INFLUENCE OF MACRO- VERSUS MICROCOOLING ON THE PHYSIOLOGICAL AND PSYCHOLOGICAL PERFORMANCE OF THE HUMAN OPERATOR

BY

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ABSTRACT

This study evaluated the effect of a macro- versus a microcooling system on the cognitive, psychomotor and physiological performance of human operators.

Male subjects (n = 24) were acclimatized for four days and then subjected to three different environmental conditions: hot ambient (40°C; 40% RH), microcooling and macrocooling. Each environmental condition was repeated twice; once under a rest condition and once while simulating a physical workload of 40 W. Four performance tests (reasoning, eye-hand coordination, memory, reaction time) were conducted once every hour for four hours. Five physiological measurements, viz rectal temperature, skin temperature, heart rate, total sweat loss and sweat rate, were taken. A significant difference existed between the physiological responses under the hot ambient condition and both cooling conditions. For all five physiological parameters he human operator benefitted substantially whatever the cooling condition. The psychological performance results indicated a greater benefit under the cooling conditions, though various external factors may have influenced responses. User perception showed that macrocooling was perceived to be the optimal method of cooling.

The results showed that there was no difference in the extent to which both rectal temperature and heart rate (for rest and work conditions) decreased over the 4-hour study period with micro- and macrocooling. In the baseline hot environment both increase. Sweat rate was lowest when resting or working in a microcooled environment and at its highest in the hot baseline environment. Mean skin temperature was lowest (for rest and work conditions) with microcooling and highest in the hot baseline environment.

Reaction time and memory/attention were the same under all three environmental conditions. Eye-hand coordination was better with cooling than without, but did not differ between the two cooling conditions. Reasoning ability was poorest under the hot baseline condition and best in the macrocooled environment.

User perception showed that the subjects found macrocooling highly acceptable. Microcooling was found to be uncomfortable, particularly because cold air (18 - 21°C) entered the jacket at one point which caused numbness of the skin at that point. Jackets did not always fit subjects well and the umbilical cord restricted free movement.

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CHAPTER ONE : INTRODUCTION

1.1 Background to the Study

The human operator is sometimes exposed in working environments to very high temperatures which may have a detrimental effect on both physiological and psychological performance. Numerous studies conducted throughout the world have demonstrated the relationship between a human operator's physiological responses, performance ability and the thermal environment in which work is done. Wyon (1976, 1977) reviewed studies concerning the effects of heat and cold stress on the efficiency of the human operator. Although these studies demonstrated that temperatures had an effect on a variety of skills, some conflicting results were reported. When the human operator in a hot environment is burdened with physical work, or required to solve complicated cognitive problems, work performance may be affected. Grether (1973) and Meese (1988) also provided summaries of thermal effects on performance. An experimental study by Pepler and Warner (1968) showed that the optimal comfortable temperature for humans is not necessarily the best for maximum efficiency.

The work environment of human operators influences their thermal states, the major factors being drybulb temperature, humidity, air movement, radiant temperature, clo-factor and metabolic rate. A disequilibrium in the combination of the above-mentioned factors may lead to discomfort, heat stress and even death (Meese, 1988).

In order to ensure that the health and performance of human operators working in very hot environments are not affected negatively, it is important to maintain the thermal environment at an optimal level by providing artificial cooling methods. This artificial cooling can take the form either of macrocooling (whole-environment cooling) or microcooling (individual cooling) systems. Both these types of cooling are used worldwide in various military and industrial applications and each has its own advantages and disadvantages in specific applications.

With macrocooling systems the total environment of the operator is cooled down and kept at a specific operating temperature for the duration of the task or shift. Although this type of cooling can be costly and a heavy drain on power, it holds many advantages for the human operator (Kok et al., 1982).

Microcooling systems on the other hand involve the creation and regulation of the micro-environment of an individual to the extent that -

a) the physiological tension created by activities and the environment is limited;
b) it will not interfere with the effective execution of a task; and
c) it will enhance the operator's effectiveness and productivity (Pienaar, 1988).

Owing to the fact that modern technological systems are becoming more advanced, and that operators increasingly have to make use of their cognitive abilities in order to be able to operate these systems, the question arises which of the above-mentioned cooling methods ("macro" vs "micro") is the most effective when the human's performance is taken into consideration. As far as can be ascertained, virtually no research has as yet been conducted to compare the effects of micro- versus macrocooling on human cognitive and psychomotor performance. The fact that a microcooling system cools only parts of the human body and therefore influences only the operator's micro-environment, begs the question as to effectiveness of the operator's cognitive abilities with the use of a microcooling system.

The issue of micro- versus macrocooling raises important questions such as cost-effectiveness, practical implications and the effectiveness of the human operator. Although numerous studies have concluded that both these cooling methods have definite advantages in specific applications, the question still remains whether microcooling is adequate in situations where the human operator has to perform critical tasks. This question is especially valid in the military environment, with specific reference to combat vehicle applications and where chemical warfare is a reality.

In order to determine the effect of macro- versus microcooling on the cognitive and psychomotor performance of the human operator when subjected to a high temperature work environment, the empirical research must satisfy the following objectives:

a) It must determine the effect of a high temperature environment on the cognitive and psychomotor performance of the human operator in order to establish baseline data.

b) It must determine the effect of macrocooling on the cognitive and psychomotor performance of the human operator in a high temperature work environment.

c) It must determine the effect of microcooling on the cognitive and psychomotor performance of the human operator in a high temperature environment.

d) It must determine the relative effects of micro- and macrocooling on specific physiological parameters, as well as on the human operator's perception of the two types of cooling systems.

e) It must determine the effect of micro- versus macrocooling on the cognitive and psychomotor performance of the human operator in a high temperature work environment while performing a variety of physical tasks.

1.2 Statement of the Problem

The problem addressed in the present study was the evaluation of the effect of a macro- versus a microcooling system on the cognitive, psychomotor and physiological performance of the human operator. The major components of this study, namely the thermal regulation of the human body, the effect of heat on human performance and the two types of cooling (macro- and microcooling), were examined to illustrate the relationship.

1.3 Research Hypotheses

The following hypotheses were established to test the potential difference in the effect of micro- versus macrocooling on human performance:

1.3.1 Hypothesis 1

The physiological and psychological (cognitive and psychomotor) performance of the human operator in a hot ambient environment (40°C; 40% RH) is equal to that under macro- and microcooling conditions.

H_0 : $\mu 1$ (baseline environment) = $\mu 2$ (macrocooling) = $\mu 3$ (microcooling)

H_a : At least one $\mu 1 \neq \mu 2 \neq \mu 3$

1.3.2 Hypothesis 2

The physiological and psychological (cognitive and psychomotor) performance of the human operator is equal under non-working (resting) and moderate work (40 W) conditions, under similar ambient thermal conditions.

$H_o : \mu \text{ (rest)} = \mu \text{ (work)}$

$H_a : \mu \text{ (rest)} \neq \mu \text{ (work)}$

1.3.3 Hypothesis 3

The physiological and psychological (cognitive and psychomotor) performance of the human operator is equal when repeated four times over a period of four hours, once per hour.

$H_o : \mu T_1 = \mu T_2 = \mu T_3 = \mu T_4$

$H_a : \mu T_1 \neq \mu T_2 \neq \mu T_3 \neq \mu T_4$

The physiological tests involved 21 measurements over a four-hour period and the psychological tests involved four measurements over a period of four hours, once per hour.

1.4 Delimitations

The subjects chosen for the experiment were selected from a homogenous group of Caucasian male students between the ages of

18 and 30 years. All subjects were examined medically and acclimatized before commencing with the experiment to ensure their general physical condition and physical ability for participation.

The subjects were trained in the performance tasks to ensure optimal performance for each in each task, thus minimizing the effect of the learning curve. Subjects were divided into morning and afternoon groups and were tested in their respective time slots under all conditions to minimize the effect of the circadian rhythm (Folkard, 1988).

The procedure commenced daily at 07:00 for the morning group and at 12:00 for the afternoon group, and the sequence in which performance tests were conducted remained the same throughout the experiment.

All subjects were dressed in the same type of clothing for the purposes of the study and it was not altered at any time for the duration of the study. Subjects were allowed to drink as much cold water as they wanted to during this experiment to prevent dehydration from occurring. The liquid intake and urine passed during the experiment were monitored strictly.

1.5 Limitations

Subjects were not randomly selected but were volunteers who were approached with an explanation of the experimental procedures. Although every effort was made to ensure that each subject's attitude towards the experiment was positive and that his motivation level was constant throughout the study, this factor could not be evaluated objectively. However, the size of the sample (n = 24) contributed to reducing negative influences in this regard.

Although the subjects were requested not to imbibe alcohol in excess for the duration of the experiment, since this might influence their physical ability during their next cycle, this possibility could not be controlled strictly.

Regarding the results of the physiological measurements, it should be noted that owing to various practical limitations, such as breakage of thermocouples and other instrumentation, irritation caused by sensors to parts of the subjects' anatomy and interference with readings on heart rate monitors, some of the data could not be used for the statistical analysis during different cycles.

Owing to time, logistical and financial limitations individual subjects could not be exposed to the three environmental conditions in random order. However, to compensate for this subjects were pre-trained and habituated before commencing with the actual experiment.

CHAPTER TWO : REVIEW OF RELATED LITERATURE

2.1 Thermal Regulation of the Human Body

2.1.1 Human Body Temperature

In order for humans to function normally it is of great importance to maintain body temperature within specific limits. The human body controls its own temperature actively and is influenced in this by internal factors such as disease states, or externally by the environment. Body temperature at any given time will be determined by the balance between heat being produced and heat-loss by the body. Under ordinary resting conditions the internal or core temperature of the human body will be maintained within the narrow limits of between 36.1°C and 37.2°C. This mechanism is called homeothermy and refers to the controlling of temperature in the central regions of the body where vital organs such as the heart and liver are situated.

McIntyre (1980) surveyed the distinction between two measures of body temperature, namely core and skin temperature. Core temperature represents the internal or deep body temperature of the human and is held constant over a wide range of ambient temperatures. There are various methods of measuring core temperatures, oral and rectal measurements of which are the most commonly used.

