,'VALPHAV',4X,'VALPHAH',7X,'PVEL')
6013  FORMAT(1H ,27X,'NDELYCOR',3X,'NDELPCOR',6X,
     *  'BVELV',3X,'VALPHAV2',3X,'VALPHAH2',4X,'PVEL250')
6014  FORMAT(/1H ,30X,'N5CTR',5X,'N25CTR',10X,'R',6X,
     *  'BETAV',6X,'BETAH',5X,'PACCEL')
6015  FORMAT(1H ,28X,'N100CTR',6X,'IFLAG',8X,'PHI',5X,
     *  'VBETAV',5X,'VBETAH',4X,'PACCSTD')
6016  FORMAT(1H ,31X,'DTGO',7X,'TTGO',3X,'BETAV250',5X,
     *  'ABETAV',5X,'ABETAH',3X,'VBETAV25')
6017  FORMAT(1H ,29X,'DTG250',5X,'TTG250',3X,'BETAH250',
     *  3X,'ABETAV25',3X,'ABETAH25',3X,'VBETAH25')
C  HITTER SELECTS EITHER CROSS-COURT OR DOWN-THE-LINE SHOT
C  BY ESTIMATING COURT ANGLES TO LEFT OF AND TO RIGHT OF
C  OPPONENT AND CHOOSING MID-POINT OF LARGER OF TWO AREAS
            TAU = ATAN((27 - YO)/(39 - XO))
            SIG = ATAN((PY - YO)/(PX - XO))
            RHO = ATAN((YO)/(39 - XO))
        IF(TAU - SIG .LT. SIG - RHO) GO TO 30
              THETA = (SIG + TAU)/2
                GO TO 35
30            THETA = (SIG + RHO)/2
C  HITTER SELECTS STARTING HEIGHT AND VELOCITY OF TRAJECTORY.
35                BHEIGHT = 3.5
                  BVELVO = 12.0
                  BVELHO = 50.0
C  CHECK BOUNDARY CONDITIONS ON TRAJECTORY, USING ISIGN FOR CONTROL.
```

```
                  Z = ABS((PX - XO)*TAN(THETA))
                    V = ABS(YO - PY)

             IF(YO .GE. PY) GO TO 41
            IF(THETA .GE. 0.0) GO TO 42
             IF(Z .GE. V) GO TO 48

47                    ISIGN = -1
                       GO TO 49

41           IF(THETA .GE. 0.0) GO TO 44
                IF(Z .GE. V) GO TO 47

43                    ISIGN = 1
                       GO TO 49

44              IF(Z .GE. V) GO TO 47
                       GO TO 48

42              IF(Z .GE. V) GO TO 48
                       GO TO 47


49          DTGOO = ISIGN*((PX - XO)*TAN(THETA) - PY + YO) - 3
            TTGOO = (PX - XO)/(BVELHO*COS(THETA))
              TM1 = BVELVO/32.0
            BHEIGHT1 = BVELVO - 16.0*TM1*TM1 + BHEIGHTO
              TGR = SQRT(BHEIGHT1/16.0)
                 TG = TGR + TM1

             IF(BVELHO*TG*COS(THETA) + XO .GT. 78.0) GO TO 50
             IF(BVELHO*TG*SIN(THETA) + YO .GE. 0.0) GO TO 60
50            WRITE(6,6500)
6500       FORMAT(//////1H ,50X,'BALL OUT OF BOUNDS')
                 STOP

60          TN = (39.0 - XO)/(BVELHO*COS(THETA))
               IF(TN .LE. TM1) GO TO 70
               IF(TN .LT. TG) GO TO 68
68          IF(BHEIGHT1-16.0*(TN-TM1)**2 .LT. 3.0) GO TO 71
                     GO TO 90
70         IF(BVELVO*TN-16.0*TN**2+BHEIGHTO .GT. 3.0) GO TO 90
71                 WRITE(6,6600)
6600        FORMAT(//////1H , 53X, 'BALL IN NET')
                       STOP

90                      K = -4
                  GO TO 104
100        IF(I .LT. TTGOO*100) GO TO 101
               IF (SWITCH .EQ. 1) GO TO 1070
                       SWITCH = 1
              IF(PVEL .GT. PVMSTD/3.0) GO TO 1050

C   SET STARTING CONDITIONS FOR RECEIVER TO HIT AND OPPONENT
C   TO RECEIVE, USING JSIGN FOR CONTROL

                        AX = XO
                        AY = YO
                    XO = 78 - PX
                    YO = 37 - PY - JSIGN*PDIST
                      BHEIGHTO = BHEIGHT

                    PX = 78 - AX
                    PY = 37 - AY
                      PHEIGHT = 5.6
                        PDIST = 0.0


                     MULT1 = 2700
                     MULT2 = 425
                     MULT3 = 260

                      GO TO 20

1050       WRITE(6,6800)
6800       FORMAT(//////1H , 51X, 'MISSED INTERCEPT')

C   END OF RUN

1070                    STOP
```

```
101        IF(K .NE. 1) GO TO 102

       WRITE (6,6444) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
                  K = -5
               GO TO 103
102    WRITE (6,6130) I,TIME,BHEIGHT,ALPHAV,ALPHAH,PDIST
103    WRITE (6,6100) IFOLLOW,INTERCEPT,BDIST,ALPHAV25,ALPHAH25,PDIST250
       WRITE (6,6100) NDELYIN,NDELPIN,BDIST250,VALPHAV,VALPHAH,PVEL
       WRITE (6,6100) NDELYCOR,NDELPCOR,BVELV,VALPHAV2,VALPHAH2,PVEL250
       WRITE (6,6110) N5CTR,N25CTR,R,BETAV,BETAH,PACCEL
       WRITE (6,6100) N100CTR,IFLAG,PHI,VBETAV,VBETAH,PACCSTD
       WRITE (6,6120) DTG0,TTG0,BETAV250,ABETAV,ABETAH,VBETAV25
       WRITE (6,6120) DTG250,TTG250,BETAH250,ABETAV25,ABETAH25,VBETAH25

104           K = K + 1
          BVELH = BVELHO

6100   FORMAT (1H ,24X,2I11,4F11.4)
6110   FORMAT (/1H ,24X,2I11,4F11.4)
6120   FORMAT (1H ,24X,6F11.4)
6130   FORMAT (/////1H ,24X,I11,5F11.4)
6444   FORMAT (1H1,24X,I11,5F11.4)

C   UPDATE TIME-SLICE AND TIME FROM PROGRAM START.  TEST TIME FOR
C   RECEIVER TO BEGIN HIS DECELERATION.  INITIATE PROCESSING OF
C   GENERAL FOLLOW AND INTERCEPT LOOP.

105                 I = I + 1
                 TIME = TIME + 0.01
               TTG0 = TTG00 - TIME
               DTG0 = DTG00 - PDIST
              IF (TIME .LT. 2.0*TTG00/3.0) GO TO 110
               IF (IFLAG .NE. 1) GO TO 110
                  PACCEL = PACCSTD

C   POSITION AND VELOCITY OF BALL ARE COMPUTED IN COURT COORDINATES

110               CALL COMPUTE

               IF(I .NE. 1) GO TO 112

C   SET STARTING ANGULAR POSITION FOR EYES OF PLAYER "B"

                BETAV = ALPHAV
                BETAH = ALPHAH

C   RECEIVER ESTIMATES DIRECTION OF MOTION AND STARTING
C   ACCELERATIONS FOR BODY AND EYE MOVEMENTS.

               ALPHAV1 = ALPHAV
               ALPHAH1 = ALPHAH
112           IF(I .NE. 10) GO TO 116
               ALPHAVD = ALPHAV - ALPHAV1
               ALPHAHD = ALPHAH - ALPHAH1

             IF(ALPHAHD .LT. 0.0) GO TO 113
                  JSIGN = 1
                 GO TO 114
113               JSIGN = -1

114            PACCEL = ABS(MULT1*ALPHAHD)
               ABETAV = ABS(MULT2*ALPHAVD)
               ABETAH = ABS(MULT3*ALPHAHD)

               IFOLLOW = 0
             INTERCEPT = 0
              N100CTR = 10

                NDELYIN = 2
                NDELPIN = 3

116          IF(I .EQ. 1) GO TO 821

C   UPDATE COUNTERS
                N5CTR = N5CTR - 1
               N25CTR = N25CTR - 1
            N100CTR = N100CTR - 1
```

```
          NDELYIN = NDELYIN - 1
          NDELPIN = NDELPIN - 1
         NDELYCOR = NDELYCOR - 1
         NDELPCOR = NDELPCOR - 1

C  STATUS CHECKS ARE REQUIRED TO DETERMINE CONDITION OF CORRECTION
C  DELAY COUNTERS BEFORE INTERCEPT AND/OR FOLLOW LOGICS CAN BE
C  PROCESSED.

              IF(NDELPCOR) 200, 210, 220
200         IF(NDELYCOR) 300, 250, 260

C  CORRECT FOLLOW MOVEMENT ONLY
250           ABETAV = ABETAVT
                ABETAH = ABETAHT
                GO TO 820
C  NO CORRECTION.  DELAY STILL OPERATIVE.
260           GO TO 830

210         IF(NDELYCOR) 230, 270, 280

C  CORRECT INTERCEPT MOVEMENT ONLY
230                 PACCEL = PACCSTD
                GO TO 820

C  CORRECT BOTH FOLLOW AND INTERCEPT MOVEMENTS.
270          ABETAV = ABETAVT
               ABETAH = ABETAHT
                GO TO 230

C  CORRECT INTERCEPT MOVEMENT ONLY.  FOLLOW CORRECTION DELAY
C  STILL OPERATIVE.

280                 PACCEL = PACCSTD
                GO TO 820

220         IF(NDELYCOR) 240, 290, 299

C  NO CORRECTION.  DELAY STILL OPERATIVE.
240           GO TO 830

C  CORRECT FOLLOW MOVEMENT ONLY.  INTERCEPT CORRECTION DELAY
C  STILL OPERATIVE.
290          ABETAV = ABETAVT
               ABETAH = ABETAHT
                GO TO 820

C  NO CORRECTION.  BOTH DELAYS STILL OPERATIVE.
299           GO TO 100


C  CHECK CONDITION OF DELAYS ON FOLLOW AND INTERCEPT MOVEMENTS

300         IF(NDELYIN .GT. 0) GO TO 320
              IF(NDELPIN .GT. 0) GO TO 400

C  STARTING DELAYS NO LONGER OPERATIVE, SO CHECK STATUS OF
C  THE FOLLOW AND/OR INTERCEPT LOGIC TO ESTABLISH PROGRAM
C  SEQUENCE.

              IF(IFOLLOW .EQ. 1) GO TO 500
              IF(INTERCEPT .EQ. 1) GO TO 600

C  OTHERWISE ACTIVATE BOTH FOLLOW AND INTERCEPT LOGIC.
310               IFOLLOW = 1
                    INTERCEPT = 1

C  ENTER INFORMATION PROCESSING LOOP FOR FOLLOW AND INTERCEPT
                GO TO 820

C  FOLLOW LOGIC STILL NOT ACTIVE.  STARTING DELAY STILL OPERATIVE

320         IF(NDELPIN .GT. 0) GO TO 550

C  INTERCEPT LOGIC DELAY NO LONGER OPERATIVE, SO CHECK STATUS
C  OF INTERCEPT LOGIC TO ESTABLISH PROGRAM SEQUENCE.

              IF(INTERCEPT .EQ. 1) GO TO 600
```

```
C   INTERCEPT LOGIC NOT ACTIVE, SO ACTIVATE AND BEGIN PROCESSING.
                       INTERCEPT = 1

C   ENTER INFORMATION PROCESSING LOOP FOR INTERCEPT AND
C   POSSIBLY FOLLOW LOGIC.
                       GO TO 820

C   BOTH FOLLOW AND INTERCEPT LOGIC DELAYS STILL OPERATIVE,
C   SO NO PLAYER ACTION.
350                 GO TO 100

C   INTERCEPT LOGIC DELAY STILL OPERATIVE, SO TEST FOLLOW LOGIC
C   STATUS.
400             IF(IFOLLOW .EQ. 1) GO TO 450
                     IFOLLOW = 1

C   ENTER INFORMATION PROCESSING LOOP FOR FOLLOW AND POSSIBLY
C   INTERCEPT LOGIC.
                       GO TO 820

C   FOLLOW LOGIC ACTIVE, SO ENTER INFORMATION PROCESSING LOOP
C   AS IF INTERCEPT ALSO ACTIVE.
450             IF(N100CTR .LE. 0) GO TO 700
                       GO TO 830

C   FOLLOW LOGIC ACTIVE, SO TEST INTERCEPT LOGIC.
500             IF(INTERCEPT .EQ. 1) GO TO 550
                  IF(N100CTR .LE. 0) GO TO 700
                     INTERCEPT = 1

C   ENTER INFORMATION LOOP TO PROCESS FOLLOW AND INTERCEPT LOGIC
                       GO TO 830

C   BOTH FOLLOW AND INTERCEPT LOGICS ACTIVE.
550                 GO TO 830

C   INTERCEPT LOGIC ACTIVE, SO TEST 100 MS COUNTER.
600             IF(N100CTR .GT. 0) GO TO 650
                      IFOLLOW = -1

C   ENTER INFORMATION LOOP TO PROCESS ONLY INTERCEPT LOGIC.
                       GO TO 830

C   100 MS COUNTER STILL OPERATIVE, SO ENTER INFORMATION LOOP
C   TO PROCESS INTERCEPT AND   FOLLOW LOGIC.
650               IFOLLOW = 1
                       GO TO 830

C   FOLLOW LOGIC ACTIVE AND 100 MS DELAY TIME PASSED, SO
C   PROCESS ONLY FOLLOW LOGIC.
700               INTERCEPT = -1
                       GO TO 830


C   INITIALIZE TRAJECTOPY VELOCITY COUNTERS FOR RECEIVER TO BEGIN
C   VELOCITY AVERAGING.