It is generally accepted (McIntyre, 1980; Vander, et al., 1980; Guyton, 1981) that oral temperatures are on average approximately 0.5°C lower than rectal temperatures because of effects such as mouth breathing, drinking of hot or cold liquids, constant cooling by the facial surfaces and by evaporation in the mouth and nose. Fox (1974) provided a comprehensive review of the advantages and disadvantages of the different measurement sites for core temperature. Figure 1 shows the normal temperature of the human body under different conditions. Both oral and rectal temperatures are displayed.

McIntyre (1980) described the three favoured sites for the measurement of "core" body temperature, namely tympanic, oesophageal and rectal. Of these three methods rectal temperature is the most commonly used although each method has its own practical problems and disadvantages. According to Brobeck (1979) the lower lethal temperature of the human body is approximately 26°C and the upper limit 43°C rectal temperature. Vander et al. (1980) noted that most people will suffer convulsions at a body temperature of 41°C and that 43°C is the absolute limit for life.

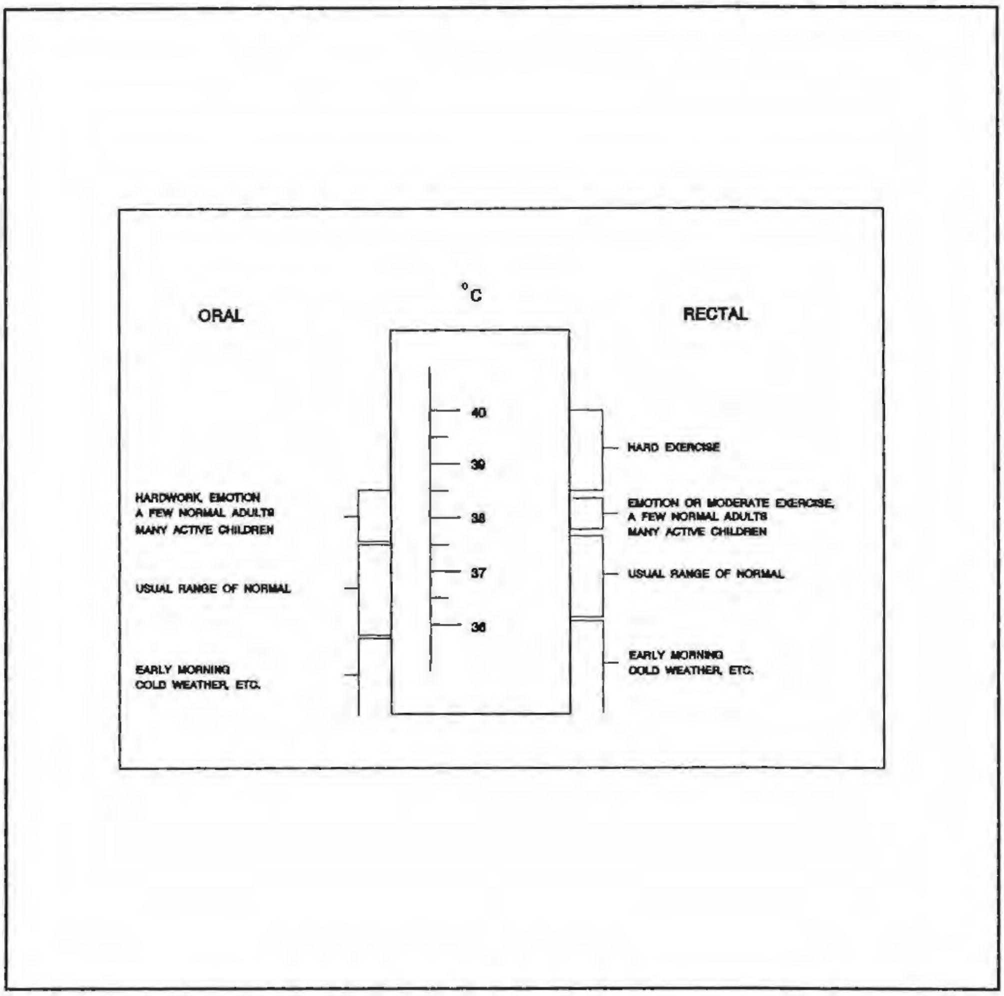


Figure 1: Ranges of body temperature in normal persons (Adapted from Du Bois, 1937).

The temperature on the surface of the human skin will change according to change in environmental temperature. The skin temperature is not the same all over the human body and the technique of thermography can be used to determine the temperature of a naked body. This technique measures the thermal radiation from the body and a coloured image is produced via a camera in which different temperature levels are shown as different colours (McIntyre, 1980). To obtain a more even picture of skin temperature, measurements are taken at eight different positions on the human skin. The results are weighted by means of the Hardy-Du Bois System (1938) or the simpler Ramanathan System (1964) to calculate the mean skin temperature. Table I shows these two systems with reference measurement positions and their weighting. The mean skin temperature (Tsk) represents the sum of weighted individual skin temperatures. Generally, the weighting is based on the percentage of body surface area that is represented by the body region from where the temperature is measured. Mean skin temperature can be calculated by means of, for example, the equation developed by Ramanathan:

Tsk C = 0.3 (chest + upper arm temp) + 0.2(thigh + calf temp).

Table I : Mean skin temperature as weighted by the Hardy-Du Bois and Ramanathan systems respectively (Adapted from McIntyre, 1980)

POSITION	WEIGHTING	
	HARDY-DU BOIS (1938)	RAMANATHAN (1964)
Head (forehead)	0.07	
Chest (pectoral)	0.175	0.3
Back (sub-scapular)	0.175	
Upper Arms (lateral dorsal)	0.07	0.3
Lower Arms (lateral dorsal)	0.07	
Hands (lateral dorsal)	0.05	
Thighs (medial)	0.19	0.2
Legs (medial)	0.20	0.2

2.1.2 Thermoregulation

The balance between heat production and heat loss determines the internal temperature of the human body. If a balance exists, there will be no rise or fall of internal temperature. To keep heat production and heat loss in balance, a regulatory system is at work in the human body. Konz (1979) illustrated human thermoregulation as a closed-loop system (Figure 2).

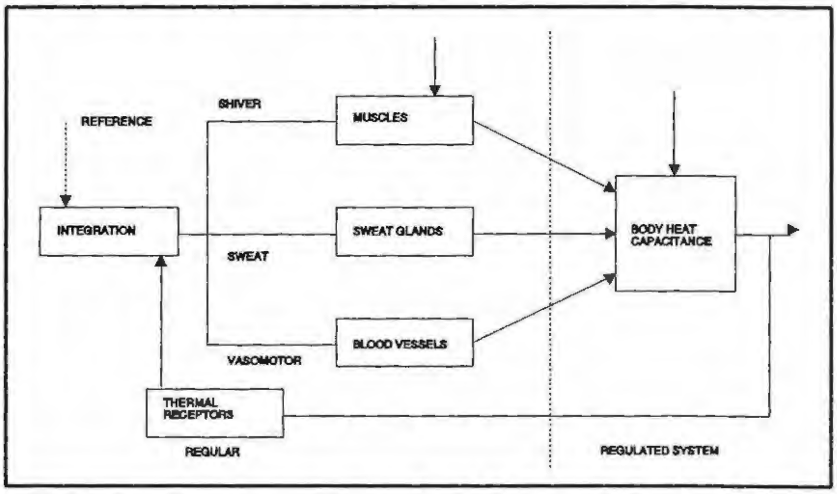


Figure 2 : Human thermoregulation, a closed-loop system (Adapted from Konz, 1979)

This closed-loop system consists of two basic subsystems, the controlling system (regulator) and the controlled system (regulated system). Skin and internal temperatures are fed back through the thermoreceptors. The difference between the desired temperature and the existing body temperature will activate one of three controllers, namely sweat, shivering or the vasomotor activity. Each controller acts via its control element as indicated in Figure 2. The muscles, sweat glands and blood vessels, which are the control elements, actuate heat transfer by means of heat loss or heat production. The resulting body temperature is fed back to the thermal receptors and the cycle is completed and then repeated (Konz, 1979). Balance between heat production and heat loss is constantly influenced by changes in metabolic rate, as a result of exercise or by changes in the external environment.

In order to understand the thermoregulatory process better, it is necessary to discuss the aspects of heat production and heat loss briefly.

Heat Production

The production of heat in the human body is a continuous process mediated by chemical reactions and normal organ functioning. There are several different mechanisms to increase body heat. Vander et al. (1980) and Guyton (1981) have described these mechanisms in detail. The most important mechanism is the change in muscle activity which ultimately results in shivering. These activities will occur when the environmental temperature is lowered, and will stimulate heat production. The increase in muscle tension will increase the metabolic rate and at a skin temperature level of approximately 23°C the action of shivering will start. Vander et al. (1980) defined shivering as oscillating rhythmic muscle tremors occurring at the rate of 10 to 20 per second. Body heat conservation is increased several hundred percent by this muscular activity. Guyton (1981) briefly discussed other mechanisms which are lesser contributors to heat conservation, namely vasoconstriction, pilo-erection and increased thyroid hormone production.

Heat Loss

There are several ways for the human body to lose heat. Brobeck (1979) identified four main mechanisms of heat loss. These four mechanisms are (a) radiation (59%), conduction and convection (15%), (b) evaporation of water (sweat) from skin and lungs (30%), (c) warming inspired air (3%) and (d) urine and faeces (2%).

Heat is constantly radiated from the body surface. The rate of radiation will depend on the difference between the surface temperature of the body and the average temperature of the objects in the environment.

Heat loss will therefore occur if the surface temperature of the human body is higher than its immediate environment, while heat loss by radiation will decrease if the environment is warmer than the body. Brobeck (1979) pointed out that there are several internal physiological mechanisms which may cause a change in skin temperature. These mechanisms work through the blood-vascular system and include (a) redistribution of blood flow; (b) variation in blood volume and (c) increased blood circulation rate.

Complementary to radiation as mechanisms of heat loss are conduction and convection. Vander et al. (1980) defined conduction as the exchange of heat by the transfer of thermal energy from molecule to molecule. The human body will therefore only lose or gain heat by conduction through direct contact with warmer or colder objects in the environment. This obviously also includes the air in the environment (Kerslake, 1972). The process of convection on the other hand involves the flow of air over the human body, whose heat is constantly transferred to the moving colder air. Convection may be increased by external agents such as fans, air-cooling systems and the wind.

The second mechanism and second highest contributor to the heat loss processes is the evaporation of water. When the environmental temperature is higher than the surface temperature of the human body, the amount of heat lost by means of radiation, convection and conduction is minimal. The body will then gain heat by means of radiation from the environment. The process of vaporization involves the conversion of liquid to a vapour state by thermal energy (Brobeck, 1979; Konz, 1979; Vander et al. 1980). The water vapour concentration in the air (humidity) is an important factor in determining the rate of evaporation. On days when the environmental humidity is high, evaporation will be limited, while on dry days the rate of evaporation will be much greater. Vander et al. (1980) noted that the human body can survive temperatures of 130°C for 20 min or longer when the air is completely dry, whereas a temperature of 46°C in very humid conditions is intolerable. Another important heat loss mechanism which is related to evaporation is the process of sweating. The sweating process is activated when normal heat loss mechanisms are unable to reduce body heat to normal body temperature (Guyton, 1969). In such instances it is important to have a cooling effect (Kerslake, 1972). The remaining mechanisms of heat loss, namely via warming and humidifying of inspired air and by means of the excretion of urine and faeces, are together only responsible for 5% of the total daily heat loss of the human body and are not directly under physiological control.

2.1.3 The Internal Temperature Control Centre

The temperature control centre is located in the hypothalamus, a part of the brain which is important in several diverse functions of the human body (McIntyre, 1980). The hypothalamus is divided into several sections, two of which are concerned with the regulation of internal body temperature. Guyton (1981) described these two divisions as the anterior heat losing centre which, when stimulated, reduces the body heat and the posterior heat producing centre which, when stimulated, increases body heat.

Any increase in the temperature of the anterior hypothalamus higher than its setpoint (37°C under steady-state conditions) will trigger nerve impulses to activate the body's heat loss mechanisms via evaporation and sweating (McIntyre, 1980). It is important, however, to note that the setpoint of the internal body temperature is not constant. Variables like workrate and external environmental temperature levels will influence this temperature, though influence by the latter occurs only at the very high temperature of 30°C and more. Kerslake (1972) and McIntyre (1980) both illustrated the equilibrium levels of rectal temperature at three work rates in different environments as shown in Figure 3.

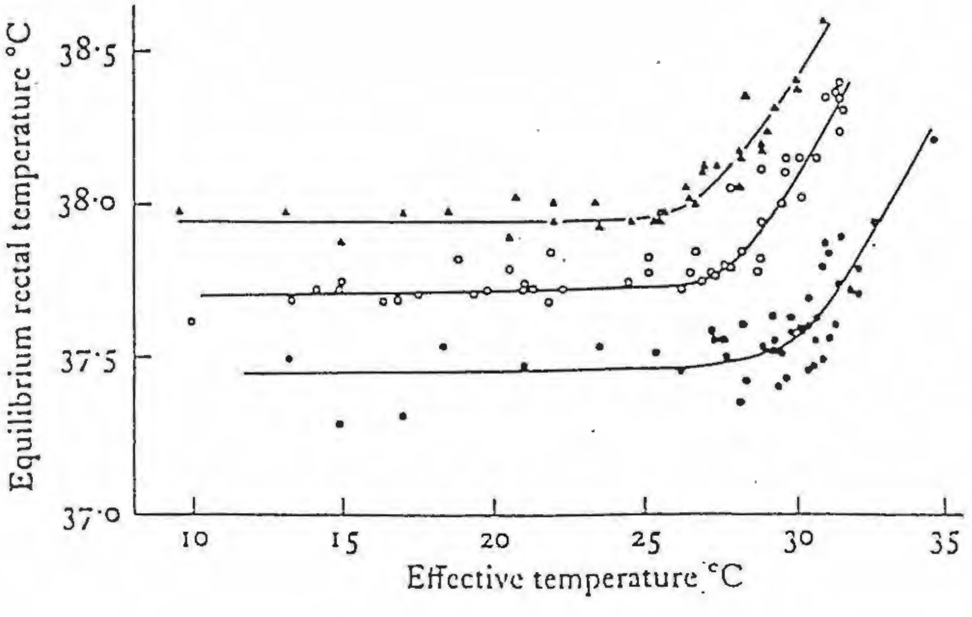


Figure 3: Equilibrium levels of rectal temperature at three work rates in different environments (Taken from Kerslake, 1972)

When the human body experiences cold, the posterior area of the hypothalamus is stimulated, which in turn activates the two important mechanisms of heat retention, namely vasoconstriction and shivering. There is a close interaction between the anterior and posterior centres of the hypothalamus in a way that they can inhibit each other. McIntyre (1980) illustrated the thermoregulatory control system in a very simplified diagram (Figure 4).

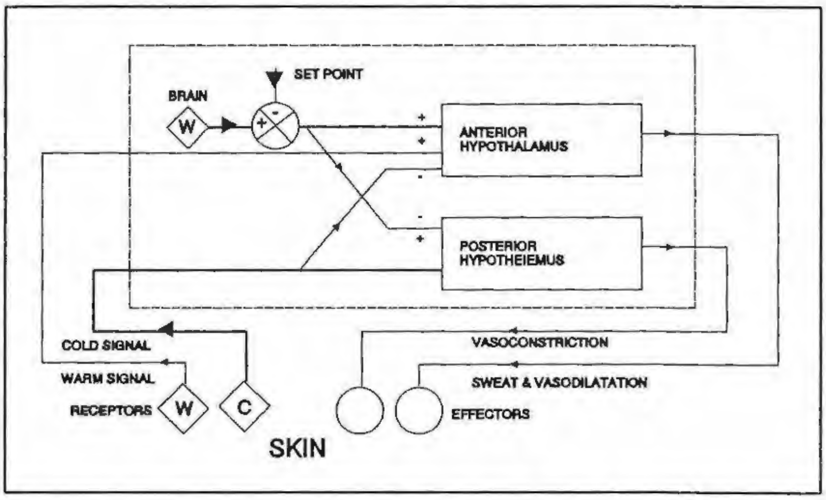


Figure 4 : Simplified diagram of the thermoregulatory system (Taken from McIntyre, 1980)

If the internal body temperature of the human rises, sweat will be produced. Cooling of the skin will stimulate vasoconstriction and shivering and sweating will be limited or even stopped, but the increased core temperature will simultaneously prevent the body from shivering. However, at this point in time there are still many unanswered questions regarding the thermoregulatory control system. Contrary to the reaction of the human body to rising temperature, its reaction to cold is not that effective. When cold, the human being tends to react in a behavioral manner, i.e. increase the amount of clothing to wear. It is therefore important to discuss briefly the effect of clothing on thermoregulation.

2.1.4 Clothing and Temperature

The effect of temperature, hot or cold, on a nude human body differs from that on a clothed body. Because the human body is constantly generating heat, this heat is trapped between the skin and the first layer of clothes and the heat loss process is slowed down. Clothes will influence the amount of heat exchange between the skin and the ambient air by convection, radiation and evaporation. On the other hand clothes are a means of protection against cold in winter or arctic conditions, as well as against the damaging rays of the sun in summer.

Kerslake (1972) discussed clothing as an insulator mechanism in cold conditions and as a ventilation mechanism in hot conditions. Studies on the insulation of clothing have shown that the amount of insulation provided by clothing is a function of the thickness of the material. The insulation provided by clothing is the result of the air between the fibres. Peirce and Rees (1945) noted that the nature of clothing fibres did not influence the insulation capability significantly, but the density thereof did influence it. The fibres in material are more conductive than insulating.

The amount of insulation is measured in "clo" units where clo is that amount of insulation required to keep a nude seated person comfortable at 21°C, 50% humidity in a normally ventilated room (see Kantowitz and Sorkin, 1983). Salvendy (1987) adopted the clo values for individual clothing from Sprague and Munson (1974) as shown in Table II.

To obtain the clo value of a specific set of clothing the values of the separate clothing items should be totalled and then multiplied by the factor of 0.82. Rohles et al. (1980) developed a linear model to predict the amount of clothing necessary for thermal comfort, namely:

$$\mathbf{CET^{*} = 29.75 - 7.28\ Icl}$$

where CET^{*} is the new effective temperature (°C) at which a person can act comfortable, and Icl is the summation of the individual clo values of each item multiplied by 0.82.

Table II : Clo units for individual items of clothing
(Taken from Salvendy, 1987)

MEN		WOMEN	
ITEM	Clo	ITEM	Clo
UNDERWEAR			
Long underwear upper	0.10	Full slip	0.19
Long underwear lower	0.10	Half slip	0.13
T-shirt	0.09	Long underwear upper	0.10
Sleeveless	0.06	Long underwear lower	0.10
Briefs	0.06	Bra and panties	0.05
SHIRTS			
Heavy long sleeve	0.29	Heavy blouse	0.29
Heavy short sleeve	0.25	Light blouse	0.20
Light long sleeve	0.22	Heavy dress	0.70
Light short sleeve	0.14	Light dress	0.22
(Plus 5% for tie or turtleneck)			
Heavy vest	0.29	Heavy skirt	0.22
Light vest	0.15	Light skirt	0.10
Heavy sweater	0.37	Heavy sweater	0.37
Light sweater	0.20	Light sweater	0.17
Heavy jacket	0.49	Heavy jacket	0.37
Light jacket	0.22	Light jacket	0.17
Heavy trousers	0.32	Heavy slacks	0.44
Light trousers	0.26	Light slacks	0.26
SOCKS		**STOCKINGS**	
Knee-high	0.10	Any length	0.01
Ankle length	0.04	Panty hose	0.01
SHOES		**SHOES**	
Boots	0.08	Boots	0.08
Oxfords	0.04	Pumps	0.04
Sandals	0.02	Sandals	0.02

Although each practical situation of heat loss by the human body is unique, clothing does play an important role in the thermoregulation process, especially during exercising. The different types of clothing material also have an influence on the effect of clothing on the thermoregulation process and should therefore be given attention during research of this nature.