820                     N5CTR = 5
                         N25CTR = 25
                       N100CTR = 10
821                       BVSUMV = 0
                          BVSUMH = 0
                          TOTALV = 0
                          TOTALH = 0
C   INITIALIZE FEEDFORWARD COMPUTATION USING CURRENT VALUES OF POSITION
C   AND VELOCITY OF PLAYER AND LINE OF SIGHT AND LINE TO BALL.
               BETAVST = BETAV
                 BETAHST = BETAH
             VBETAVST = VBETAV
             VBETAHST = VBETAH
             GAMMAVST = ALPHAV - BETAV
             GAMMAHST = ALPHAH - BETAH
             VGAMAVST = VALPHAV - VBETAV
             VGAMAHST = VALPHAH - VBETAH
             PDISTST = PDIST
               PVELST = PVEL
             PACCELST = PACCEL
                  RST = R
             RHEIGHST = RHEIGHT
               TIMEST = TIME
```

```
            ABETAVST = ABETAV
            ABETAHST = ABETAH
             IST = 1

C   BEGIN PROCESSING FOLLOW AND/OR INTERCEPT LOGIC.  FIRST
C   OBTAIN AVERAGE OF VERTICAL COMPONENTS OF TRAJECTORY
C   VELOCITY AND AVERAGE OF HORIZONTAL COMPONENTS.

830         IF(TTGO .LE. 0.25) GO TO 100

            BVSUMV = BVSUMV + BVELV
            BVSUMH = BVSUMH + BVELH

          IF(N5CTR .GT. 1) GO TO 835
             BVAVE1V = BVSUMV/5.0
             BVAVE1H = BVSUMH/5.0
              BVSUMV = 0.0
              BVSUMH = 0.0

                N5CTR = 6

           TOTALV = TOTALV + BVAVE1V
           TOTALH = TOTALH + BVAVE1H

835     IF(N25CTR .NE. 1) GO TO 100

C   COMPUTE PLAYER'S ESTIMATE OF TRAJECTORY VELOCITY
C   COMPONENTS USING AVERAGE VELOCITY.  VCON IS A CONSTANT THAT
C   ALLOWS FOR VARIABLE STARTING CONDITIONS.

           BVAVE2V = TOTALV/(5.0 - VCON)
           BVAVE2H = TOTALH/(5.0 - VCON)

             VCON = 0.0

C   COMPUTE ESTIMATED VALUES OF PLAYER'S DISTANCE ATTAINED
C   IN 250 MS AND PLAYER VELOCITY AT 250 MS.  DATA USED
C   FOR BOTH FOLLOW AND INTERCEPT LOGICS.

          PDIST250=PDISTST+PVELST*DELTAT2+PACCELST*DELTAT2**2
         PVEL250=PVELST+PACCELST*DELTAT2

C   TEST STATUS OF FOLLOW LOGIC FOR INFO PROCESSING.

                IF(IFOLLOW .EQ. -1) GO TO 970

C   PROCESS FOLLOW LOGIC USING ESTIMATED PLAYER POSITION
C   AND VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                        CALL FOLLOW

C   TEST STATUS OF INTERCEPT LOGIC FOR INFO PROCESSING.

970         IF(INTERCEPT .EQ. -1) GO TO 998

C   PROCESS INTERCEPT LOGIC USING ESTIMATED PLAYER POSITION
C   AND VELOCITY AND PREPARE CORRECTION IF NECESSARY.

                  IF(TIMEST .GT. TTG00/3) GO TO 972
             DTG250 = 1.15*(DTG00 - PDIST250)
                     GO TO 973

972             IF(TIMEST .GT. 2.0*TTG00/3.0) GO TO 974
             DTG250 = 1.10*(DTG00 - PDIST250)
                     GO TO 973

974      DTG250 = 1.05*(DTG00 - PDIST250)

973         TTG250 = TTG00 - TIMEST - 0.25

C   RECEIVER COMPARES ESTIMATED ACTUAL WITH ESTIMATED DESIRED
C   VELOCITY AT THE 250 MARK.

             PVMSTD = 18.0*DTG00/(15.0*TTG00)

                  IF(TIMEST .GT. TTG00/3) GO TO 980
              PACCSTD = 3.0*PVMSTD/TTG00
                 PVSTDST = PACCSTD * TIMEST
             PVSTD250 = PVSTDST + PACCSTD * DELTAT2
```

```
      IF(ABS(PVSTD250 - PVEL250) .LE. 0.05*(PVSTD250+PVEL250))GO TO 987
          IF(PVSTD250 - PVEL250 .GT. 0.0) GO TO 987
                PACCSTD = 0.0

C   PACCEL MUST BE SET TO ZERO ALSO, BUT THIS CAN'T BE DONE
C   UNTIL THE DELAY, NDELPCOR, FOR PLAYER CORRECTION HAS
C   COUNTED DOWN

                NDELPCOR = 4
                 GO TO 987

980            IF(TIMEST .GT. 2.0*TTG00/3.0) GO TO 987
                PVSTD250 = PVMSTD

                 PACCSTD = 0.0
                NDELPCOR = 4

      IF(ABS(PVSTD250 - PVEL250) .LE. 0.05*(PVSTD250+PVEL250))GO TO 985
           IF(PVSTD250 - PVEL250 .LT. 0.0) GO TO 981

        PACCSTD = -(2.0*PVMSTD/3)/(TTG00 - 2*TTG00/3)

C   PACCEL IS ALSO SET TO  THIS VALUE, BUT NOT UNTIL TIME
C   EQUALS 2*TTG00/3.

                  GO TO 986

981             PACCSTD = -PVMSTD/(TTG00 -2*TTG00/3)
                    GO TO 986
985          PACCSTD = -(5.0*PVMSTD/6.0)/(TTG00 -2.0*TTG00/3.0)
986                IFLAG = 1
987              INTERCEPT = 0
                  IFOLLOW = 0
                    GO TO 100

998          IF(IFOLLOW .EQ. 1) GO TO 100
                 INTERCEPT = 0
                  IFOLLOW = 0
                    GO TO 100
          END

  END OF SEGMENT, LENGTH  2234, NAME TENNIS
```

```
                 SUBROUTINE COMPUTE

       COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
      *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
      *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
      *  BETAH, VBETAH,   NDELPIN, PVEL, PACCEL,
      *  TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
      *  R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
      *  ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
      *  VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
      *  VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
      *  VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
      *  ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
      *  NDELYCOR, TM1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
      *  X0, Y0, PX, PY, BVELVGR

C   COMPUTE POSITION AND VELOCITY OF BALL IN COURT COORDS.

                       R = BVELH*TIME
                     BVELVGR = 32.0*TGR
                   IF(TIME .LE. TM1) GO TO 130
                   IF(TIME .LE. TG) GO TO 120

         BHEIGHT = 16.0*(TIME - TG) - 16.0*(TIME - TG)**2
            BVELV = 16.0 - 32.0*(TIME - TG)
                  GO TO 140

120       BHEIGHT = BHEIGHT1 - 16.0*(TIME - TM1)**2
              BVELV = 32.0*(TIME - TM1)
                  GO TO 140

130       BHEIGHT = BVELV0*TIME - 16.0*TIME**2 + BHEIGHT0
              BVELV = BVELV0 - 32.0*TIME

C   COMPUTE DISTANCE AND ANGULAR POSITION AND VELOCITY OF BALL

140            X = R*COS(THETA) + X0
               Y = R*SIN(THETA) + Y0
          BDIST = SQRT((PX - X)**2 + (PY + JSIGN*PDIST - Y)**2)
                 ALPHAV = ATAN((BHEIGHT - 5.0)/BDIST)
               ALPHAH = ATAN((Y - PY - JSIGN*PDIST)/(PX - X))
                 VALPHAV = BVELV/BDIST
             W = (PY + JSIGN*PDIST - Y)/(PX - X)
                 PHI = ATAN(W)
         VALPHAH = (BVELH*SIN(THETA - PHI) - PVEL*COS(PHI))/BDIST

C   MOVEMENT OF PLAYER "B"'S LINE OF SIGHT (LOS) IS DELAYED BY AN
C   AMOUNT EQUAL TO THE PLAYER'S REACTION TIME TO OPPONENT'S
C   STRIKING THE BALL.

                IF(NDELYIN .GT. 0) GO TO 180

C   AFTER THE DELAY, ANGULAR POSITION AND VELOCITY OF LOS ARE
C   COMPUTED.

         BETAV = BETAV + VBETAV*DELTAT1 + ABETAV*DELTAT1**2
         BETAH = BETAH + VBETAH*DELTAT1 + ABETAH*DELTAT1**2
            VBETAV = VBETAV + ABETAV*DELTAT1
            VBETAH = VBETAH + ABETAH*DELTAT1

C   MOVEMENT OF PLAYER IS DELAYED BY AN AMOUNT EQUAL TO HIS
C   REACTION TIME TO OPPONENT'S STRIKING THE BALL.

180          IF(NDELPIN .GT. 0) GO TO 190

C   THE NEW POSITION AND VELOCITY OF PLAYER "B" IN HIS INTERCEPT
C   PATH ARE COMPUTED AS SOON AS THE DELAY HAS COUNTED DOWN.

         PDIST = PDIST + PVEL*DELTAT1 + PACCEL*DELTAT1**2
            PVEL = PVEL + PACCEL*DELTAT1

190             RETURN
                    END


END OF SEGMENT, LENGTH    585, NAME  COMPUTE
```

```
                    SUBROUTINE FOLLOW

      COMMON/BALL/ R, BVELV, BVELH, TIME, BHEIGHT,BDIST,
     *  PDIST, ALPHAV, ALPHAH, PHI, VALPHAV, VALPHAH,
     *  X, Y, NDELYIN, BETAV, VBETAV, DELTAT1,
     * BETAH, VBETAH, [illegible], PVEL, PACCEL,
     * TIMEST, BHEIT250, BHEIGTST, BVAVE2V, DELTAT2,
     * R250, RST, BVAVE2H, BDIST250, THETA, PDIST250, ALPHAV25,
     * ALPHAH25, VALPHAV2, VALPHAH2, PVEL250, BETAV250, BETAVST,
     * VBETAVST, ABETAVST, BETAH250, BETAHST, VBETAHST, ABETAHST,
     * VBETAV25, VBETAH25, GAMAV250, GAMAH250, VGAMAV25,
     * VGAMAH25, VANGDIFF, HANGDIFF, VANVDIFF, HANVDIFF,
     * ABETAV25, ABETAH25, ABETAV, ABETAVT, ABETAH, ABETAHT,
     * NDELYCOR, TM1, TG, TGR, BHEIGHT0, BHEIGHT1, BVELV0,
     * X0, Y0, PX, PY, BVELVGR

C   PROCESS FOLLOW LOGIC USING ESTIMATED PLAYER POSITION AND
C   VELOCITY AND PREPARE CORRECTION IF NECESSARY.

              IF(TIMEST .LE. TM1) GO TO 841
              IF(TIMEST .LE. TG) GO TO 842

841       BHEIT250 = BHEIGTST + BVAVE2V*DELTAT2
                GO TO 843

842       BHEIT250 = BHEIGTST - BVAVE2V*DELTAT2
843           R250 = RST + BVAVE2H*DELTAT2
        BDIST250 = SQRT((PX - R250*COS(THETA))**2
     *          + (PY + PDIST250 - R250*SIN(THETA))**2)

C   FIND ANGULAR POSITION AND VELOCITY OF LINE TO BALL

              ALPHAV25 = ATAN((BHEIT250 - 5.0)/BDIST250)
      ALPHAH25=ATAN((R250*SIN(THETA)-PDIST250)/(PX-R250*COS(THETA)))
           VALPHAV2 = BVAVE2V/BDIST250
            W250 = (PY+PDIST250-R250*SIN(THETA))/(PX-R250*COS(THETA))
      VALPHAH2=(BVAVE2H*SIN(THETA-ATAN(W250))-PVEL250*COS(ATAN(W250)))/
     *                          BDIST250

C   FIND ANGULAR POSITION AND VELOCITY OF LOS AND FORM DIFFERENCES

        BETAV250 = BETAVST + VBETAVST*DELTAT2 + ABETAVST*DELTAT2**2
        BETAH250 = BETAHST + VBETAHST*DELTAT2 + ABETAHST*DELTAT2**2
            VBETAV25 = VBETAVST + ABETAVST*DELTAT2
            VBETAH25 = VBETAHST + ABETAHST*DELTAT2
              GAMAV250 = ALPHAV25 - BETAV250
              GAMAH250 = ALPHAH25 - BETAH250


            VGAMAV25 = VALPHAV2 - VBETAV25
            VGAMAH25 = VALPHAH2 - VBETAH25

C   THE ANGULAR DIFFERENCES AND ANGULAR VELOCITY DIFFERENCES MUST
C   NOW BE COMPARED AGAINST THE PLAYER'S STANDARDS OF MAGNITUDE

      IF(ABS(GAMAV250).LE.0.05*(ALPHAV25 + BETAV250)) GO TO 844
            IF(GAMAV250 .LT. 0.0) GO TO 845
          IF(ABS(GAMAV250) .LE. 0.18) GO TO 846
          IF(ABS(GAMAV250) .LE. 0.9) GO TO 847

C   VERTICAL ANGULAR DIFF IS LARGE POSITIVE
                VANGDIFF = 3
                  GO TO 851
846           VANGDIFF = 1
                  GO TO 851
847           VANGDIFF = 2