2.1.5 Effect of Human Bodily Characteristics on Heat

The heat exchange process in the human body, as well as the rate of this process, is influenced by anthropometric features. Firstly there are the size and shape of the human body. Physique differences between population groups all over the world are of significance in climatic adaptation. The ecological "rules" of Bergman (1847) and Allen (1877) can also be applicable to climatic adaptation by humans:

> "The Bergman rule states that within a polytypic warm-blooded species, the body-size of a subspecies usually increases with decreasing temperature of its habitat. The Allen rule states that in warm blooded species there tends to be an increase in the relative size of protruding organs such as the ears and tail with increasing temperature of the habitat." (Harrison et al., 1977 p 434)

Several studies have demonstrated that human body size and shape tend to follow these rules and that the mean body-mass of populations in hot regions is less than that of populations in colder climates. The ratio of sitting height to total height is less in hotter than in colder climates. The trunk dimensions of the human body are also smaller in hotter climates. These and other studies demonstrate that the body-weight/surface-area ratio declines from cooler to hotter climates (Harrison et al., 1977). An excellent example of Allen's rule is demonstrated in the contrast between Eskimos, as the one extreme, and the Australian Aborigines as the other extreme. Humans with atypical Mongoloid faces are specially adapted to extreme cold climatic areas; features like the reduction of brow-ridges and flatter and wider orbital and molar regions of the face which create more fat padding and reduce nasal prominence. Harrison et al. (1977) concluded that distributions of racial types, occupying a wide range of climates, may be ascribed firstly to the widespread phenomenon of physiological acclimatization, secondly to the existence of the Bergman and Allen body-size and other physical differences and thirdly to technological adjustments to climatic conditions, e.g. cooling systems.

2.2 Thermal Comfort

Thermal comfort is generally defined as that condition of mind expressed as satisfaction with the thermal environment (ASHRAE, 1966). Owing to biological and perceptual differences between humans it is impossible to create a thermal environment which will be "comfortable" to every person at the same time. Parsons (1993) stated that an understanding of why people express their thermal comfort is complex and unknown but that there are clear consequences of not maintaining thermal comfort, e.g. health, safety and a decrease in productivity. Where people are working in a group the aim should therefore be to satisfy the highest possible percentage of the group as far as thermal comfort is concerned. Fanger (1970) noted two main reasons for creating a comfortable environment for the human operator: To satisfy the desire to feel thermally comfortable (perception of comfort) and to ensure optimal performance. The assumption is that human performance will in general be optimised in a comfortable thermal environment. The question whether thermal comfort is necessary to maintain optimal human health can be argued in various ways. Exposure to severe thermal conditions (heat or cold) for protracted periods would indeed be detrimental to a person's health. An important fact, however, is that people are not alike and therefore experience thermal conditions differently.

Although there have been numerous studies into thermal comfort over the last century, those of Fanger (1970) and Gagge et al. (1967) are probably the most well-known. Fanger (1970) identified six important factors that influence the condition of thermal comfort. Four of these factors are of an environmental nature; the mean air temperature, mean radiant temperature, mean relative air velocity and the vapour pressure in ambient air. The two remaining factors that influence man's comfort are his activity level and the thermal resistance of his clothing. On the basis of experimental research and literature surveys Fanger (1970) developed a heat balance equation which he then combined with two other factors (activity level and clothing) to form a comfort equation. This heat balance equation consists of the following elements:

$$H - E_d - E_{sw} - E_{re} - L - K = R + C$$

where a description of the terms used is given in Table III.

Table III : Terms used in the heat balance equation of Fanger (1970)

SYMBOL	DEFINITION
H	Internal heat production in the human body
E_d	Heat loss by water vapour diffusion through skin
E_{sw}	Heat loss by evaporation of sweat from skin surface
E_{re}	Latent respiration heat loss
L	Dry respiration heat loss
K	Heat transfer from skin to outer surface of clothing
R	Heat transfer by radiation from clothing surface
C	Heat transfer by convection from clothing surface and others

It is important to note that in most of the experimental work on which Fanger's comfort equation was based the subjects used were young American or European students (Olesen et al., 1972). It can therefore not be assumed that this equation will be applicable to all other groups of people all over the world. Fanger (1970) went further and developed a method to quantify the degree of discomfort experienced by people. This method for evaluating and analysing thermal environments is called the "Predicted Mean Vote" (PMV) and gives the mean vote, on the ASHRAE seven-point scale, of a large group of subjects in a given thermal environment. The ASHRAE scale is a standard based on studies by the American Society for Heating, Refrigeration and Air Conditioning Engineers on several thousands of subjects who voted their comfort. Table IV shows the seven-point scale of warmth sensation according to ASHRAE.

Table IV : Scale of warmth sensation from ASHRAE

ASHRAE SENSATION SCALE	
Hot	7
Warm	6
Slightly warm	5
Neutral	4
Slightly cool	3
Cool	2
Cold	1

The creation of thermal comfort for the modern worker at his workplace is the primary objective of today's heating and air-conditioning industry. A basic quantitative knowledge of the correct combination of the above six variables for thermal comfort is therefore essential. Fanger (1970) divided comfort conditions into two categories, namely physiological and environmental comfort conditions. He stated that man probably possesses one of the most effective physiological mechanisms for maintaining a heat balance. It is, however, not enough to have knowledge of just the physiological comfort conditions. In order to create a comfortable thermal environment it is essential also to have a quantitative knowledge of the environmental variables which will provide thermal comfort. Finally it is interesting to note that Fanger (1970) found that various other factors also influence the thermal comfort of man, including individual differences, variability in man's comfort conditions from day to day, age, adaption/acclimatization, sex and circadian rhythms.

2.3 **Effect of Heat on Human Performance**

The human operators functioning within a system are constantly required to perform some kind of task in a definable working environment. Bailey (1982) sees this performance as the result of a pattern of actions carried out to satisfy an objective or objectives according to some set standard. There are three major components in this definition that require brief mention. The first conceptualises performance as the result of a pattern of actions; observable behaviour like the pressing of a knob or the pulling of a lever, or non-observable intellectual processing such as problem-solving, reasoning and decision-making. The second sees performance as executed in order to achieve a predetermined objective or series of objectives. The last advances the view that performance should be evaluated against a set standard, which may be qualitative or quantitative, and which should be clearly defined before the performance can be evaluated.

Bailey (1982) described four commonly identified evaluative standards for human performance, namely accuracy, speed of performance, skill development time and satisfaction. The efficient human operator in a system should therefore be able to execute the task as accurately as possible in the shortest possible time with a satisfactory outcome. The time in which the operator should develop the applicable skills must be kept as short as possible.

Bailey (1982) furthermore developed a general human performance model which can be used to assess most performance situations. According to this model it is essential to have a clear understanding of the human performer, the activity being performed and the context in which it is performed. This model is shown in Figure 5.

For optimal performance a highly skilled operator needs to perform a familiar activity in a favourable context. Indeed the effective prediction of human performance depends on the critical interaction between the three components, of which the human element is the most complex. The "human element" mainly refers to the sensors, brain and responders. The human operator uses sensors (eyes, ears, nose, hands) and reacts via responders (limbs and mouth). It is therefore clear that any degradation in the functioning of these basic components may have a negative influence on human performance.

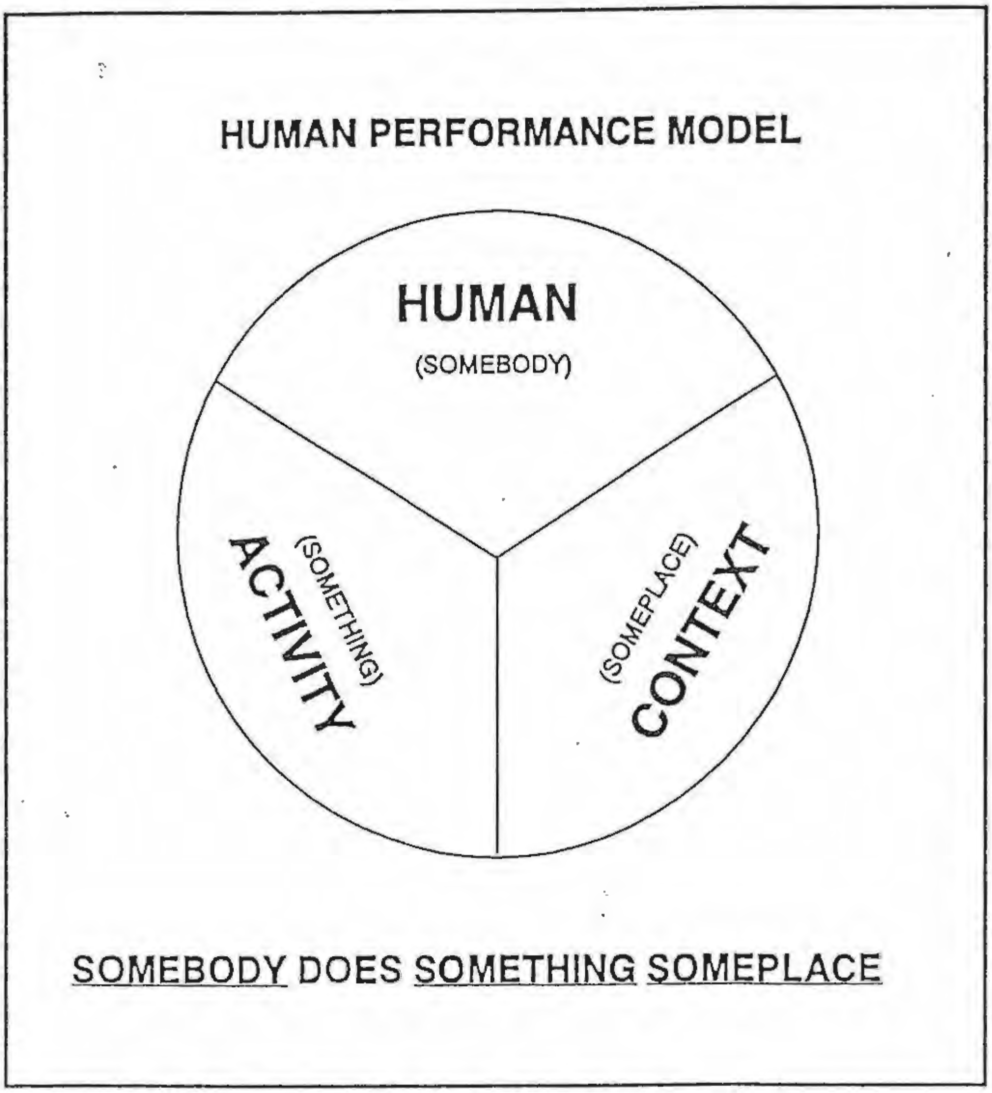


Figure 5 : Human Performance Model
(Adapted from Bailey, 1982)

The second element in the model refers to the requisite activities performed. The major characteristics of this element include work analysis and design, interfaces (controls, displays, workplace, man-machine interaction), performance aids, instructions and training.

The third element represents the context in which the operator performs the activity. This context may be physical and/or social. One aspect of the social context that may influence performance is the effect that other people have on the operator performing the activity. The physical conditions usually regarded as most relevant to the context include environmental factors such as noise, lighting, vibration and ambient temperature. In this study the physical component of the contextual element of primary concern is that of thermal effect on human performance.

Heat and Performance

The effects of heat on human performance have been a topic of concerted research since early in the century. The results, especially of earlier studies, engendered conflicting opinions regarding the effect of heat on performance. McIntyre (1980) questioned whether there was, in fact, objective evidence of the effects of temperature on performance and whether an optimum temperature could be specified for the best performance.

The review by Bell and associates (1978) of laboratory studies dealing with the effects of heat on performance concluded that some researchers found improvement in performance, while others found degradation of performance and yet others found no change in performance at all. Other findings suggested that an effective temperature of 32°C increased arousal and tended to help performance of simple tasks, but degraded performance of complex tasks (Bell et al., 1978). Earlier Pepler and Warner (1968) had shown that the optimum comfortable temperature was not necessarily the best for maximum efficiency and Mackworth (1961) had reported some seminal evaluations of the effect of raised body temperature on performance. He exposed young enlisted World War II veterans to heat for 3 hours daily for 2 weeks. He then put them in a hot environment for one hour and gave them performance tasks to do, relating their efficiency at the tasks to the effective ambient temperature. He concluded that performance on all tasks remained fairly constant until a dry-/wetbulb temperature of about 30/24°C to 32/27°C was reached, after which the performance on all tasks decreased dramatically. The performance tests used by Mackworth (1961) were mainly to tests of vigilance and cognitive abilities; however he also used tests to evaluate physical work performance such as arm strength. An interesting observation drawn from the results of this series is that performance reductions appear to apply as much to physical as to cognitive tasks.

Oborne (1987) elaborated on Mackworth's studies by discussing other variables which affected the heat/performance relationship; aspects such as operator experience, incentives and the exposure time to the heat source. With reference to exposure time, Wing (1965) combined the data from various performance studies in an attempt to indicate the temperature levels at which cognitive performance degradation becomes visible. Figure 6 shows the upper tolerance limit for impaired mental performance as summarized by Wing (1965).

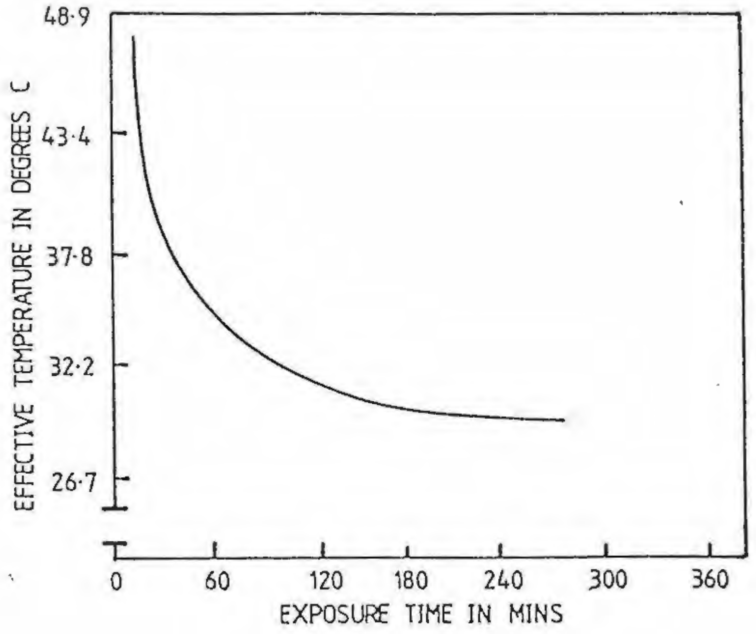


Figure 6 : Upper tolerance limit for impaired mental performance (Wing, 1965)

The effect of heat on performance has also been researched in actual work situations. Bailey (1982) noted that the actual level of heat necessary to degrade performance varied from situation to situation and person to person. It is, however, generally accepted that high temperatures will influence human performance negatively. A modern trend in research on this topic is to combine the effects of the physical environment (noise, heat, vibration) and those of the social environment on human performance. In their study on the effects of heat, social facilitation, sex differences and task difficulty on reaction time, Bell et al. (1982) found that an elevation in temperature would result in an increase in reaction time, though its effect was statistically weak at 38°C. Teichner (1954) studied the effect of temperature on the performance of cotton-pickers. He found that production was optimal between 24°C and 27°C and decreased at temperatures higher than 32°C.

Vernon, et al. (1972) studied the loading performance of individual miners and recorded the total time taken to fill a 500kg tub with coal. The effective work time per hour fell from 55 to less than 40 min as the temperature increased from 17°C to 32°C. This study and numerous others concluded that heavy muscular work in heat is limited by the physiological strain produced by the environment (McIntyre, 1980).

To understand the effect of high temperature on cognitive performance is not a simple matter. The same environmental stress may improve performance on some tasks while worsening it on others (McIntyre, 1980). Researchers generally feel that the results of laboratory experiments should be interpreted in the light of the concept of arousal. The experimental results seem to suggest that an effective temperature of approximately 32°C increases arousal and tends to improve the standard of performance of simple tasks and degrade performance of complex tasks (Bailey, 1982). The state of activeness of the human can vary from sleep to the other extreme of great excitement. McIntyre (1980) noted that performance on a given task would be optional at some intermediate level of arousal and not a very low or very high arousal level. It is therefore difficult to determine whether a degradation in performance can be attributed to the arousal level of the operator or to an environmental factor such as temperature. This aspect should be borne in mind when researching the effect of heat on human performance.

The majority of experiments in this field aimed at determining the absolute temperature at which human performance starts to degrade. Poulton (1976) listed nine experiments in which high temperature improved performance. Mainly two aspects, speed and vigilance, were noted to improve under high temperature. McIntyre (1980) summarized the effect of temperature on learning by distinguishing between classroom and laboratory studies. He discussed the study Mayo carried out on two groups of technical trainees in the US Navy in 1955. One group was taught in an air-conditioned classroom in which a temperature of 24°C was maintained. The other group was exposed to a non-air-conditioned room with a temperature of 33.6°C. A comparison of test scores over a period of two and four weeks found no difference in results, although 79% of the group exposed to the higher temperatures felt that the hot conditions had affected their learning. Schaer and Shaffran (1973), on the other hand, found in their series of studies in which students carried out a set of learning tasks for 20 min twice-daily for nine weeks, that temperature affected the more complex tasks which demanded more thought.

Laboratory studies were carried out by Pepler and Warner (1968) who concluded that the optimum temperature for learning was 25.6°C, even though the work rate in their study was lowest at this temperature. Wyon (1970) and Johansson (1975) both found in experiments on schoolchildren that mild heat (27°C) lowered arousal and elicited significantly worse performance than at 20°C. McIntyre (1980) indicated that a review of experiments on students shows learning would deteriorate at temperatures of 27°C and higher. This deterioration in performance will only appear after some time and does not occur during short-term exposure.

In their study of the time-on-task effect on tracking performance under heat stress Beshir et al. (1981) used three levels of ambient temperature, namely 20°C, 26°C and 30°C. This investigation indicated that as the ambient temperature increased, a deterioration in tracking performance occurred. It was found that a temperature increase from 20°C to 26°C would bring about an approximate doubling in tracking errors, while an increase of 26°C to 30°C produced less prominent deterioration in tracking performance. Grether (1973) stated that mental and perceptual performance decreased at an effective temperature above 29.4°C, while Johansson (1975) concluded that effective temperature higher than 30°C would most likely impair performance of cognitive, perceptual and psychomotor tasks. Nunneley et al. (1978) studied subjects exposed to 28.7°C - 31.1°C WBGT and found that a decrement in performance at both temperatures occurred for most tasks, in particular learning tasks. Ramsey and Kwon (1988) concluded, after reviewing more than 150 studies, that the effect of heat on performance is rather complicated and contradictory.

Performance Models

Although the above literature review indicates definite conflicting findings by different researchers, the general feeling is that different thermal environments do interfere with human activities and task performance. Ramsey et al. (1988) gave four possible explanations for the effects of thermal environments on task performance, namely arousal, physiological functions, distraction and perceived control. These four explanations were summarized by Parsons as follows:

The arousal level of the human operator will influence the task performance and should be in line with the optimum required level for a specific task. It was found that hot ambient environments would reduce arousal levels which may cause performance to degrade. The physiological functions, for example rectal and skin temperatures, sweat rate and sweat loss, are directly affected by the thermal condition in which the human operator functions and will in turn affect the task performance. Thermal stress may distract a person from performing a given task effectively and may cause work overload to occur. It may also result in performance degradation due to a feeling of perceived lost control of the thermal environment.

Parsons (1993) created a rational performance model which can be used to determine the effects of thermal environments. The proposed performance model is shown in Figure 7.

The essence of this model lies in the fact that the human thermal environment consists of psychological factors on the one side and physiological factors on the other. A capacity to perform human activity is derived from these psychological and physiological factors respectively which are then brought in relevance to the specific task to perform. The task performance can then be measured and productivity rated. Productivity is related to the goals of the organization and any measurement should be related to these set goals (Parsons, 1993). Two other factors relevant to this performance model are motivation and the level of skill of the operator. Researchers agree that the level of motivation will largely influence human performance, even in stressful environmental conditions. The effect of these stressful environments on performance will also depend on the level of skill of the operator performing the task. The studies of Mackworth (1952) illustrated the fact that higher skilled operators were less affected by heat even in extremely stressful conditions.