                  GO TO 851

C VERTICAL ANG DIFF IS NEGATIVE

845       IF(ABS(GAMAV250) .LE. 0.18) GO TO 848
            IF(ABS(GAMAV250) .LE. 0.9) GO TO 849

                VANGDIFF = -3
                  GO TO 851
848           VANGDIFF = -1
                  GO TO 851
```

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849          VANGDIFF = -2
                GO TO 851

844          VANGDIFF = 0

851     IF(ABS(GAMAH250) .LE. 0.05*(ALPHAH25 + BETAH250)) GO TO 854
              IF(GAMAH250 .LT. 0.0) GO TO 855
             IF(ABS(GAMAH250) .LE. 0.18) GO TO 856
             IF(ABS(GAMAH250) .LE. 0.9) GO TO 857

C  HORIZONTAL ANGULAR DIFF IS LARGE POSITIVE

               HANGDIFF = 3
                GO TO 861
856          HANGDIFF = 1
                GO TO 861
857          HANGDIFF = 2
                GO TO 861

C  HORIZONTAL ANG DIFF IS NEGATIVE

855       IF(ABS(GAMAH250) .LE. 0.18) GO TO 858
            IF(ABS(GAMAH250) .LE. 0.9) GO TO 859

               HANGDIFF = -3
                GO TO 861
858          HANGDIFF = -1
                GO TO 861
859          HANGDIFF = -2
                GO TO 861

854           HANGDIFF = 0

861     IF(ABS(VGAMAV25) .LE. 0.05*(VALPHAV2+VBETAV25)) GO TO 864
              IF(VGAMAV25 .LT. 0.0) GO TO 865
              IF(ABS(VGAMAV25) .LE. 0.18) GO TO 866
              IF(ABS(VGAMAV25) .LE. 0.9) GO TO 867

C  VERTICAL ANGULAR VELOCITY DIFF IS LARGE POSITIVE

                VANVDIFF = 3
                  GO TO 871
866           VANVDIFF = 1
                  GO TO 871
867           VANVDIFF = 2
                  GO TO 871

C  HORIZONTAL ANGULAR VELOCITY DIFF IS NEGATIVE

865        IF(ABS(VGAMAV25) .LE. 0.18) GO TO 868
             IF(ABS(VGAMAV25) .LE. 0.9) GO TO 869

                VANVDIFF = -3
                  GO TO 871
868           VANVDIFF = -1
                  GO TO 871
869           VANVDIFF = -2
                  GO TO 871

864           VANVDIFF = 0

871    IF(ABS(VGAMAH25) .LE. 0.05*(VALPHAH2 + VBETAH25)) GO TO 874
              IF(VGAMAH25 .LT. 0.0) GO TO 875
             IF(ABS(VGAMAH25) .LE. 0.18) GO TO 876
             IF(ABS(VGAMAH25) .LE. 0.9) GO TO 877

C  HORIZONTAL ANGULAR VELOCITY DIFF IS LARGE POSITIVE

                HANVDIFF = 3
                  GO TO 881
876           HANVDIFF = 1
                  GO TO 881
877           HANVDIFF = 2
                  GO TO 881

C  HORIZONTAL ANGULAR VELOCITY DIFF IS NEGATIVE

875        IF(ABS(VGAMAH25) .LE. 0.18) GO TO 878
             IF(ABS(VGAMAH25) .LE. 0.9) GO TO 879
```

```
                     HANVDIFF = -3
                        GO TO 881
878                  HANVDIFF = -1
                        GO TO 881
879                  HANVDIFF = -2
                        GO TO 881

874                  HANVDIFF = 0

881                  L1 = VANGDIFF + VANVDIFF
                        L2 = HANGDIFF + HANVDIFF

                    IF(L1 .LT. 0) GO TO 884
                    IF(L1 .EQ. 0) GO TO 885
                    IF(L1 .EQ. 1) GO TO 886
                    IF(L1 .EQ. 2) GO TO 887

C  VERTICAL DRIVING ACCELERATION IS LARGE POSITIVE.

                          ABETAV25 = 20.0
                             GO TO 891
885                    ABETAV25 = 0.0
                             GO TO 891
886                    ABETAV25 = 5.0
                             GO TO 891
887                    ABETAV25 = 10.0
                             GO TO 891

884             IF(L1 .EQ. -1) GO TO 888
                    IF(L1 .EQ. -2) GO TO 889

C  VERTICAL DRIVING ACCELERATION IS LARGE NEGATIVE.

                          ABETAV25 = -20.0
                             GO TO 891
888                    ABETAV25 = -5.0
                             GO TO 891
889                    ABETAV25 = -10

891                 IF(L2 .LT. 0) GO TO 894
                       IF(L2 .EQ. 0) GO TO 895
                       IF(L2 .EQ. 1) GO TO 896
                       IF(L2 .EQ. 2) GO TO 897

C  HORIZONTAL DRIVING ACCELERATION IS LARGE POSITIVE.

                          ABETAH25 = 20.0
                             GO TO 900
895                    ABETAH25 = 0.0
                             GO TO 900
896                    ABETAH25 = 5.0
                             GO TO 900
897                    ABETAH25 = 10.0
                             GO TO 900

894                IF(L2 .EQ. -1) GO TO 898
                      IF(L2 .EQ. -2) GO TO 899

C  HORIZONTAL DRIVING ACCELERATION IS LARGE NEGATIVE.

                          ABETAH25 = -20.0
                             GO TO 900
898                    ABETAH25 = -5.0
                             GO TO 900
899                    ABETAH25 = -10.0

C  DETERMINE VALUE OF PLAYER'S CORRECTION TO EYE MOVEMENT.

900            IF(ABS(ABETAV + ABETAV25) .LE. 20.0) GO TO 920
                    IF(ABETAV + ABETAV25 .LT. 0.0) GO TO 930

C  PLAYER APPLIES MAXIMUM VERTICAL ACCELERATION.
                             ABETAVT = 20.0
                               GO TO 940

C  PLAYER APPLIES MAXIMUM VERTICAL DECELERATION.
930                          ABETAVT = -20.0
                               GO TO 940
```

```
C  CORRECTIVE ADDITION DOESN'T EXCEED MAXIMUM ACCELERATION.
920                 ABETAVT = ABETAV + ABETAV25
940      IF(ABS(ABETAH + ABETAH25) .LE. 20.0) GO TO 950
               IF(ABETAH + ABETAH25 .LT. 0.0) GO TO 960
C  PLAYER APPLIES MAXIMUM HORIZONTAL ACCELERATION.
                         ABETAHT = 20.0
                          GO TO 965
C  PLAYER APPLIES MAXIMUM HORIZONTAL DECELERATION.
960                    ABETAHT = -20.0
                           GO TO 965
C  CORRECTIVE ADDITION DOESN'T EXCEED MAXIMUM DECELERATION.
950                 ABETAHT = ABETAH + ABETAH25
965                    NDELYCOR = 2
                       IFOLLOW = 0
              RETURN
               END

END OF SEGMENT, LENGTH  1237, NAME  FOLLOW
```

```
                              FINISH
END OF COMPILATION -  NO ERRORS

S/C SUBFILE:                [illegible] BUCKETS USED


CONSOLIDATED BY XPCK 12K    DATE    30/10/79   TIME 23/33/40

PROGRAM TENN
COMPACT DATA (15AM)
COMPACT PROGRAM (DBM)
CORE              8384

                SEG     TENNIS
                CUV     BALL
                SEG     ATAN
                SEG     ABS
                SEG     TAN
                SEG     COS
                SEG     SQRT
                SEG     SIN
                SEG     COMPUTE
                SEG     FOLLOW
                CLV     SFFIL
```

- TENNIS -

SIMULATION OF THE VISUO-MOTOR PROCESSES

THIRD EXTENSION OF PROTOTYPE MODEL

H. A. PAPPO
RHODES UNIVERSITY
1979

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                             TIME-SLICE DATA BLOCK


         I          TIME        BHEIGHT       ALPHAV       ALPHAH        PDIST
   IFOLLOW     INTERCEPT          BDIST     ALPHAV25     ALPHAH25     PDIST250
   NDELYIN       NDELPIN       BDIST250      VALPHAV      VALPHAH         PVEL
  NDELYCOR      NDELPCOR          BVELV     VALPHAV2     VALPHAH2      PVEL250

     N5CTR        N25CTR              R        BETAV        BETAH       PACCEL
   N100CTR         IFLAG            PHI       VBETAV       VBETAH      PACCSTD
      DTGO          TTGO       BETAV250       ABETAV       ABETAH     VBETAV25
    DTG250        TTG250       BETAH250     ABETAV25     ABETAH25     VBETAH25


         1        0.0100         0.1184      -0.0701      -0.1518       0.0000
         1             1        69.5358       0.0000       0.0000       0.0000
        -1            -1         0.0000       0.1680       0.1660       0.0000
        -1            -1        11.6800       0.0000       0.0000       0.0000

         5            10         0.5000      -0.0701      -0.1518       0.0000
        -1             0         0.1518       0.0000       0.0000       0.0000
   14.3161        1.4831         0.0000       0.0000       0.0000       0.0000
    0.0000        0.0000         0.0000       0.0000       0.0000       0.0000


         2        0.0200         0.2336      -0.0689      -0.1501       0.0000
         1             1        69.0494       0.0000       0.0000       0.0000
        -2            -2         0.0000       0.1645       0.1653       0.0000
        -2            -2        11.3600       0.0000       0.0000       0.0000

         4             9         1.0000      -0.0701      -0.1518       0.0000
        -2             0         0.1501       0.0000       0.0000       0.0000
   14.3161        1.4731         0.0000       0.0000       0.0000       0.0000
    0.0000        0.0000         0.0000       0.0000       0.0000       0.0000


         3        0.0300         0.3456      -0.0678      -0.1484       0.0000
         1             1        68.5532       0.0000       0.0000       0.0000
        -3            -3         0.0000       0.1610       0.1707       0.0000
        -3            -3        11.0400       0.0000       0.0000       0.0000

         3             8         1.5000      -0.0701      -0.1518       0.0000
        -3             0         0.1484       0.0000       0.0000       0.0000
   14.3161        1.4631         0.0000       0.0000       0.0000       0.0000
    0.0000        0.0000         0.0000       0.0000       0.0000       0.0000


         4        0.0400         0.4544      -0.0667      -0.1447       0.0000
         1             1        68.0771       0.0000       0.0000       0.0000
        -4            -4         0.0000       0.1575       0.1732       0.0000
        -4            -4        10.7200       0.0000       0.0000       0.0000

         2             7         2.0000      -0.0701      -0.1518       0.0000
        -4             0         0.1447       0.0000       0.0000       0.0000
   14.3161        1.4531         0.0000       0.0000       0.0000       0.0000
    0.0000        0.0000         0.0000       0.0000       0.0000       0.0000
```

```
       5       0.0500       0.5600      -0.0656      -0.1449       0.0000
       1            1      67.5913       0.0000       0.0000       0.0000
      -5           -5       0.0000       0.1539       0.1757       0.0000
      -5           -5      10.4000       0.0000       0.0000       0.0000

       6            6       2.5000      -0.0701      -0.1518       0.0000
      -5            0       0.1449       0.0000       0.0000       0.0000
 14.3161       1.4431       0.0000       0.0000       0.0000       0.0000
  0.0000       0.0000       0.0000       0.0000       0.0000       0.0000



       6       0.0600       0.6624      -0.0645      -0.1432       0.0000
       1            1      67.1058       0.0000       0.0000       0.0000
      -6           -6       0.0000       0.1502       0.1782       0.0000
      -6           -6      10.0800       0.0000       0.0000       0.0000

       5            5       3.0000      -0.0701      -0.1518       0.0000
      -6            0       0.1432       0.0000       0.0000       0.0000
 14.3161       1.4331       0.0000       0.0000       0.0000       0.0000
  0.0000       0.0000       0.0000       0.0000       0.0000       0.0000



       7       0.0700       0.7616      -0.0635      -0.1414       0.0000
       1            1      66.6204       0.0000       0.0000       0.0000
      -7           -7       0.0000       0.1465       0.1808       0.0000
      -7           -7       9.7600       0.0000       0.0000       0.0000

       4            4       3.5000      -0.0701      -0.1518       0.0000
      -7            0       0.1414       0.0000       0.0000       0.0000
 14.3161       1.4231       0.0000       0.0000       0.0000       0.0000
  0.0000       0.0000       0.0000       0.0000       0.0000       0.0000



       8       0.0800       0.8576      -0.0626      -0.1395       0.0000
       1            1      66.1352       0.0000       0.0000       0.0000
      -8           -8       0.0000       0.1427       0.1835       0.0000
      -8           -8       9.4400       0.0000       0.0000       0.0000

       3            3       4.0000      -0.0701      -0.1518       0.0000
      -8            0       0.1395       0.0000       0.0000       0.0000
 14.3161       1.4131       0.0000       0.0000       0.0000       0.0000
  0.0000       0.0000       0.0000       0.0000       0.0000       0.0000



       9       0.0900       0.9504      -0.0616      -0.1377       0.0000
       1            1      65.6503       0.0000       0.0000       0.0000
      -9           -9       0.0000       0.1389       0.1862       0.0000
      -9           -9       9.1200       0.0000       0.0000       0.0000

       2            2       4.5000      -0.0701      -0.1518       0.0000
      -9            0       0.1377       0.0000       0.0000       0.0000
 14.3161       1.4031       0.0000       0.0000       0.0000       0.0000
  0.0000       0.0000       0.0000       0.0000       0.0000       0.0000



      10       0.1000       1.0400      -0.0607      -0.1358       0.0000
       0            0      65.1656       0.0000       0.0000       0.0000
       1            2       0.0000       0.1350       0.1890       0.0000
     -10          -10       8.8000       0.0000       0.0000       0.0000

       1            1       5.0000      -0.0701      -0.1518      51.0087
       9            0       0.1358       0.0000       0.0000       0.0000
 14.3161       1.3931       0.0000       3.7576       3.9851       0.0000
  0.0000       0.0000       0.0000       0.0000       0.0000       0.0000
```

```
      11        0.1100        1.1264       -0.0598       -0.1359        0.0000
       1             0       64.6811        0.0000        0.0000        0.0000
       0             1        0.0000        0.1311        0.1918        0.0000
     -11           -11        8.4800        0.0000        0.0000        0.0000