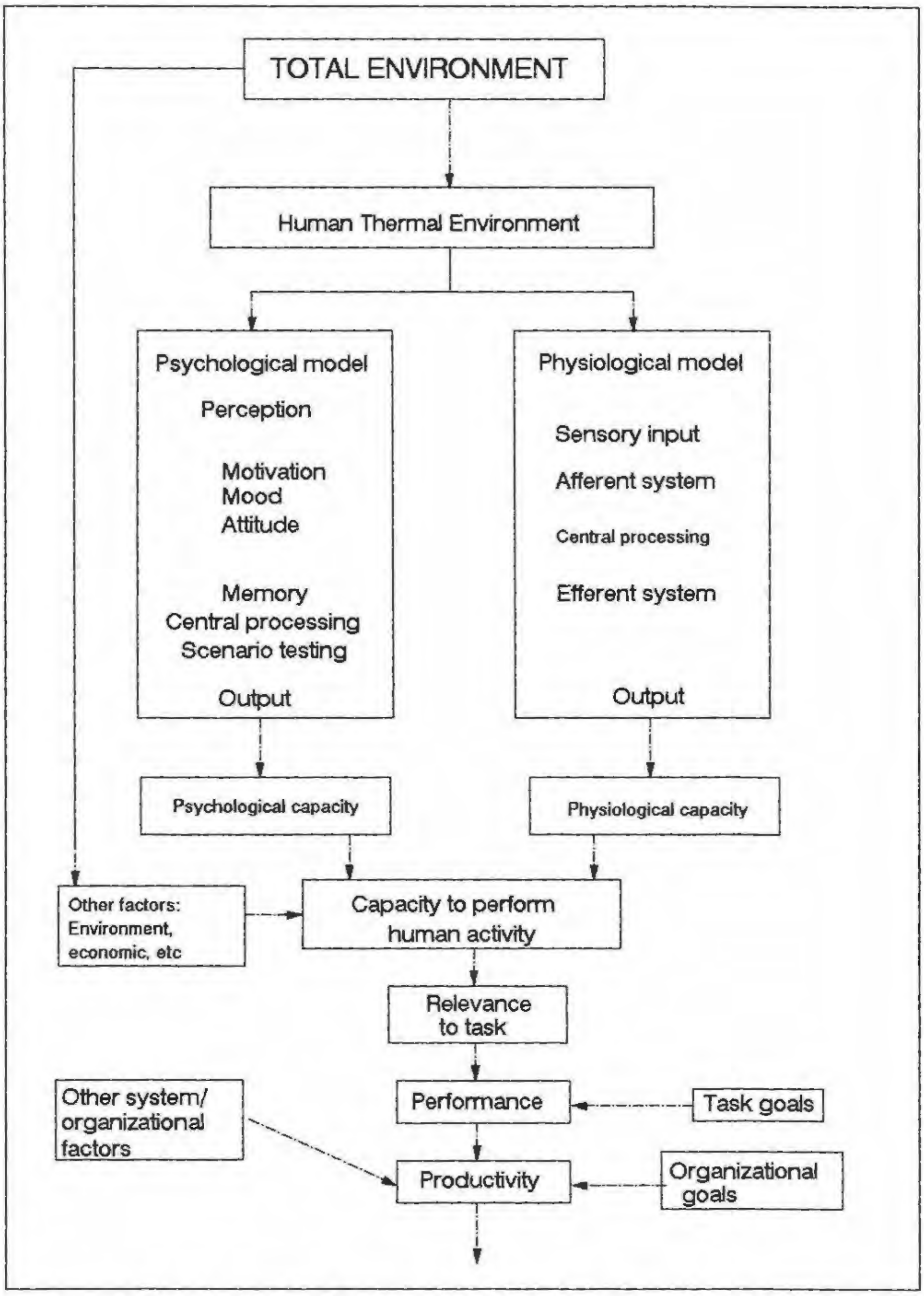


Figure 7 : Model for considering the effects of the thermal environment on human activity performance and productivity
(Taken from Parsons, 1993)

2.4 Macro- and Microcooling Systems

2.4.1 Introduction

The human operator is an integral part of a total system, be it in industrial or military context. Therefore, in addition to outstanding technical achievements, the operability and controllability of such systems are very important factors in achieving optimal overall system performance. Among the main factors influencing the operator's performance are the environmental conditions in which he has to operate. The environmental factor of concern in the present study was the ambient temperature.

Statistical data reviewed in the Statistical Abstracts of the United States, 105th edition, 1985, showed that up to 10 million industrial workers are daily exposed to a thermal environment in which heat stress is a potential health hazard (NIOSH, 1986). However, the majority of research and development in this area has been conducted in, or on behalf of, the military field. Since the aim of military commanders is to gain superiority on the battlefield by operating, where possible, in conditions in which the enemy cannot operate, military researchers have explored ways to enhance their fighting capabilities. One such area involves the ability to continue fighting in intense heat, especially in countries in which the summer heat is intense. This situation has led to the development of sophisticated air-conditioning systems for armoured fighting and personnel-carrying vehicles. As the modern technology in combat vehicles becomes ever more complex, more electric and electronic devices (which release heat) are being installed in the crew compartment. At the same time, this sophisticated technology makes ever-increasing demands on the operator with regard to physical and mental performance within this deteriorating environment (Baum, 1983). The environmental heat load, as specified in the heat balance equation, can be modified by applying certain control measures, namely ventilation, air-conditioning, screening, insulation and the modification of the process, as well as by the use of protective clothing and equipment (NIOSH, 1986). These engineering control measures are summarized in Table V. However, it is not always possible or practical to implement engineering control measures for the prevention of heat stress. Preventive practices are an alternative for engineering control measures.

Several types of preventive control measures are normally encountered, including: limiting the exposure time; reducing the metabolic heat load; improving the operator's heat tolerance by acclimatization; training of operators with regard to thermal safety and health; and medical screening of operators for heat intolerance (NIOSH, 1986). For the purpose of this study air-conditioning as a control measure is discussed in detail.

Table V : Summary of engineering controls for the modification of environmental heat load

ENVIRONMENTAL FACTORS	ENGINEERING CONTROLS
a) Convective heat control	- Modify air temperature - Modify air movement
b) Radiant heat control	- Lower the process temperature - Relocating, insulating or cooling of heat source - Line-of-sight reflective shielding - Change emissivity of source surface by coating
c) Evaporative heat control	- Increase air movement - Decrease ambient water vapour pressure

The cooling of a stressful thermal environment is basically done by means of two methods. The first method is macrocooling wherein the entire environment is cooled by supplying cold air to (and recirculating it through) the environment. The second method is the so-called auxiliary cooling or microcooling method, wherein each operator is individually cooled. These methods are now discussed in detail.

2.4.2 Macrocooling

There are various ways in which macrocooling systems function. The majority of air-conditioning systems function on the "vapour-cycle cooling-circuit" principle. The process is presented in a simplified manner in Figure 8. The starting-point of the process is where an intolerable heat load exists in an enclosure in which the human operator must perform the required task. With reference to Figure 2.7 it can be seen that a macrocooling system will withdraw the air from the enclosure by means of a fan (1).

A 10% fraction of fresh air will be added to the recycled air before the cooling process starts (2). The quantity of air in the enclosure and the heat it contains determines the amount of heat to be removed by the air-conditioning process through the vapour unit (3). This cooled air is blown into the enclosure to eliminate the heat load.

The process of cooling the air withdrawn from the enclosure is as follows. Freon gas is used as coolant, operating in a closed-loop cycle. The freon gas is at low pressure (4) when passing through the compressor unit (5) and under high pressure when it leaves the unit. This high pressure gas is condensed to liquid which is cooled down by air passing through the condenser unit (6). The condensed freon, at approximately 5°C, flows from the condenser unit into the liquid receiver (7) in which freon not required in the circuit is retained. At this liquefaction pressure the liquid freon flows through the expansion valve (8) where it expands and cools (approximately 82% liquid and 18% gas). Cold liquid freon now flows through the tubes of the evaporator and absorbs the heat from the recycled/fresh air mixture that is blown through the evaporator. Condensation water formed during this process is collected and drained away.

Baum (1983) described a refrigerant-free cooling system which uses the compressing and expanding of air to perform the cooling process. An externally mounted unit draws the air from the enclosure in which the human operator is performing and compresses it. A turbine, mounted on the same shaft as a second

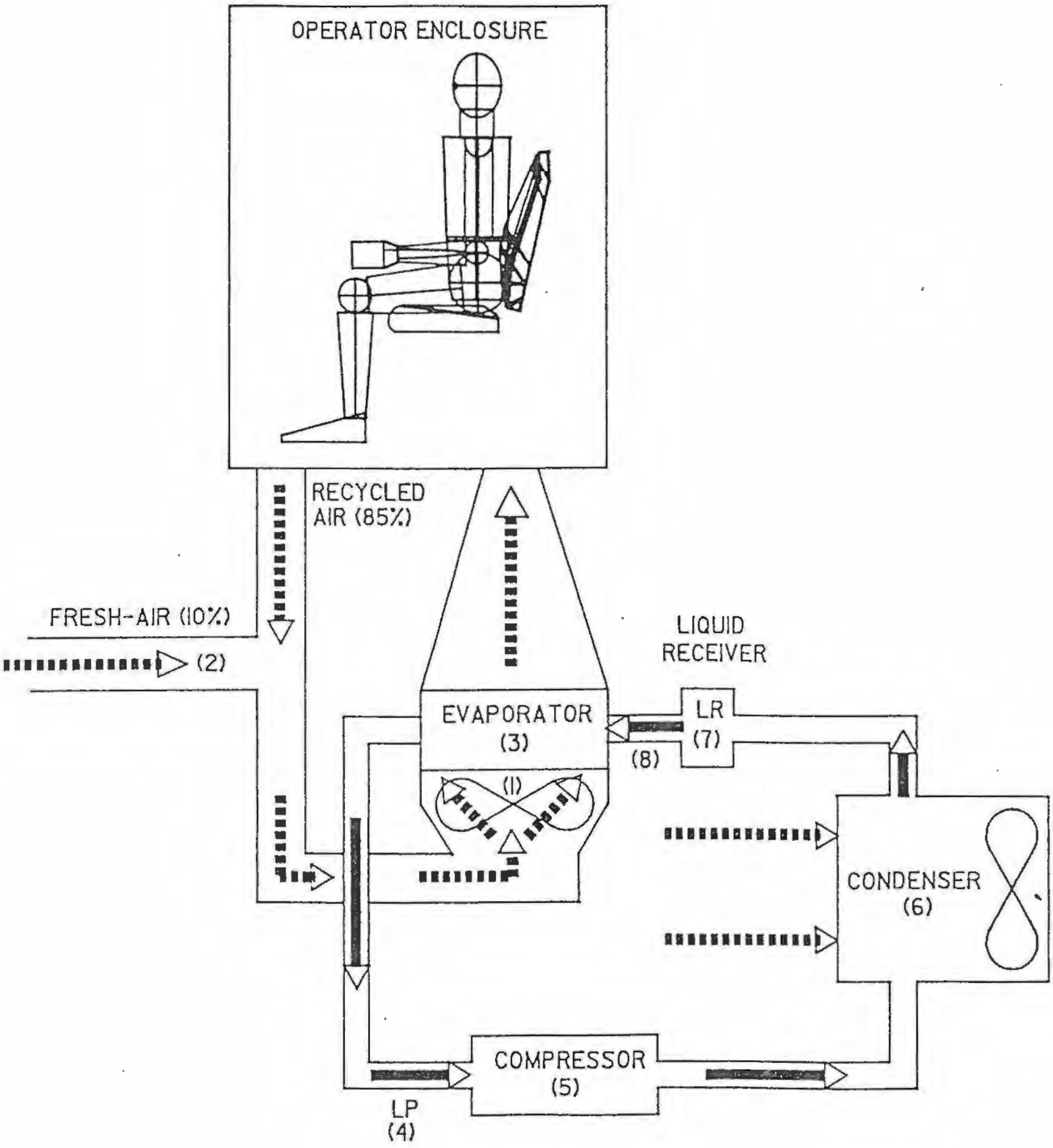


Figure 8 : Simplified macro air-conditioning process

compressor, is driven by the compressed air. This second compressor feeds a portion of air through a heat exchanger that extracts the heat from the air. The cooled air is reconnected with the main stream and flows back to the enclosure and its occupant(s).

2.4.3 Microcooling

The main objective of personal cooling is the elimination of metabolic heat produced by the operator (Pienaar, 1988). The purpose of individual cooling is the prevention of serious effects of external heat load and to remove heat from the human body to establish a thermal comfort situation in and around the human body (Webb, 1969). There are four main auxiliary cooling approaches, namely water-cooling systems, air-cooling systems, ice packet cooling systems and wettable coveralls (NIOSH, 1986). Each of these cooling systems has its own advantages and disadvantages.

Water-cooled Systems

The concept of a water-cooled microcooling system was, according to Pienaar (1988), first suggested in 1958 and a prototype was eventually developed in 1963. Speckman et al. (1988) described the process as the circulation of cooled liquid in small tubes over the skin of the human body to conduct heat away from its surface, as well as the removal of heat from the air around the tubing, so that the heat received at the skin surface is decreased. Various types of water-cooled systems were reviewed by Pienaar (1988). The basic concept of circulation of cold water is generally used and only the way in which the water is cooled, differs. These methods vary from thermo-electrical systems to the use of ice and CO_2 . A disadvantage of the latter method is that CO_2 in solid form is at a very low temperature and therefore may freeze the water (Burton, 1969). London (1969) described a two-man freon compression system which was able to perform 1,2 kW cooling at an ambient temperature of 50°C.

Shvartz et al. (1974) found that the neck, face, back and chest are the best parts of the body to cool, while the thighs and arms are the worst. Water-cooled garments include a vest type which provides cooling of the torso and head, a hood which provides cooling only to the head, a short undergarment which provides cooling to the torso, arms and legs and a long undergarment which provides cooling to the head, torso, arms and legs (NIOSH, 1986). Numerous studies indicated that no physiological problems occurred when using water-cooled systems to remove local heat from the human body (Nunneley, 1970; Konz and Duncan, 1971; Fonsca, 1976).

Air-cooled Systems

Konz (1979) identified three types of air-cooled systems. One method is to supply the body with ambient air which is released under the garment. The ambient air should, however, be filtered before setting it free beneath the garment. Another method is to decrease the air temperature. Konz (1979) described the use of a vortex tube for this purpose in which compressed air comes through the vortex tube and cold air is exhausted from one branch, hot air from the other branch of a T-shaped tube. The cold air is released onto the skin and the hot air is exhausted to the environment. A third method involves cooling by artificial sweat. This method is normally used together with protective garments. The subject sweats inside the garment and the vapour condenses on the inner side, which becomes hot. Heat passes via conduction through the garment where radiation and convection take place.

Pienaar (1988) has also reviewed a number of different methods of air-cooled systems. The USA Patent Office describes a portable system which is carried on the operator's back. The air is produced by a fan which circulates it through the isolated suit. The air is cooled by means of a cooling medium such as liquid oxygen or dry-ice.

Ice Packet Vest

The ice packet vest contains a number (up to 72 in certain types) of ice packets which are secured to the vest by tape (NIOSH, 1986). The environmental conditions affect the capability of this cooling, as well as the duration of time it is provided. This type of cooling is therefore only effective for a short time; two to four hours (Pienaar, 1988). The advantage of this cooling system is the fact that the cooling is supplied noise-free and no alternative energy source is needed. The operator is free to move without the restriction of an umbilical cord and it is also less expensive to use (NIOSH, 1986).

Wetted Overgarments

The wetted overgarment method is described in the NIOSH (1986) revised criteria. This overgarment consists of a cotton cloth overall or a two-piece cotton cover which covers the whole body except the feet and hands. The cover must be kept wet and is especially effective in a low humidity, high temperature environment.

2.5 Related Studies on the Effect of Macro- vs Microcooling on Human Performance

As far as could be established from a review of the relevant literature, no previous investigation appears to have been conducted to determine the influence of an optimal macrocooling vs an optimal microcooling system. Previous studies, apparently, have addressed evaluations of only microcooling systems as these influence the physiological performance of the human operator, mostly in military contexts.

Webb (1969) stated that normally microcooling is applied only when heat stress occurs and that its physiological effect can be seen in terms of reduced physiological strain when comparing the cooled individual with an uncooled individual. He noted that the most used methods to determine physiological strain involve measuring the subjects' sweat-rate, total sweat loss, heart rate and body temperature. London (1969) conducted various tests with a water-cooled suit and found that while sweat and heart rates could readily be controlled, internal body temperature was often higher than the required value. He also cautioned against the danger of under- or overcooling and that some form of control should exist to prevent a high degree of vasoconstriction occurring. A cut-off temperature of 15°C is normally set to prevent the latter.

Kok et al. (1989) evaluated a water-cooled microcooling system on the crew of two military vehicles. They conducted a laboratory study to investigate the concept of microcooling and found the following physiological responses:

- The wearing of the microcooling system brought about a 6°C - 7°C reduction in skin temperature (Tsk).
- While wearing the microcooling system there was no increase in heat load as assessed by heart rate and rectal temperature measurements.
- The microcooling system enabled subjects to complete a nine-hour exposure compared with a two- to three-hour exposure achieved without the system.
- Rectal temperatures (Tre) in the cooled state did not exceed 38°C and on average the microcooling condition resulted in a 0.6°C - 0.7°C reduction as compared to the non-cooled condition.

- The heart rate in the cooled condition never exceeded 140 beats/min and the microcooling system resulted in a 30 - 40 beats/min lowering of heart rate as compared with the non-cooled condition.

Van Rensburg et al. (1972) conducted a study with two different types of microcooling systems, namely a water-cooled vest and a pre-frozen jacket.

In the case of both microcooling methods the subjects benefitted to a large extent in comparison to the condition without any cooling. It was interesting to note that heart rate, sweat rate and rectal temperatures were significantly depressed for 4- and 6-hour exposure, except during the first hour of exposure. These authors noted further that the psychological effects were even more dramatic than the physiological effects. The subjects, when wearing the two types of microcooling systems, showed high spirits and the symptoms of psychological distress often shown by men exposed to high heat-stress were entirely absent throughout the study.

A study conducted by Shapiro et al. (1982) demonstrated that auxiliary cooling appeared to be an effective method of reducing the physiological stress of individuals who worked in hot-dry and hot-wet environments. In both types of environments all physiological variables were significantly lower for subjects using the microcooling systems than in environments without auxiliary cooling.

Pienaar (1988), in his literature review on microcooling systems, found that in all the applicable studies cooling of the torso and back resulted in a significant advantage to the human operator. De Koker (1988) found that a microcooling system enabled subjects in a hot environment of 32°C WBGT to perform various psychological tasks significantly better than under the same environmental conditions without cooling.

As noted earlier numerous studies have been conducted to evaluate the effectiveness of different microcooling systems and both advantages and disadvantages were recorded. However, no objective comparison between an optimal microcooling vs an optimal macrocooling system could be found in the literature and therefore, to the knowledge of this researcher, little or no scientific evidence exists to establish whether these two methods of cooling have a similar influence on the physiological and psychological performance of the human operator. It was therefore the main objective of the present project to address this apparent void in the research by comparing the two commonly used systems.

CHAPTER THREE : EXPERIMENTAL METHODS AND PROCEDURES

3.1 Experimental Design

A 3 x 2 x 4 repeated measurement, factorial, experimental design was used (Table VI). The first independent variable, namely the environmental temperature, consisted of 3 different conditions. The first condition involved a 4-hour duration constant hot environment of 40°C (± 1°C) at 40% (± 5%) relative humidity (baseline condition). The second condition, a similar hot environment exposure of 40°C (± 1°C) at 40% (± 5%) relative humidity, was one in which the subjects used a microcooling system set at 18°C - 21°C. The third condition involved a macrocooled ambient environment set at 21°C (± 1°C) at 60% (± 5%) relative humidity for the 4-hour test duration. The second independent variable was the workrate. Two exposures were conducted under each environmental condition, one in which the subjects remained seated at rest for the full duration and the second in which physical work was performed. The physical work consisted of a bench-stepping task at 24 steps/min for the first 20 min of each hour of exposure. Stepping heights were adjusted according to individual body mass to elicit comparable external workrates of 40 W (positive component). This was equivalent to an approximate oxygen consumption of 1ℓ O_2/min or a metabolic rate of 340 W (180 W/m^2). The third independent variable was the time in which the performance tasks were carried out. Each task was repeated 4 times during the 4-hour schedule. Each subject (n = 24) was tested for all three independent variables. Thus each subject, apart from orientation and acclimatization, participated in six 4-hour experimental sessions, each on a separate day.