       5            25        5.5000       -0.0701       -0.1518       51.0087
      10                      0.1339        0.0000        0.0000        0.0000
 14.3161        1.3831        0.0000        3.7576        3.9851        0.0000
  0.0000        0.0000        0.0000        0.0000        0.0000        0.0000



      12        0.1200        1.2096       -0.0590       -0.1320        0.0000
       1             1       64.1968        0.0000        0.0000        0.0000
      -1             0        0.0000        0.1271        0.1947        0.0000
     -12           -12        8.1600        0.0000        0.0000        0.0000

       4            24        6.0000       -0.0697       -0.1514       51.0087
       9             0        0.1320        0.0376        0.0399        0.0000
 14.3161        1.3731        0.0000        3.7576        3.9851        0.0000
  0.0000        0.0000        0.0000        0.0000        0.0000        0.0000



      13        0.1300        1.2896       -0.0582       -0.1300        0.0051
       1             1       63.7128        0.0000        0.0000        0.0000
      -2            -1        0.0000        0.1231        0.1977        0.5101
     -13           -13        7.8400        0.0000        0.0000        0.0000

       3            23        6.5000       -0.0690       -0.1506       51.0087
       8             0        0.1300        0.0752        0.0797        0.0000
 14.3161        1.3631        0.0000        3.7576        3.9851        0.0000
  0.0000        0.0000        0.0000        0.0000        0.0000        0.0000



      14        0.1400        1.3664       -0.0574       -0.1280        0.0153
       1             1       63.2291        0.0000        0.0000        0.0000
      -3            -2        0.0000        0.1189        0.1927        1.0202
     -14           -14        7.5200        0.0000        0.0000        0.0000

       2            22        7.0000       -0.0678       -0.1494       51.0087
       7             0        0.1280        0.1127        0.1196        0.0000
 14.3110        1.3531        0.0000        3.7576        3.9851        0.0000
  0.0000        0.0000        0.0000        0.0000        0.0000        0.0000



      15        0.1500        1.4400       -0.0567       -0.1260        0.0306
       1             1       62.7456        0.0000        0.0000        0.0000
      -4            -3        0.0000        0.1147        0.1877        1.5303
     -15           -15        7.2000        0.0000        0.0000        0.0000

       6            21        7.5000       -0.0663       -0.1478       51.0087
       6             0        0.1260        0.1503        0.1594        0.0000
 14.3008        1.3431        0.0000        3.7576        3.9851        0.0000
  0.0000        0.0000        0.0000        0.0000        0.0000        0.0000



      16        0.1600        1.5104       -0.0560       -0.1240        0.0510
       1             1       62.2624        0.0000        0.0000        0.0000
      -5            -4        0.0000        0.1105        0.1826        2.0403
     -16           -16        6.8800        0.0000        0.0000        0.0000

       5            20        8.0000       -0.0645       -0.1458       51.0087
       5             0        0.1240        0.1879        0.1993        0.0000
 14.2855        1.3331        0.0000        3.7576        3.9851        0.0000
  0.0000        0.0000        0.0000        0.0000        0.0000        0.0000
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      17      0.1700      1.5776     -0.0553     -0.1219      0.0765
       1           1     61.7794      0.0000      0.0000      0.0000
      -6          -5      0.0000      0.1062      0.1775      2.5504
     -17         -17      6.5600      0.0000      0.0000      0.0000

       4          19      8.5000     -0.0622     -0.1434     51.0087
       4           0      0.1219      0.2255      0.2391      0.0000
 14.2651      1.3231      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      18      0.1800      1.6416     -0.0547     -0.1197      0.1071
       1           1     61.2967      0.0000      0.0000      0.0000
      -7          -6      0.0000      0.1018      0.1723      3.0605
     -18         -18      6.2400      0.0000      0.0000      0.0000

       3          18      9.0000     -0.0596     -0.1406     51.0087
       3           0      0.1197      0.2630      0.2790      0.0000
 14.2396      1.3131      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      19      0.1900      1.7024     -0.0542     -0.1176      0.1428
       1           1     60.8143      0.0000      0.0000      0.0000
      -8          -7      0.0000      0.0973      0.1670      3.5706
     -19         -19      5.9200      0.0000      0.0000      0.0000

       2          17      9.5000     -0.0566     -0.1374     51.0087
       2           0      0.1176      0.3006      0.3188      0.0000
 14.2089      1.3031      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      20      0.2000      1.7600     -0.0537     -0.1154      0.1836
       1           1     60.3322      0.0000      0.0000      0.0000
      -9          -8      0.0000      0.0928      0.1617      4.0807
     -20         -20      5.6000      0.0000      0.0000      0.0000

       6          16     10.0000     -0.0532     -0.1338     51.0087
       1           0      0.1154      0.3382      0.3587      0.0000
 14.1732      1.2931      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      21      0.2100      1.8144     -0.0532     -0.1132      0.2295
       1           1     59.8503      0.0000      0.0000      0.0000
     -10          -9      0.0000      0.0882      0.1563      4.5908
     -21         -21      5.2800      0.0000      0.0000      0.0000

       5          15     10.5000     -0.0494     -0.1298     51.0087
       0           0      0.1132      0.3758      0.3985      0.0000
 14.1324      1.2831      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      22      0.2200      1.8656     -0.0527     -0.1109      0.2805
       1           1     59.3688      0.0000      0.0000      0.0000
     -11         -10      0.0000      0.0835      0.1508      5.1009
     -22         -22      4.9600      0.0000      0.0000      0.0000

       4          14     11.0000     -0.0453     -0.1255     51.0087
      -1           0      0.1109      0.4133      0.4384      0.0000
 14.0865      1.2731      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
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```
      23      0.2300       1.9136     -0.0524     -0.1086      0.3367
       1           1      58.8876      0.0000      0.0000      0.0000
     -12         -11       0.0000      0.0788      0.1453      5.6110
     -23         -23       4.6400      0.0000      0.0000      0.0000

       3          13      11.5000     -0.0408     -0.1207     51.0087
      -2           0       0.1086      0.4509      0.4732      0.0000
 14.0555      1.2631       0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000       0.0000      0.0000      0.0000      0.0000



      24      0.2400       1.9584     -0.0520     -0.1063      0.3979
       1           1      58.4067      0.0000      0.0000      0.0000
     -13         -12       0.0000      0.0740      0.1397      6.1210
     -24         -24       4.3200      0.0000      0.0000      0.0000

       2          12      12.0000     -0.0359     -0.1155     51.0087
      -3           0       0.1063      0.4885      0.5181      0.0000
 13.9794      1.2531       0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000       0.0000      0.0000      0.0000      0.0000



      25      0.2500       2.0000     -0.0517     -0.1039      0.4642
       1           1      57.9261      0.0000      0.0000      0.0000
     -14         -13       0.0000      0.0691      0.1341      6.6311
     -25         -25       4.0000      0.0000      0.0000      0.0000

       6          11      12.5000     -0.0306     -0.1099     51.0087
      -4           0       0.1039      0.5261      0.5579      0.0000
 13.9182      1.2431       0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000       0.0000      0.0000      0.0000      0.0000



      26      0.2600       2.0384     -0.0515     -0.1015      0.5356
       1           1      57.4458      0.0000      0.0000      0.0000
     -15         -14       0.0000      0.0641      0.1283      7.1412
     -26         -26       3.6800      0.0000      0.0000      0.0000

       5          10      13.0000     -0.0250     -0.1039     51.0087
      -5           0       0.1015      0.5636      0.5978      0.0000
 13.8519      1.2331       0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000       0.0000      0.0000      0.0000      0.0000



      27      0.2700       2.0736     -0.0513     -0.0991      0.6121
       1           1      56.9659      0.0000      0.0000      0.0000
     -16         -15       0.0000      0.0590      0.1226      7.6513
     -27         -27       3.3600      0.0000      0.0000      0.0000

       4           9      13.5000     -0.0190     -0.0976     51.0087
      -6           0       0.0991      0.6012      0.6376      0.0000
 13.7805      1.2231       0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000       0.0000      0.0000      0.0000      0.0000



      28      0.2800       2.1056     -0.0512     -0.0966      0.6937
       1           1      56.4863      0.0000      0.0000      0.0000
     -17         -16       0.0000      0.0538      0.1167      8.1614
     -28         -28       3.0400      0.0000      0.0000      0.0000

       3           8      14.0000     -0.0126     -0.0908     51.0087
      -7           0       0.0966      0.6388      0.6775      0.0000
 13.7040      1.2131       0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000       0.0000      0.0000      0.0000      0.0000
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      29      0.2900      2.1344     -0.0511     -0.0940      0.7804
       1           1     56.0071      0.0000      0.0000      0.0000
     -18         -17      0.0000      0.0486      0.1108      8.6715
     -29         -29      2.7200      0.0000      0.0000      0.0000

       2           7     14.5000     -0.0058     -0.0836     51.0087
      -8           0      0.0940      0.6764      0.7173      0.0000
 13.6223      1.2031      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      30      0.3000      2.1600     -0.0511     -0.0914      0.8722
       1           1     55.5283      0.0000      0.0000      0.0000
     -19         -18      0.0000      0.0432      0.1048      9.1816
     -30         -30      2.4000      0.0000      0.0000      0.0000

       6           6     15.0000      0.0013     -0.0760     51.0087
      -9           0      0.0914      0.7139      0.7572      0.0000
 13.5356      1.1931      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      31      0.3100      2.1824     -0.0511     -0.0888      0.9692
       1           1     55.0498      0.0000      0.0000      0.0000
     -20         -19      0.0000      0.0378      0.0987      9.6917
     -31         -31      2.0800      0.0000      0.0000      0.0000

       5           5     15.5000      0.0088     -0.0681     51.0087
     -10           0      0.0888      0.7515      0.7970      0.0000
 13.4438      1.1631      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      32      0.3200      2.2016     -0.0512     -0.0862      1.0712
       1           1     54.5717      0.0000      0.0000      0.0000
     -21         -20      0.0000      0.0323      0.0925     10.2017
     -32         -32      1.7600      0.0000      0.0000      0.0000

       4           4     16.0000      0.0167     -0.0597     51.0087
     -11           0      0.0862      0.7891      0.8369      0.0000
 13.3469      1.1731      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      33      0.3300      2.2176     -0.0514     -0.0834      1.1783
       1           1     54.0941      0.0000      0.0000      0.0000
     -22         -21      0.0000      0.0266      0.0863     10.7118
     -33         -33      1.4400      0.0000      0.0000      0.0000

       3           3     16.5000      0.0250     -0.0509     51.0087
     -12           0      0.0834      0.8267      0.8767      0.0000
 13.2449      1.1631      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000



      34      0.3400      2.2304     -0.0516     -0.0807      1.2905
       1           1     53.6168      0.0000      0.0000      0.0000
     -23         -22      0.0000      0.0209      0.0800     11.2219
     -34         -34      1.1200      0.0000      0.0000      0.0000

       2           2     17.0000      0.0336     -0.0418     51.0087
     -13           0      0.0807      0.8643      0.9166      0.0000
 13.1378      1.1531      0.0000      3.7576      3.9851      0.0000
  0.0000      0.0000      0.0000      0.0000      0.0000      0.0000
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       35      0.3500      2.2400     -0.0519     -0.0779      1.4078
        0           0     53.1379     -0.0237      0.2534      3.1880
      -24         -23     41.0935      0.0151      0.0737     11.7320
        2           4      0.8000      0.2823      0.5812     12.7522

        6           1     17.5000      0.0426     -0.0322     51.0087
      -14           0      0.0779      0.9018      0.9564      0.0000
  13.0255      1.1431      0.1648      3.7576      3.9851      0.9394
  12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



       36      0.3600      2.2464     -0.0522     -0.0750      1.5303
        0           0     52.6635     -0.0237      0.2534      3.1880
      -25         -24     41.0935      0.0091      0.0672     12.2421
        1           3      0.4800      0.2823      0.5812     12.7522

        5           0     18.0000      0.0520     -0.0222     51.0087
      -15           0      0.0750      0.9394      0.9963      0.0000
  12.9082      1.1331      0.1648      3.7576      3.9851      0.9394
  12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



       37      0.3700      2.2496     -0.0527     -0.0721      1.6578
        0           0     52.1875     -0.0237      0.2534      3.1880
      -26         -25     41.0935      0.0031      0.0607     12.7522
        0           2      0.1600      0.2823      0.5812     12.7522

        5          25     18.5000      0.0618     -0.0119     51.0087
       10           0      0.0721      0.9770      1.0361      0.0000
  12.7658      1.1231      0.1648    -16.2424     -1.0149      0.9394
  12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



       38      0.3800      9.7496      0.0916     -0.0691      1.7904
        0           0     51.7120     -0.0237      0.2534      3.1880
      -27         -26     41.0935      0.0031      0.0541     13.2623
       -1           1      0.1600      0.2823      0.5812     12.7522

        4          24     19.0000      0.0700     -0.0016     51.0087
        9           0      0.0691      0.8146      1.0260      0.0000
  12.6583      1.1131      0.1648    -16.2424     -1.0149      0.9394
  12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



       39      0.3900      9.7464      0.0924     -0.0661      1.9281
        0           0     51.2369     -0.0237      0.2534      3.1880
      -28         -27     41.0935      0.0094      0.0474     13.7724
       -2           0      0.4800      0.2823      0.5812     12.7522

        5          25     19.5000      0.0765      0.0085      0.0000
       10           0      0.0661      0.6521      1.0158      0.0000
  12.5257      1.1031      0.1648    -16.2424     -1.0149      0.9394
  12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



       40      0.4000      9.7400      0.0931     -0.0630      2.0659
        1           1     50.7623     -0.0237      0.2534      3.1880
      -29         -28     41.0935      0.0158      0.0407     13.7724
       -3          -1      0.6000      0.2823      0.5812     12.7522

        5          25     20.0000      0.0814      0.0186      0.0000
       10           0      0.0630      0.4897      1.0057      0.0000
  12.3879      1.0931      0.1648    -16.2424     -1.0149      0.9394
  12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963
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      41       0.4100      9.7304      0.0938     -0.0598      2.2036
       1            1     50.2862     -0.0237      0.2534      3.1880
     -30          -29     41.0935      0.0223      0.0440     13.7724
      -4           -2      1.1200      0.2823      0.5812     12.7522

       4           24     20.5000      0.0846      0.0285      0.0000
       9            0      0.0598      0.3273      0.9955      0.0000
 12.2502       1.0831      0.1648    -16.2424     -1.0149      0.9394
 12.7972       1.1331      0.0973    -20.0000     -5.0000      0.9963



      42       0.4200      9.7176      0.0944     -0.0566      2.3413
       1            1     49.8146     -0.0237      0.2534      3.1880
     -31          -30     41.0935      0.0289      0.0474     13.7724
      -5           -3      1.4400      0.2823      0.5812     12.7522

       3           23     21.0000      0.0863      0.0384      0.0000
       8            0      0.0566      0.1649      0.9854      0.0000
 12.1125       1.0731      0.1648    -16.2424     -1.0149      0.9394
 12.7972       1.1331      0.0973    -20.0000     -5.0000      0.9963



      43       0.4300      9.7016      0.0950     -0.0534      2.4790
       1            1     49.3415     -0.0237      0.2534      3.1880
     -32          -31     41.0935      0.0357      0.0509     13.7724
      -6           -4      1.7600      0.2823      0.5812     12.7522

       2           22     21.5000      0.0863      0.0481      0.0000
       7            0      0.0534      0.0024      0.9752      0.0000
 11.9748       1.0631      0.1648    -16.2424     -1.0149      0.9394
 12.7972       1.1331      0.0973    -20.0000     -5.0000      0.9963



      44       0.4400      9.6824      0.0955     -0.0500      2.6167
       1            1     48.8690     -0.0237      0.2534      3.1880
     -33          -32     41.0935      0.0426      0.0546     13.7724
      -7           -5      2.0800      0.2823      0.5812     12.7522

       6           21     22.0000      0.0847      0.0578      0.0000
       6            0      0.0500     -0.1600      0.9651      0.0000
 11.8370       1.0531      0.1648    -16.2424     -1.0149      0.9394
 12.7972       1.1331      0.0973    -20.0000     -5.0000      0.9963



      45       0.4500      9.6600      0.0960     -0.0466      2.7545
       1            1     48.3970     -0.0237      0.2534      3.1880
     -34          -33     41.0935      0.0496      0.0584     13.7724
      -8           -6      2.4000      0.2823      0.5812     12.7522

       5           20     22.5000      0.0815      0.0673      0.0000
       5            0      0.0466     -0.3224      0.9549      0.0000
 11.6993       1.0431      0.1648    -16.2424     -1.0149      0.9394
 12.7972       1.1331      0.0973    -20.0000     -5.0000      0.9963



      46       0.4600      9.6344      0.0964     -0.0432      2.8922
       1            1     47.9256     -0.0237      0.2534      3.1880
     -35          -34     41.0935      0.0568      0.0623     13.7724
      -9           -7      2.7200      0.2823      0.5812     12.7522

       4           19     23.0000      0.0766      0.0768      0.0000
       4            0      0.0432     -0.4848      0.9448      0.0000
 11.5616       1.0331      0.1648    -16.2424     -1.0149      0.9394
 12.7972       1.1331      0.0973    -20.0000     -5.0000      0.9963
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      47      0.4700      9.6056      0.0967     -0.0397      3.0299
       1           1     47.4548     -0.0237      0.2534      3.1880
     -36         -35     41.0935      0.0641      0.0664     13.7724
     -10          -8      3.0400      0.2823      0.5812     12.7522

       3          18     23.5000      0.0702      0.0861      0.0000
       3           0      0.0397     -0.6473      0.9346      0.0000
 11.4239      1.0231      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      48      0.4800      9.5736      0.0970     -0.0361      3.1676
       1           1     46.9845     -0.0237      0.2534      3.1880
     -37         -36     41.0935      0.0715      0.0706     13.7724
     -11          -9      3.3600      0.2823      0.5812     12.7522

       2          17     24.0000      0.0621      0.0954      0.0000
       2           0      0.0361     -0.8097      0.9245      0.0000
 11.2862      1.0131      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      49      0.4900      9.5384      0.0973     -0.0324      3.3054
       1           1     46.5149     -0.0237      0.2534      3.1880
     -38         -37     41.0935      0.0791      0.0750     13.7724
     -12         -10      3.6800      0.2823      0.5812     12.7522

       6          16     24.5000      0.0524      0.1045      0.0000
       1           0      0.0324     -0.9721      0.9143      0.0000
 11.1484      1.0031      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      50      0.5000      9.5000      0.0974     -0.0286      3.4431
       1           1     46.0460     -0.0237      0.2534      3.1880
     -39         -38     41.0935      0.0869      0.0795     13.7724
     -13         -11      4.0000      0.2823      0.5812     12.7522

       5          15     25.0000      0.0410      0.1136      0.0000
       0           0      0.0286     -1.1345      0.9042      0.0000
 11.0107      0.9931      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      51      0.5100      9.4584      0.0975     -0.0248      3.5808
       1           1     45.5777     -0.0237      0.2534      3.1880
     -40         -39     41.0935      0.0948      0.0842     13.7724
     -14         -12      4.3200      0.2823      0.5812     12.7522

       4          14     25.5000      0.0280      0.1225      0.0000
      -1           0      0.0248     -1.2969      0.8940      0.0000
 10.8730      0.9831      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      52      0.5200      9.4136      0.0975     -0.0209      3.7185
       1           1     45.1100     -0.0237      0.2534      3.1880
     -41         -40     41.0935      0.1029      0.0891     13.7724
     -15         -13      4.6400      0.2823      0.5812     12.7522

       3          13     26.0000      0.0134      0.1314      0.0000
      -2           0      0.0209     -1.4594      0.8839      0.0000
 10.7353      0.9731      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963
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      53      0.5300      9.3655      0.0975     -0.0169      3.8563
       1           1     44.6431     -0.0237      0.2534      3.1880
     -42         -41     41.0935      0.1111      0.0942     13.7724
     -16         -14      4.9600      0.2823      0.5812     12.7522

       2          12     26.5000     -0.0028      0.1401      0.0000
      -3           0      0.0169     -1.6218      0.8737      0.0000
 10.5975      0.9631      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      54      0.5400      9.3144      0.0974     -0.0129      3.9940
       1           1     44.1769     -0.0237      0.2534      3.1880
     -43         -42     41.0935      0.1195      0.0995     13.7724
     -17         -15      5.2800      0.2823      0.5812     12.7522

       6          11     27.0000     -0.0206      0.1487      0.0000
      -4           0      0.0129     -1.7842      0.8636      0.0000
 10.4598      0.9531      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      55      0.5500      9.2600      0.0972     -0.0087      4.1317
       1           1     43.7115     -0.0237      0.2534      3.1880
     -44         -43     41.0935      0.1281      0.1050     13.7724
     -18         -16      5.6000      0.2823      0.5812     12.7522

       5          10     27.5000     -0.0401      0.1573      0.0000
      -5           0      0.0087     -1.9466      0.8534      0.0000
 10.3221      0.9431      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      56      0.5600      9.2024      0.0969     -0.0045      4.2694
       1           1     43.2468     -0.0237      0.2534      3.1880
     -45         -44     41.0935      0.1369      0.1106     13.7724
     -19         -17      5.9200      0.2823      0.5812     12.7522

       4           9     28.0000     -0.0612      0.1657      0.0000
      -6           0      0.0045     -2.1091      0.8433      0.0000
 10.1844      0.9331      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      57      0.5700      9.1416      0.0965     -0.0001      4.4072
       1           1     42.7829     -0.0237      0.2534      3.1880
     -46         -45     41.0935      0.1459      0.1165     13.7724
     -20         -18      6.2400      0.2823      0.5812     12.7522

       3           8     28.5000     -0.0839      0.1740      0.0000
      -7           0      0.0001     -2.2715      0.8331      0.0000
 10.0466      0.9231      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963



      58      0.5800      9.0776      0.0961      0.0043      4.5449
       1           1     42.3198     -0.0237      0.2534      3.1880
     -47         -46     41.0935      0.1550      0.1227     13.7724
     -21         -19      6.5600      0.2823      0.5812     12.7522

       2           7     29.0000     -0.1082      0.1823      0.0000
      -8           0     -0.0043     -2.4339      0.8230      0.0000
  9.9089      0.9131      0.1648    -16.2424     -1.0149      0.9394
 12.7972      1.1331      0.0973    -20.0000     -5.0000      0.9963
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      59     0.5900     9.0104     0.0955     0.0088     4.6826
       1          1    41.8576    -0.0237     0.2534     3.1880
     -48        -47    41.0935     0.1644     0.1290    13.7724
     -22        -20     6.3800     0.2823     0.5812    12.7522

       6          6    29.5000    -0.1542     0.1904     0.0000
      -9          0    -0.0088    -2.5963     0.8128     0.0000
  9.7712     0.9031     0.1648   -16.2424    -1.0149     0.9394
 12.7972     1.1331     0.0973   -20.0000    -5.0000     0.9963



      60     0.6000     8.9400     0.0949     0.0135     4.8203
       1          1    41.3963    -0.0237     0.2534     3.1880
     -49        -48    41.0935     0.1739     0.1356    13.7724
     -23        -21     7.2000     0.2823     0.5812    12.7522

       5          5    30.0000    -0.1618     0.1954     0.0000
     -10          0    -0.0135    -2.7588     0.8027     0.0000
  9.6335     0.8931     0.1648   -16.2424    -1.0149     0.9394
 12.7972     1.1331     0.0973   -20.0000    -5.0000     0.9963



      61     0.6100     8.8664     0.0942     0.0182     4.9580
       1          1    40.9358    -0.0237     0.2534     3.1880
     -50        -49    41.0935     0.1837     0.1425    13.7724
     -24        -22     7.5200     0.2823     0.5812    12.7522

       4          4    30.5000    -0.1910     0.2063     0.0000
     -11          0    -0.0182    -2.9212     0.7925     0.0000
  9.4957     0.8831     0.1648   -16.2424    -1.0149     0.9394
 12.7972     1.1331     0.0973   -20.0000    -5.0000     0.9963



      62     0.6200     8.7396     0.0934     0.0231     5.0958
       1          1    40.4764    -0.0237     0.2534     3.1880
     -51        -50    41.0935     0.1937     0.1497    13.7724
     -25        -23     7.8400     0.2823     0.5812    12.7522

       3          3    31.0000    -0.2218     0.2142     0.0000
     -12          0    -0.0231    -3.0836     0.7824     0.0000
  9.3580     0.8731     0.1648   -16.2424    -1.0149     0.9394
 12.7972     1.1331     0.0973   -20.0000    -5.0000     0.9963



      63     0.6300     8.7096     0.0924     0.0280     5.2335
       1          1    40.0178    -0.0237     0.2534     3.1880
     -52        -51    41.0935     0.2039     0.1571    13.7724
     -26        -24     8.1600     0.2823     0.5812    12.7522

       2          2    31.5000    -0.2543     0.2219     0.0000
     -13          0    -0.0280    -3.2460     0.7722     0.0000
  9.2203     0.8631     0.1648   -16.2424    -1.0149     0.9394
 12.7972     1.1331     0.0973   -20.0000    -5.0000     0.9963



      64     0.6400     8.6264     0.0914     0.0331     5.3712
       0          0    39.5603     0.0785     0.1479     5.5089
     -53        -52    45.4997     0.2144     0.1648    13.7724
       2        -25     8.4800     0.1020    -0.0600    13.7724

       6          1    32.0000    -0.2884     0.2295     0.0000
     -14          0    -0.0331    -3.4085     0.7621    26.6737
  9.0826     0.8531    -0.8114   -16.2424    -1.0149    -3.5709
 10.1282     0.3431     0.2066    20.0000   -20.0000     0.7519
```

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      65      0.6500      8.5400      0.0903      0.0383      5.5089
       0           0     39.1039      0.0785      0.1479      5.5089
     -54         -53     45.4997      0.2250      0.1729     13.7724
       1         -26      8.6000      0.1020     -0.0600     13.7724

       5           0     32.5000     -0.3241      0.2370      0.0000
     -15           0     -0.0383     -3.5709      0.7519     26.6737
  8.9449      0.8431     -0.8114    -16.2424     -1.0149     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      66      0.6600      8.4504      0.0890      0.0436      5.6467
       0           0     38.6485      0.0785      0.1479      5.5089
     -55         -54     45.4997      0.2360      0.1813     13.7724
       0         -27      9.1200      0.1020     -0.0600     13.7724

       5          25     33.0000     -0.3614      0.2444      0.0000
      10           0     -0.0436     -3.7333      0.7418     26.6737
  8.8071      0.8331     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      67      0.6700      8.3576      0.0877      0.0490      5.7844
       1           1     38.1942      0.0785      0.1479      5.5089
     -56         -55     45.4997      0.2472      0.1900     13.7724
      -1         -28      9.4400      0.1020     -0.0600     13.7724

       5          25     33.5000     -0.3984      0.2499      0.0000
      10           0     -0.0490     -3.6957      0.5418     26.6737
  8.6694      0.8231     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      68      0.6800      8.2616      0.0862      0.0546      5.9221
       1           1     37.7411      0.0785      0.1479      5.5089
     -57         -56     45.4997      0.2586      0.1990     13.7724
      -2         -29      9.7600      0.1020     -0.0600     13.7724

       4          24     34.0000     -0.4350      0.2533      0.0000
       9           0     -0.0546     -3.6582      0.3418     26.6737
  8.5317      0.8131     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      69      0.6900      8.1624      0.0846      0.0603      6.0598
       1           1     37.2891      0.0785      0.1479      5.5089
     -58         -57     45.4997      0.2703      0.2085     13.7724
      -3         -30     10.0800      0.1020     -0.0600     13.7724

       3          23     34.5000     -0.4712      0.2547      0.0000
       8           0     -0.0603     -3.6206      0.1418     26.6737
  8.3940      0.8031     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      70      0.7000      8.0600      0.0829      0.0661      6.1976
       1           1     36.8385      0.0785      0.1479      5.5089
     -59         -58     45.4997      0.2823      0.2183     13.7724
      -4         -31     10.4000      0.1020     -0.0600     13.7724

       2          22     35.0000     -0.5070      0.2541      0.0000
       7           0     -0.0661     -3.5830     -0.0582     26.6737
  8.2562      0.7931     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519
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     71     0.7100     7.7544     0.0810     0.0721     6.3353
      1          1    36.5891     0.0785     0.1479     5.5089
    -60        -59    45.4997     0.2946     0.2266    13.7724
     -5        -32    10.7200     0.1020    -0.0600    13.7724

      6         21    35.5000    -0.5424     0.2515     0.0000
      6          0    -0.0721    -3.5454    -0.2582    26.6737
 8.1185     0.7831    -0.8114     3.7576   -20.0000    -3.5709
10.1282     0.8431     0.2066    20.0000   -20.0000     0.7519


     72     0.7200     7.8456     0.0790     0.0783     6.4730
      1          1    35.9410     0.0785     0.1479     5.5089
    -61        -60    45.4997     0.3072     0.2392    13.7724
     -6        -33    11.0400     0.1020    -0.0600    13.7724

      5         20    36.0000    -0.5775     0.2469     0.0000
      5          0    -0.0783    -3.5078    -0.4582    26.6737
 7.9808     0.7731    -0.8114     3.7576   -20.0000    -3.5709
10.1282     0.8431     0.2066    20.0000   -20.0000     0.7519


     73     0.7300     7.7336     0.0769     0.0845     6.6107
      1          1    35.4943     0.0785     0.1479     5.5089
    -62        -61    45.4997     0.3201     0.2504    13.7724
     -7        -34    11.3600     0.1020    -0.0600    13.7724

      4         19    36.5000    -0.6122     0.2404     0.0000
      4          0    -0.0845    -3.4703    -0.6582    26.6737
 7.8431     0.7631    -0.8114     3.7576   -20.0000    -3.5709
10.1282     0.8431     0.2066    20.0000   -20.0000     0.7519


     74     0.7400     7.6184     0.0746     0.0910     6.7485
      1          1    35.0491     0.0785     0.1479     5.5089
    -63        -62    45.4997     0.3332     0.2620    13.7724
     -8        -35    11.6800     0.1020    -0.0600    13.7724

      3         18    37.0000    -0.6465     0.2318     0.0000
      3          0    -0.0910    -3.4327    -0.8582    26.6737
 7.7053     0.7531    -0.8114     3.7576   -20.0000    -3.5709
10.1282     0.8431     0.2066    20.0000   -20.0000     0.7519


     75     0.7500     7.5000     0.0721     0.0976     6.8862
      1          1    34.6054     0.0785     0.1479     5.5089
    -64        -63    45.4997     0.3468     0.2741    13.7724
     -9        -36    12.0000     0.1020    -0.0600    13.7724

      2         17    37.5000    -0.6805     0.2212     0.0000
      2          0    -0.0976    -3.3951    -1.0582    26.6737
 7.5676     0.7431    -0.8114     3.7576   -20.0000    -3.5709
10.1282     0.8431     0.2066    20.0000   -20.0000     0.7519


     76     0.7600     7.3764     0.0695     0.1044     7.0239
      1          1    34.1632     0.0785     0.1479     5.5089
    -65        -64    45.4997     0.3606     0.2867    13.7724
    -10        -37    12.3200     0.1020    -0.0600    13.7724

      6         16    38.0000    -0.7141     0.2086     0.0000
      1          0    -0.1044    -3.3575    -1.2582    26.6737
 7.4299     0.7331    -0.8114     3.7576   -20.0000    -3.5709
10.1282     0.8431     0.2066    20.0000   -20.0000     0.7519
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      77      0.7700      7.2556      0.0667      0.1114      7.1616
       1           1     33.7220      0.0785      0.1479      5.5089
     -66         -65     45.4997      0.3748      0.2998     13.7724
     -11         -38     12.6400      0.1020     -0.0600     13.7724

       5          15     38.5000     -0.7473      0.1940      0.0000
       0           0     -0.1114     -3.3200     -1.4582     26.6737
  7.2922      0.7231     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      78      0.7800      7.1256      0.0638      0.1185      7.2993
       1           1     33.2837      0.0785      0.1479      5.5089
     -67         -66     45.4997      0.3894      0.3135     13.7724
     -12         -39     12.9600      0.1020     -0.0600     13.7724

       4          14     39.0000     -0.7801      0.1775      0.0000
      -1           0     -0.1185     -3.2824     -1.6582     26.6737
  7.1544      0.7131     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      79      0.7900      6.9944      0.0606      0.1259      7.4371
       1           1     32.8466      0.0785      0.1479      5.5089
     -68         -67     45.4997      0.4043      0.3279     13.7724
     -13         -40     13.2800      0.1020     -0.0600     13.7724

       3          13     39.5000     -0.8125      0.1589      0.0000
      -2           0     -0.1259     -3.2448     -1.8582     26.6737
  7.0167      0.7031     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      80      0.8000      6.8600      0.0573      0.1334      7.5748
       1           1     32.4113      0.0785      0.1479      5.5089
     -69         -68     45.4997      0.4196      0.3428     13.7724
     -14         -41     13.6000      0.1020     -0.0600     13.7724

       2          12     40.0000     -0.8446      0.1383      0.0000
      -3           0     -0.1334     -3.2072     -2.0582     26.6737
  6.8790      0.6931     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      81      0.8100      6.7224      0.0538      0.1411      7.7125
       1           1     31.9779      0.0785      0.1479      5.5089
     -70         -69     45.4997      0.4353      0.3584     13.7724
     -15         -42     13.9200      0.1020     -0.0600     13.7724

       6          11     40.5000     -0.8763      0.1157      0.0000
      -4           0     -0.1411     -3.1697     -2.2582     26.6737
  6.7413      0.6831     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519



      82      0.8200      6.5816      0.0501      0.1491      7.8502
       1           1     31.5464      0.0785      0.1479      5.5089
     -71         -70     45.4997      0.4514      0.3747     13.7724
     -16         -43     14.2400      0.1020     -0.0600     13.7724

       5          10     41.0000     -0.9076      0.0911      0.0000
      -5           0     -0.1491     -3.1321     -2.4582     26.6737
  6.6035      0.6731     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519
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      83      0.8300      6.4376      0.0462      0.1573      7.9880
       1           1     31.1170      0.0785      0.1479      5.5089
     -72         -71     45.4997      0.4679      0.3917     13.7724
     -17         -44     14.5600      0.1020     -0.0600     13.7724

       4           9     41.5000     -0.9386      0.0645      0.0000
      -6           0     -0.1573     -3.0945     -2.6582     26.6737
  6.4658      0.6631     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519


      84      0.8400      6.2904      0.0420      0.1657      8.1257
       1           1     30.6897      0.0785      0.1479      5.5089
     -73         -72     45.4997      0.4849      0.4095     13.7724
     -18         -45     14.8800      0.1020     -0.0600     13.7724

       3           8     42.0000     -0.9692      0.0360      0.0000
      -7           0     -0.1657     -3.0569     -2.8582     26.6737
  6.3281      0.6531     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519


      85      0.8500      6.1400      0.0376      0.1743      8.2634
       1           1     30.2647      0.0785      0.1479      5.5089
     -74         -73     45.4997      0.5022      0.4280     13.7724
     -19         -46     15.2000      0.1020     -0.0600     13.7724

       2           7     42.5000     -0.9993      0.0054      0.0000
      -8           0     -0.1743     -3.0194     -3.0582     26.6737
  6.1904      0.6431     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519


      86      0.8600      5.9864      0.0330      0.1832      8.4011
       1           1     29.8420      0.0785      0.1479      5.5089
     -75         -74     45.4997      0.5201      0.4474     13.7724
     -20         -47     15.5200      0.1020     -0.0600     13.7724

       6           6     43.0000     -1.0292     -0.0272      0.0000
      -9           0     -0.1832     -2.9818     -3.2582     26.6737
  6.0527      0.6331     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519


      87      0.8700      5.8296      0.0282      0.1923      8.5389
       1           1     29.4217      0.0785      0.1479      5.5089
     -76         -75     45.4997      0.5384      0.4676     13.7724
     -21         -48     15.8400      0.1020     -0.0600     13.7724

       5           5     43.5000     -1.0586     -0.0618      0.0000
     -10           0     -0.1923     -2.9442     -3.4582     26.6737
  5.9149      0.6231     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519


      88      0.8800      5.6696      0.0231      0.2017      8.6766
       1           1     29.0039      0.0785      0.1479      5.5089
     -77         -76     45.4997      0.5572      0.4888     13.7724
     -22         -49     16.1600      0.1020     -0.0600     13.7724

       4           4     44.0000     -1.0877     -0.0934      0.0000
     -11           0     -0.2017     -2.9066     -3.6582     26.6737
  5.7772      0.6131     -0.8114      3.7576    -20.0000     -3.5709
 10.1282      0.8431      0.2066     20.0000    -20.0000      0.7519
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      89        0.8900       5.5066      0.0177      0.2114      8.8145
       1             1      28.5868      0.0785      0.1479      5.5089
     -78           -77      45.4997      0.5764      0.5109     13.7724
     -23           -50      16.4800      0.1020     -0.0600     13.7724

       3             3      44.5000     -1.1164     -0.1370      0.0000
     -12             0      -0.2114     -2.8690     -3.6582     26.6737
  5.6595        0.5931      -0.6114      3.7576    -20.0000     -3.5709
 10.1282        0.8431       0.2066     20.0000    -20.0000      0.7519



      90        0.9000       5.3400      0.0121      0.2214      8.9520
       1             1      28.1764      0.0785      0.1479      5.5089
     -79           -78      45.4997      0.5962      0.5340     13.7724
     -24           -51      16.8000      0.1020     -0.0600     13.7724

       2             2      45.0000     -1.1447     -0.1775      0.0000
     -13             0      -0.2214     -2.8315     -4.0582     26.6737
  5.5018        0.5931      -0.6114      3.7576    -20.0000     -3.5709
 10.1282        0.8431       0.2066     20.0000    -20.0000      0.7519



      91        0.9100       5.1704      0.0061      0.2316      9.0898
       0             0      27.7670      0.0011      0.2434      9.2275
     -80           -79      32.9459      0.6166      0.5581     13.7724
       2             4      17.1200      0.4031     -0.1144     13.7724

       6             1      45.5000     -1.1726     -0.2201      0.0000
     -14             1      -0.2316     -2.7939     -4.2582    -22.2281
  5.3640        0.5631      -1.0874      3.7576    -20.0000     -2.7563
  5.5975        0.5731      -0.8647     20.0000     20.0000     -4.4582



      92        0.9200       4.9976     -0.0001      0.2422      9.2275
       0             0      27.3605      0.0011      0.2434      9.2275
     -81           -80      32.9459      0.6374      0.5834     13.7724
       1             3      17.4400      0.4031     -0.1144     13.7724

       5             0      46.0000     -1.2002     -0.2647      0.0000
     -15             1      -0.2422     -2.7563     -4.4582    -22.2281
  5.2263        0.5731      -1.0874      3.7576    -20.0000     -2.7563
  5.5975        0.5731      -0.8647     20.0000     20.0000     -4.4582



      93        0.9300       4.8216     -0.0066      0.2531      9.3652
       0             0      26.9572      0.0011      0.2434      9.2275
     -82           -81      32.9459      0.6588      0.6097     13.7724
       0             2      17.7600      0.4031     -0.1144     13.7724

       5            25      46.5000     -1.2274     -0.3113      0.0000
      10             1      -0.2531     -2.7187     -4.6582    -22.2281
  5.0886        0.5631      -1.0874     20.0000      0.0000     -2.7563
  5.5975        0.5731      -0.8647     20.0000     20.0000     -4.4582



      94        0.9400       4.6424     -0.0135      0.2643      9.5029
       0             0      26.5571      0.0011      0.2434      9.2275
     -83           -82      32.9459      0.6808      0.6373     13.7724
      -1             1      18.0800      0.4031     -0.1144     13.7724

       4            24      47.0000     -1.2526     -0.3579      0.0000
       9             1      -0.2643     -2.5187     -4.6582    -22.2281
  4.9509        0.5531      -1.0874     20.0000      0.0000     -2.7563
  5.5975        0.5731      -0.8647     20.0000     20.0000     -4.4582
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    95      0.9500      4.4500     -0.0206      0.2759      9.6406
     0           0     26.1605      0.0011      0.2434      9.2275
   -84         -83     32.9439      0.7034      0.6651     13.7724
    -2           0     18.4000      0.4031     -0.1144     13.7724

     5          25     47.5000     -1.2757     -0.4044    -22.2281
    10           1     -0.2759     -2.3187     -4.6582    -22.2281
4.8131      0.5431     -1.0874     20.0000      0.0000     -2.7563
5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



    96      0.9600      4.2744     -0.0282      0.2878      9.7761
     1           1     25.7675      0.0011      0.2434      9.2275
   -85         -84     32.9439      0.7265      0.6962     13.5501
    -3          -1     18.7200      0.4031     -0.1144     13.7724

     5          25     48.0000     -1.2969     -0.4510    -22.2281
    10           1     -0.2878     -2.1187     -4.6582    -22.2281
4.6754      0.5331     -1.0874     20.0000      0.0000     -2.7563
5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



    97      0.9700      4.0856     -0.0360      0.3000      9.9094
     1           1     25.3783      0.0011      0.2434      9.2275
   -86         -85     32.9439      0.7502      0.7360     13.3278
    -4          -2     19.0400      0.4031     -0.1144     13.7724

     4          24     48.5000     -1.3161     -0.4976    -22.2281
     9           1     -0.3000     -1.9187     -4.6582    -22.2281
4.5399      0.5231     -1.0874     20.0000      0.0000     -2.7563
5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



    98      0.9800      3.8936     -0.0442      0.3127     10.0405
     1           1     24.9930      0.0011      0.2434      9.2275
   -87         -86     32.9439      0.7746      0.7774     13.1055
    -5          -3     19.3600      0.4031     -0.1144     13.7724

     3          23     49.0000     -1.3333     -0.5442    -22.2281
     8           1     -0.3127     -1.7187     -4.6582    -22.2281
4.4066      0.5131     -1.0874     20.0000      0.0000     -2.7563
5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



    99      0.9900      3.6984     -0.0528      0.3257     10.1693
     1           1     24.6118      0.0011      0.2434      9.2275
   -88         -87     32.9439      0.7996      0.8204     12.8832
    -6          -4     19.6800      0.4031     -0.1144     13.7724

     2          22     49.5000     -1.3485     -0.5908    -22.2281
     7           1     -0.3257     -1.5187     -4.6582    -22.2281
4.2756      0.5031     -1.0874     20.0000      0.0000     -2.7563
5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



   100      1.0000      3.5000     -0.0618      0.3392     10.2959
     1           1     24.2349      0.0011      0.2434      9.2275
   -89         -88     32.9439      0.8253      0.8651     12.6609
    -7          -5     20.0000      0.4031     -0.1144     13.7724

     6          21     50.0000     -1.3617     -0.6374    -22.2281
     6           1     -0.3392     -1.3187     -4.6582    -22.2281
4.1468      0.4931     -1.0874     20.0000      0.0000     -2.7563
5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582
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     101      1.0100      3.2984     -0.0712      0.3531     10.4203
       1           1     23.8620      0.0011      0.2434      9.2275
     -90         -89     32.9439      0.8515      0.9115     12.4387
      -8          -6     20.3200      0.4031     -0.1144     13.7724

       5          20     50.5000     -1.3729     -0.6839    -22.2281
       5           1     -0.3531     -1.1187     -4.6582    -22.2281
  4.0201      0.4831     -1.0874     20.0000      0.0000     -2.7563
  5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



     102      1.0200      3.0936     -0.0810      0.3674     10.5425
       1           1     23.4950      0.0011      0.2434      9.2275
     -91         -90     32.9439      0.8785      0.9597     12.2164
      -9          -7     20.6400      0.4031     -0.1144     13.7724

       4          19     51.0000     -1.3821     -0.7305    -22.2281
       4           1     -0.3674     -0.9187     -4.6582    -22.2281
  3.8958      0.4731     -1.0874     20.0000      0.0000     -2.7563
  5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



     103      1.0300      2.8856     -0.0912      0.3821     10.6624
       1           1     23.1324      0.0011      0.2434      9.2275
     -92         -91     32.9439      0.9061      1.0097     11.9941
     -10          -8     20.9600      0.4031     -0.1144     13.7724

       3          18     51.5000     -1.3892     -0.7771    -22.2281
       3           1     -0.3821     -0.7187     -4.6582    -22.2281
  3.7736      0.4631     -1.0874     20.0000      0.0000     -2.7563
  5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



     104      1.0400      2.6744     -0.1018      0.3974     10.7801
       1           1     22.7750      0.0011      0.2434      9.2275
     -93         -92     32.9439      0.9344      1.0616     11.7718
     -11          -9     21.2800      0.4031     -0.1144     13.7724

       2          17     52.0000     -1.3944     -0.8237    -22.2281
       2           1     -0.3974     -0.5187     -4.6582    -22.2281
  3.6537      0.4531     -1.0874     20.0000      0.0000     -2.7563
  5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



     105      1.0500      2.4600     -0.1128      0.4131     10.8956
       1           1     22.4230      0.0011      0.2434      9.2275
     -94         -93     32.9439      0.9633      1.1153     11.5495
     -12         -10     21.6000       .4031     -0.1144     13.7724

       6          16     52.5000     -1.3976     -0.8703    -22.2281
       1           1     -0.4131     -0.3187     -4.6582    -22.2281
  3.5359      0.4431     -1.0874     20.0000      0.0000     -2.7563
  5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582



     106      1.0600      2.2424     -0.1243      0.4293     11.0089
       1           1     22.0768      0.0011      0.2434      9.2275
     -95         -94     32.9439      0.9929      1.1709     11.3273
     -13         -11     21.9200      0.4031     -0.1144     13.7724

       5          15     53.0000     -1.3988     -0.9169    -22.2281
       0           1     -0.4293     -0.1187     -4.6582    -22.2281
  3.4204      0.4331     -1.0874     20.0000      0.0000     -2.7563
  5.5975      0.5731     -0.8647     20.0000     20.0000     -4.4582
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   107     1.0700     2.0216    -0.1352     0.4460    11.1199
     1          1    21.7365     0.0011     0.2434     9.2275
   -96        -95    32.9439     1.0232     1.2284    11.1050
   -14        -12    22.2400     0.4031    -0.1144    13.7724

     4         14    53.5000    -1.3980    -0.9654   -22.2281
    -1          1    -0.4460     0.0813    -4.6582   -22.2281
3.3072     0.4231    -1.0874    20.0000     0.0000    -2.7563
5.5975     0.5731    -0.8647    20.0000    20.0000    -4.4582



   108     1.0800     1.7976    -0.1485     0.4633    11.2288
     1          1    21.4025     0.0011     0.2434     9.2275
   -97        -96    32.9439     1.0541     1.2878    10.8827
   -15        -13    22.5600     0.4031    -0.1144    13.7724

     3         13    54.0000    -1.3952    -1.0100   -22.2281
    -2          1    -0.4633     0.2813    -4.6582   -22.2281
3.1961     0.4131    -1.0874    20.0000     0.0000    -2.7563
5.5975     0.5731    -0.8647    20.0000    20.0000    -4.4582



   109     1.0900     1.5704    -0.1613     0.4811    11.3354
     1          1    21.0751     0.0011     0.2434     9.2275
   -98        -97    32.9439     1.0856     1.3491    10.6604
   -16        -14    22.8800     0.4031    -0.1144    13.7724

     2         12    54.5000    -1.3904    -1.0566   -22.2281
    -3          1    -0.4811     0.4813    -4.6582   -22.2281
3.0873     0.4031    -1.0874    20.0000     0.0000    -2.7563
5.5975     0.5731    -0.8647    20.0000    20.0000    -4.4582



   110     1.1000     1.3400    -0.1746     0.4994    11.4398
     1          1    20.7546     0.0011     0.2434     9.2275
   -99        -98    32.9439     1.1178     1.4122    10.4381
   -17        -15    23.2000     0.4031    -0.1144    13.7724

     6         11    55.0000    -1.3836    -1.1032   -22.2281
    -4          1    -0.4994     0.6813    -4.6582   -22.2281
2.9807     0.3931    -1.0874    20.0000     0.0000    -2.7563
5.5975     0.5731    -0.8647    20.0000    20.0000    -4.4582



   111     1.1100     1.1064    -0.1882     0.5183    11.5419
     1          1    20.4412     0.0011     0.2434     9.2275
  -100        -99    32.9439     1.1506     1.4771    10.2159
   -18        -16    23.5200     0.4031    -0.1144    13.7724

     5         10    55.5000    -1.3747    -1.1498   -22.2281
    -5          1    -0.5183     0.8813    -4.6582   -22.2281
2.8763     0.3831    -1.0874    20.0000     0.0000    -2.7563
5.5975     0.5731    -0.8647    20.0000    20.0000    -4.4582



   112     1.1200     0.8696    -0.2023     0.5378    11.6419
     1          1    20.1355     0.0011     0.2434     9.2275
  -101       -100    32.9439     1.1840     1.5437     9.9936
   -19        -17    23.8400     0.4031    -0.1144    13.7724

     4          9    56.0000    -1.3639    -1.1963   -22.2281
    -6          1    -0.5378     1.0813    -4.6582   -22.2281
2.7741     0.3731    -1.0874    20.0000     0.0000    -2.7563
5.5975     0.5731    -0.8647    20.0000    20.0000    -4.4582
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     113       1.1300      0.5296     -0.2168      0.5579     11.7396
       1            1     19.8376      0.0011      0.2434      9.2275
    -102         -101     32.9439      1.2179      1.6119      9.7713
     -20          -18     24.1600      0.4031     -0.1144     13.7724

       3            8     56.5000     -1.3511     -1.2429    -22.2281
      -7            1     -0.5579      1.2813     -4.6582    -22.2281
  2.6742       0.3631     -1.0874     20.0000      0.0000     -2.7563
  5.5975       0.5731     -0.8647     20.0000     20.0000     -4.4582



     114       1.1400      0.3864     -0.2318      0.5786     11.8351
       1            1     19.5479      0.0011      0.2434      9.2275
    -103         -102     32.9439      1.2523      1.6817      9.5490
     -21          -19     24.4800      0.4031     -0.1144     13.7724

       2            7     57.0000     -1.3363     -1.2895    -22.2281
      -8            1     -0.5786      1.4813     -4.6582    -22.2281
  2.5765       0.3531     -1.0874     20.0000      0.0000     -2.7563
  5.5975       0.5731     -0.8647     20.0000     20.0000     -4.4582



     115       1.1500      0.1400     -0.2471      0.5999     11.9283
       1            1     19.2669      0.0011      0.2434      9.2275
    -104         -103     32.9439      1.2872      1.7528      9.3267
     -22          -20     24.8000      0.4031     -0.1144     13.7724

       6            6     57.5000     -1.3195     -1.3361    -22.2281
      -9            1     -0.5999      1.6813     -4.6582    -22.2281
  2.4810       0.3431     -1.0874     20.0000      0.0000     -2.7563
  5.5975       0.5731     -0.8647     20.0000     20.0000     -4.4582



     116       1.1600      0.0697     -0.2540      0.6219     12.0194
       1            1     18.9949      0.0011      0.2434      9.2275
    -105         -104     32.9439      0.8350      1.8252      9.1045
     -23          -21     15.8600      0.4031     -0.1144     13.7724

       5            5     58.0000     -1.3007     -1.3827    -22.2281
     -10            1     -0.6219      1.8813     -4.6582    -22.2281
  2.3877       0.3331     -1.0874     20.0000      0.0000     -2.7563
  5.5975       0.5731     -0.8647     20.0000     20.0000     -4.4582



     117       1.1700      0.2267     -0.2495      0.6444     12.1082
       1            1     18.7322      0.0011      0.2434      9.2275
    -106         -105     32.9439      0.8296      1.8985      8.8822
     -24          -22     15.5400      0.4031     -0.1144     13.7724

       4            4     58.5000     -1.2799     -1.4293    -22.2281
     -11            1     -0.6444      2.0813     -4.6582    -22.2281
  2.2967       0.3231     -1.0874     20.0000      0.0000     -2.7563
  5.5975       0.5731     -0.8647     20.0000     20.0000     -4.4582



     118       1.1800      0.3805     -0.2450      0.6676     12.1948
       1            1     18.4794      0.0011      0.2434      9.2275
    -107         -106     32.9439      0.8236      1.9726      8.6599
     -25          -23     15.2200      0.4031     -0.1144     13.7724

       3            3     59.0000     -1.2571     -1.4758    -22.2281
     -12            1     -0.6676      2.2813     -4.6582    -22.2281
  2.2079       0.3131     -1.0874     20.0000      0.0000     -2.7563
  5.5975       0.5731     -0.8647     20.0000     20.0000     -4.4582
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   119      1.1900       0.5311     -0.2403      0.6914     12.2792
     1           1      18.2566      0.0011      0.2454      9.2275
  -108        -107      32.9459      0.8170      2.0472      8.4376
   -26         -24      14.9000      0.4031     -0.1144     13.7724

     2           2      59.5000     -1.2322     -1.5274    -22.2281
   -13           1      -0.6914      2.4813     -4.6582    -22.2281
2.1213      0.5931      -1.0674     20.0000      0.0000     -2.7563
5.5975      0.5731      -0.8647     20.0000     20.0000     -4.4582



   120      1.2000       0.6785     -0.2556      0.7159     12.3613
     0           0      18.0048     -0.2952      0.5238     11.7744
  -109        -108      19.2022      0.8098      2.1220      8.2153
     2           4      14.5800      1.0651      0.1416      7.9931

     6           1      60.0000     -1.2054     -1.5690    -22.2281
   -14           1      -0.7159      2.6813     -4.6582    -17.7825
2.0369      0.2931      -0.5766     20.0000      0.0000      2.8813
2.7958      0.2831      -1.6156     -5.0000     20.0000     -4.6582



   121      1.2100       0.8227     -0.2307      0.7409     12.4417
     0           0      17.7838     -0.2952      0.5238     11.7744
  -110        -109      19.2022      0.8019      2.1957      8.0375
     1           3      14.2600      1.0651      0.1416      7.9931

     5           0      60.5000     -1.1766     -1.6156    -17.7825
   -15           1      -0.7409      2.8813     -4.6582    -17.7825
1.9547      0.2831      -0.5766     20.0000      0.0000      2.8813
2.7958      0.2831      -1.6156     -5.0000     20.0000     -4.6582



   122      1.2200       0.9637     -0.2258      0.7666     12.5203
     0           0      17.5743     -0.2952      0.5238     11.7744
  -111        -110      19.2022      0.7932      2.2690      7.8597
     0           2      13.9400      1.0651      0.1416      7.9931

     5          25      61.0000     -1.1458     -1.6622    -17.7825
    10           1      -0.7666      3.0813     -4.6582    -17.7825
1.8744      0.2731      -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831      -1.6156     -5.0000     20.0000     -4.6582



   123      1.2300       1.1015     -0.2207      0.7929     12.5971
     0           0      17.3767     -0.2952      0.5238     11.7744
  -112        -111      19.2022      0.7838      2.3404      7.6819
    -1           1      13.6200      1.0651      0.1416      7.9931

     4          24      61.5000     -1.1135     -1.7067    -17.7825
     9           1      -0.7929      3.2813     -4.4582    -17.7825
1.7958      0.2631      -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831      -1.6156     -5.0000     20.0000     -4.6582



   124      1.2400       1.2361     -0.2155      0.8198     12.6722
     0           0      17.1913     -0.2952      0.5238     11.7744
  -113        -112      19.2022      0.7736      2.4105      7.5040
    -2           0      13.3000      1.0651      0.1416      7.9931

     5          25      62.0000     -1.0797     -1.7493    -17.7825
    10           1      -0.8198      3.3813     -4.2582    -17.7825
1.7190      0.2531      -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831      -1.6156     -5.0000     20.0000     -4.6582
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     125        1.2500        1.3675       -0.2103        0.8472       12.7454
       1             1       17.0190       -0.2952        0.5238       11.7744
    -114          -113       19.2022        0.7527        2.4769        7.3262
      -3            -1       12.9800        1.0651        0.1416        7.9931

       5            25       62.5000       -1.0444       -1.7899      -17.7825
      10             1       -0.8472        3.5313       -4.0582      -17.7825
  1.6439        0.2431       -0.5766       15.0000       20.0000        2.8813
  2.7958        0.2831       -1.6156       -5.0000       20.0000       -4.6582



     126        1.2600        1.4957       -0.2049        0.8752       12.8159
       1             1       16.8590       -0.2952        0.5238       11.7744
    -115          -114       19.2022        0.7509        2.5451        7.1484
      -4            -2       12.6600        1.0651        0.1416        7.9931

       4            24       63.0000       -1.0076       -1.8285      -17.7825
       9             1       -0.8752        3.6813       -3.8582      -17.7825
  1.5707        0.2331       -0.5766       15.0000       20.0000        2.8813
  2.7958        0.2831       -1.6156       -5.0000       20.0000       -4.6582



     127        1.2700        1.6207       -0.1995        0.9037       12.8866
       1             1       16.7128       -0.2952        0.5238       11.7744
    -116          -115       19.2022        0.7384        2.6085        6.9706
      -5            -3       12.3400        1.0651        0.1416        7.9931

       3            23       63.5000       -0.9692       -1.8651      -17.7825
       8             1       -0.9037        3.8313       -3.6582      -17.7825
  1.4992        0.2231       -0.5766       15.0000       20.0000        2.8813
  2.7958        0.2831       -1.6156       -5.0000       20.0000       -4.6582



     128        1.2800        1.7425       -0.1940        0.9326       12.9545
       1             1       16.5804       -0.2952        0.5238       11.7744
    -117          -116       19.2022        0.7250        2.6686        6.7927
      -6            -4       12.0200        1.0651        0.1416        7.9931

       2            22       64.0000       -0.9294       -1.8997      -17.7825
       7             1       -0.9326        3.9813       -3.4582      -17.7825
  1.4295        0.2131       -0.5766       15.0000       20.0000        2.8813
  2.7958        0.2831       -1.6156       -5.0000       20.0000       -4.6582



     129        1.2900        1.8611       -0.1884        0.9620       13.0207
       1             1       16.4621       -0.2952        0.5238       11.7744
    -118          -117       19.2022        0.7107        2.7254        6.6149
      -7            -5       11.7000        1.0651        0.1416        7.9931

       1            21       64.5000       -0.8881       -1.9322      -17.7825
       6             1       -0.9620        4.1313       -3.2582      -17.7825
  1.3613        0.2031       -0.5766       15.0000       20.0000        2.8813
  2.7958        0.2831       -1.6156       -5.0000       20.0000       -4.6582



     130        1.3000        1.9765       -0.1828        0.9918       13.0851
       1             1       16.3585       -0.2952        0.5238       11.7744
    -119          -118       19.2022        0.6957        2.7778        6.4371
      -8            -6       11.3800        1.0651        0.1416        7.9931

       0            20       65.0000       -0.8453       -1.9626      -17.7825
       5             1       -0.9918        4.2813       -3.0582      -17.7825
  1.2954        0.1931       -0.5766       15.0000       20.0000        2.8813
  2.7958        0.2831       -1.6156       -5.0000       20.0000       -4.6582
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   131      1.3100      2.0887     -0.1771      1.0220     13.1476
     1           1     16.2691     -0.2952      0.5238     11.7744
  -120        -119     19.2022      0.6798      2.8256      6.2593
    -9          -7     11.0600      1.0651      0.1416      7.9931

    -1          19     65.5000     -0.8010     -1.9914    -17.7825
     4           1     -1.0220      4.4313     -2.6582    -17.7825
1.2310      0.1831     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831     -1.6156     -5.0000     20.0000     -4.6582



   132      1.3200      2.1977     -0.1713      1.0525     13.2065
     1           1     16.1950     -0.2952      0.5238     11.7744
  -121        -120     19.2022      0.6632      2.8684      6.0814
   -10          -8     10.7400      1.0651      0.1416      7.9931

    -2          18     66.0000     -0.7552     -2.0180    -17.7825
     3           1     -1.0525      4.5813     -2.6582    -17.7825
1.1684      0.1731     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831     -1.6156     -5.0000     20.0000     -4.6582



   133      1.3300      2.3035     -0.1656      1.0832     13.2675
     1           1     16.1360     -0.2952      0.5238     11.7744
  -122        -121     19.2022      0.6458      2.9057      5.9036
   -11          -9     10.4200      1.0651      0.1416      7.9931

    -3          17     66.5000     -0.7079     -2.0426    -17.7825
     2           1     -1.0832      4.7313     -2.4582    -17.7825
1.1076      0.1631     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831     -1.6156     -5.0000     20.0000     -4.6582



   134      1.3400      2.4061     -0.1598      1.1141     13.3248
     1           1     16.0923     -0.2952      0.5238     11.7744
  -123        -122     19.2022      0.6276      2.9372      5.7258
   -12         -10     10.1000      1.0651      0.1416      7.9931

    -4          16     67.0000     -0.6591     -2.0652    -17.7825
     1           1     -1.1141      4.8813     -2.2582    -17.7825
1.0486      0.1531     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831     -1.6156     -5.0000     20.0000     -4.6582



   135      1.3500      2.5055     -0.1541      1.1451     13.3802
     1           1     16.0640     -0.2952      0.5238     11.7744
  -124        -123     19.2022      0.6088      2.9628      5.5480
   -13         -11      9.7800      1.0651      0.1416      7.9931

    -5          15     67.5000     -0.6087     -2.0857    -17.7825
     0           1     -1.1451      5.0313     -2.0582    -17.7825
0.9913      0.1431     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831     -1.6156     -5.0000     20.0000     -4.6582



   136      1.3600      2.6017     -0.1483      1.1763     13.4339
     1           1     16.0513     -0.2952      0.5238     11.7744
  -125        -124     19.2022      0.5894      2.9820      5.3701
   -14         -12      9.4600      1.0651      0.1416      7.9931

    -6          14     68.0000     -0.5569     -2.1043    -17.7825
    -1           1     -1.1763      5.1813     -1.8582    -17.7825
0.9358      0.1331     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831     -1.6156     -5.0000     20.0000     -4.6582
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     137       1.3700       2.6947      -0.1426       1.2074      13.4859
       1            1      16.0547      -0.2952       0.5238      11.7744
    -126         -125      19.2022       0.5693       2.9949       5.1923
     -15          -13       9.1400       1.0651       0.1416       7.9931

      -7           13      68.5000      -0.5036      -2.1209     -17.7825
      -2            1      -1.2074       5.3313      -1.6582     -17.7825
  0.8821       0.1231      -0.5766      15.0000      20.0000       2.8813
  2.7958       0.2031      -1.6156      -5.0000      20.0000      -4.6582


     138       1.3800       2.7845      -0.1370       1.2385      13.5360
       1            1      16.0726      -0.2952       0.5238      11.7744
    -127         -126      19.2022       0.5488       3.0012       5.0145
     -16          -14       8.8200       1.0651       0.1416       7.9931

      -8           12      69.0000      -0.4488      -2.1355     -17.7825
      -3            1      -1.2385       5.4813      -1.4582     -17.7825
  0.8302       0.1131      -0.5766      15.0000      20.0000       2.8813
  2.7958       0.2031      -1.6156      -5.0000      20.0000      -4.6582


     139       1.3900       2.8711      -0.1314       1.2695      13.5844
       1            1      16.1066      -0.2952       0.5238      11.7744
    -128         -127      19.2022       0.5277       3.0011       4.8367
     -17          -15       8.5000       1.0651       0.1416       7.9931

      -9           11      69.5000      -0.3925      -2.1481     -17.7825
      -4            1      -1.2695       5.6313      -1.2582     -17.7825
  0.7801       0.1031      -0.5766      15.0000      20.0000       2.8813
  2.7958       0.2031      -1.6156      -5.0000      20.0000      -4.6582


     140       1.4000       2.9545      -0.1259       1.3004      13.6310
       1            1      16.1559      -0.2952       0.5238      11.7744
    -129         -128      19.2022       0.5063       2.9947       4.6588
     -18          -16       8.1800       1.0651       0.1416       7.9931

     -10           10      70.0000      -0.3347      -2.1586     -17.7825
      -5            1      -1.3004       5.7813      -1.0582     -17.7825
  0.7317       0.0931      -0.5766      15.0000      20.0000       2.8813
  2.7958       0.2031      -1.6156      -5.0000      20.0000      -4.6582


     141       1.4100       3.0347      -0.1206       1.3310      13.6758
       1            1      16.2205      -0.2952       0.5238      11.7744
    -130         -129      19.2022       0.4846       2.9820       4.4810
     -19          -17       7.8600       1.0651       0.1416       7.9931

     -11            9      70.5000      -0.2754      -2.1672     -17.7825
      -6            1      -1.3310       5.9313      -0.8582     -17.7825
  0.6851       0.0831      -0.5766      15.0000      20.0000       2.8813
  2.7958       0.2031      -1.6156      -5.0000      20.0000      -4.6582


     142       1.4200       3.1117      -0.1153       1.3614      13.7188
       1            1      16.3002      -0.2952       0.5238      11.7744
    -131         -130      19.2022       0.4626       2.9633       4.3032
     -20          -18       7.5400       1.0651       0.1416       7.9931

     -12            8      71.0000      -0.2145      -2.1738     -17.7825
      -7            1      -1.3614       6.0813      -0.6582     -17.7825
  0.6403       0.0731      -0.5766      15.0000      20.0000       2.8813
  2.7958       0.2031      -1.6156      -5.0000      20.0000      -4.6582
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   143      1.4300      [illegible]     -0.1102      1.3914     13.7601
     1           1     16.3948     -0.2952      0.5238     11.7744
  -132        -131     19.2022      0.4404      2.9389      4.1254
   -21         -19      7.2200      1.0651      0.1416      7.9931

   -13           7     71.5000     -0.1522     -2.1784    -17.7825
    -8           1     -1.3914      6.2313     -0.4582    -17.7825
0.5973  0.[illegible]     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2631     -1.6156     -5.0000     20.0000     -4.6582


   144      1.4400      3.2561     -0.1053      1.4211     13.7995
     1           1     16.5040     -0.2952      0.5238     11.7744
  -133        -132     19.2022      0.4181      2.9091      3.9475
   -22         -20      6.9000      1.0651      0.1416      7.9931

   -14           6     72.0000     -0.0884     -2.1810    -17.7825
    -9           1     -1.4211      6.3813     -0.2582    -17.7825
0.5560      0.0531     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2631     -1.6156     -5.0000     20.0000     -4.6582


   145      1.4500      3.3235     -0.1005      1.4503     13.8372
     1           1     16.6275     -0.2952      0.5238     11.7744
  -134        -133     19.2022      0.3957      2.8742      3.7697
   -23         -21      6.5800      1.0651      0.1416      7.9931

   -15           5     72.5000     -0.0231     -2.1816    -17.7825
   -10           1     -1.4503      6.5313     -0.0582    -17.7825
0.5165      0.0431     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831     -1.6156     -5.0000     20.0000     -4.6582


   146      1.4600      3.3877     -0.0959      1.4791     13.8731
     1           1     16.7650     -0.2952      0.5238     11.7744
  -135        -134     19.2022      0.3734      2.8347      3.5919
   -24         -22      6.2600      1.0651      0.1416      7.9931

   -16           4     73.0000      0.0437     -2.1801    -17.7825
   -11           1     -1.4791      6.6813      0.1418    -17.7825
0.4788      0.0331     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2631     -1.6156     -5.0000     20.0000     -4.6582


   147      1.4700      3.4487     -0.0914      1.5074     13.9073
     1           1     16.9162     -0.2952      0.5238     11.7744
  -136        -135     19.2022      0.3511      2.7910      3.4141
   -25         -23      5.9400      1.0651      0.1416      7.9931

   -17           3     73.5000      0.1120     -2.1767    -17.7825
   -12           1     -1.5074      6.8313      0.3418    -17.7825
0.4429      0.0231     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2831     -1.6156     -5.0000     20.0000     -4.6582


   148      1.4800      3.5065     -0.0872      1.5352     13.9396
     1           1     17.0807     -0.2952      0.5238     11.7744
  -137        -136     19.2022      0.3290      2.7436      3.2362
   -26         -24      5.6200      1.0651      0.1416      7.9931

   -18           2     74.0000      0.1818     -2.1713    -17.7825
   -13           1     -1.5352      6.9813      0.5418    -17.7825
0.4038      0.0131     -0.5766     15.0000     20.0000      2.8813
2.7958      0.2631     -1.6156     -5.0000     20.0000     -4.6582
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