Table VI : 3 X 2 X 4 factorial design

3 x 2 x 4 factorial design		Performance Condition							
		Rest				Moderate workrate (40 W)			
		T1	T2	T3	T4	T1	T2	T3	T4
Temperature Condition	Hot (40°C; 40% RH)	n=24	n=24	n=24	n=24	n=24	n=24	n=24	n=24
	Microcooling (40°C; 40% RH Micro = 18-21°C)	n=24	n=24	n=24	n=24	n=24	n=24	n=24	n=24
	Macrocooling (21°C; 60% RH)	n=24	n=24	n=24	n=24	n=24	n=24	n=24	n=24

T1 = Hour 1 responses in the 4-hour test session; etc.

3.2 Subject Characteristics

Healthy young adult male (n=24) subjects were selected for this study from volunteers of the student population of the University of Pretoria and Normaal Kollege Pretoria. Each subject was medically screened with specific emphasis on the fact that no subject had any history of heat illness or related heat injury. The selection criteria were further based on willingness to participate voluntarily for the whole period of 13 days for at least 4 hours per day. Each subject was paid a basic allowance of R40.00 per day with an incentive bonus of up to R20.00 per day for successful completion of the daily task.

A biographical data list of each subject was completed (see Appendix A). Each subject provided written consent for participation in the experiment (see Appendix B).

The experimental subjects were randomly divided into two subgroups, namely a morning group (Group A: 07:00 - 12:00) and an afternoon group (Group B: 12:00 - 17:00). This grouping remained the same for the duration of the experiment to eliminate the chronobiological effects.

3.3 Procedure and Instrumentation

3.3.1 Experimental Procedure

The experiment was scheduled over a period of 13 days and conducted in the climate chamber of Lifestyle Management (Pty.) Ltd., Pretoria. The experiment was conducted in the following 5 phases:

Phase One: Administration

On a set pretest examination day (phase 1) the subjects were examined medically and their biographical and anthropometric data were collected (see Appendix A). The subjects were introduced to the climate chamber and to all the instrumentation to be used during the experiment. They were furnished with detailed instructions of the daily programme and divided into morning and afternoon groups. Each performance test was demonstrated and all administrative procedures were completed. A perceptual questionnaire on the subjective effect of the two different cooling systems was completed by each subject after completion of the last test day (see Appendix C for questionnaire). The detailed programme is shown in Table VII.

Table VII : Detailed programme - Pretest examination day (phase 1)

TIME OF DAY	ACTIVITY
08:00	Subjects arrive at laboratory.
08:00 - 09:00	General briefing, introduction to research personnel and facilities.
09:00 - 10:00	Detailed discussion of project schedule. Allocation to groups (A and B).
10:00 - 12:00	Medical examination. Collection of each subject's biographical and physiological data.
12:00 - 13:00	Lunch
13:00 - 14:00	Administration: consent forms.
14:00 - 16:00	Conducting of psychometric tests and final administration.

Phase Two: Acclimatization

The second phase of the experiment was the acclimatization process of the subjects and their training in the performance tests which were to be used. This phase was conducted from day 1 to day 4 (see Table VIII for detailed programme of days 1 - 4). The acclimatization process was carried out in the two respective groups with group A (morning group) going through the process from 08:00 - 12:00 and group B (afternoon group) going through the process from 13:00 - 17:00 for the four days. The acclimatization process consisted of a daily exposure (4-hour duration) of the subjects to the experimental environmental conditions (40°C, ± 1°C; 40%, ± 5% RH). The work time performed by the subjects was progressively increased each day to ensure a gradual increase of stress intensity over the acclimatization period. The acclimatization procedure is described in Table IX.

Table VIII : Detailed programme - Days 1 - 4 (phase 2)

Acclimatization and performance test training

TIME OF DAY	ACTIVITY	
	GROUP A (Morning group)	GROUP B (Afternoon group)
07:30	Report at LSM laboratory	Report at LSM laboratory
08:00 - 12:00	Acclimatization in LSM climate chamber: - 30 minutes' exercise (40 W) 24 steps/min positive component - 30 minutes' rest The above cycle was repeated 4 times.	Training in performance tests at LSM - 4 tests at 15 min/test The above cycle was repeated 4 times.
12:00 - 13:00	Lunch	
13:00 - 17:00	Training in performance tests at LSM - 4 tests at 15 min/ test. The above cycle was repeated 4 times.	Acclimatization in LSM climate chamber. - 30 minutes' exercise (40 W) 24 steps/min positive component - 30 minutes' rest The above cycle was repeated 4 times.

Table IX : Acclimatization schedule

DAY	EXPOSURE INTERVAL (MINUTES)							
	0-30	31-61	61-90	91-120	121-150	151-180	181-210	211-240
1	Rest	Rest	Rest	Work	Rest	Rest	Rest	Work
2	Work	Rest	Rest	Work	Rest	Rest	Work	Rest
3	Work	Rest	Work	Rest	Work	Rest	Work	Rest
4	Work	Rest	Work	Rest	Work	Rest	Work	Rest

During acclimatization the subjects were instrumented as for the experiment. The rectal temperatures were monitored at 5-minute intervals during the acclimatization procedure. When rectal temperatures reached 38.5°C the subject was instructed to rest (seated) for at least 30 min before workrate could be resumed. This was done to minimise the risk of mandatory withdrawal of subjects from exposure on the basis of safety precautions (see paragraph 3.3.2.7), thus ensuring full 4-hour exposure of subjects to the experimental environmental conditions.

The performance test habituation for each group was alternated with the acclimatization process where group A was trained in the afternoon after the morning's acclimatization and group B in the morning before the afternoon's acclimatization. The reason for habituating the subjects in the performance tests was to eliminate the effects of learning. Each subject's optimum performance on each test was established on day 4 to be used as a response standard under comfortable conditions (room temperature).

Phase Three: Baseline Environment

The third phase of the experiment involved the conducting of the performance tests and physiological measurements in a baseline environment of 40°C (± 1°C) at a 40% (± 5%) relative humidity (RH). This was done over a period of two days, one day with no work intensity and one day with an external moderate workrate of 40 W (positive component) repeated 4 times in the 4-hour schedule. Each 1-hour period consisted of 20 min rest or work, depending on the experimental condition, followed by 40 min performance testing (see Tables X and XI for the detailed programmes). This procedure was carried out in the two groups respectively for a duration of 4 hours.

Phase Four: Microcooling

Phase four of the experiment was a repetition of phase three with the addition of microcooling systems which provided cooling to the individual subjects (see p 65 for a detailed description of the microcooling system). The same procedure as described in phase three was followed. This phase was carried out over a period of four days because no more than eight subjects could be accommodated simultaneously by the microcooling system (see Tables X and XI for the detailed programmes). The operating temperature of the microcooling system was controlled at 18°C - 21°C.

Phase Five: Macrocooling

The fifth and last phase of the experiment was the conducting of performance tests and physiological measurements as described in phases three and four, but now under macrocooling conditions. The macrocooled environment was controlled at 21°C (±1°C) with a 60% (±5%) relative humidity (RH) and this condition was again conducted over a period of two days, the first with no work intensity and the second with an external moderate workrate of

40 W (positive component) repeated 4 times in the 4-hour schedule (see Tables X and XI for the detailed programmes).

Table X : Detailed programme - Days 5 - 12 (phases 3 - 5)
Baseline environment, microcooling and macrocooling
Days 5, 7, 8 and 11: No work intensity

TIME OF DAY	ACTIVITY	
	GROUP A (Morning group)	GROUP B (Afternoon group)
07:00	Report at LSM laboratory.	-
07:00 - 08:00	Prepare for day's schedule.	-
08:00 - 08:20	Rest (sitting position).	-
08:20 - 09:00	Performance test cycle 1 - 4 tests at 10 min/ test.	-
09:00 - 09:20	Rest (sitting position).	-
09:20 - 10:00	Performance test cycle 2 - 4 tests at 10 min/ test.	-
10:00 - 10:20	Rest (sitting position).	-
10:20 - 11:00	Performance test cycle 4 - 4 tests at 10 min/ test.	-
11:00 - 11:20	Rest (sitting position).	-
11:20 - 12:00	Performance test cycle 4 - 4 tests at 10 min/ test.	Report at LSM laboratory.
12:00 - 13:00	Remove instrumentation and clean up.	Prepare for day's schedule.
13:00 - 13:20	-	Rest (sitting position).
13:20 - 14:00	-	Performance test cycle 1 - 4 tests at 10 min/ test.
14:00 - 14:20	-	Rest (sitting position).
14:20 - 15:00	-	Performance test cycle 2 - 4 tests at 10 min/ test.
15:00 - 15:20	-	Rest (sitting position).
15:20 - 16:00	-	Performance test cycle 3 - 4 tests at 10 min/ test.
16:00 - 16:20	-	Rest (sitting position).
16:20 - 17:00	-	Performance test cycle 4 - 4 tests at 10 min/ test.
17:00 - 18:00	-	Remove instrumentation and clean up.

Table XI : Detailed programme - Days 5 - 12 (phases 3 - 5) Baseline environment, microcooling and macrocooling Days 6, 9, 10 and 12: Moderate work intensity (40 W)

TIME OF DAY	ACTIVITY	
	GROUP A (Morning group)	GROUP B (Afternoon group)
07:00	Report at LSM laboratory.	-
07:00 - 08:00	Prepare for day's schedule.	-
08:00 - 08:20	Moderate work intensity (40 W).	-
08:20 - 09:00	Performance test cycle 1 - 4 tests at 10 min/ test.	-
09:00 - 09:20	Moderate work intensity (40 W).	-
09:20 - 10:00	Performance test cycle 2 - 4 tests at 10 min/ test.	-
10:00 - 10:20	Moderate work intensity (40 W).	-
10:20 - 11:00	Performance test cycle 3 - 4 tests at 10 min/ test.	-
11:00 - 11:20	Moderate work intensity (40 W).	-
11:20 - 12:00	Performance test cycle 4 - 4 tests at 10 min/ test.	Report at LSM laboratory.
12:00 - 13:00	Remove instrumentation and clean up.	Prepare for day's schedule.
13:00 - 13:20	-	Moderate work intensity (40 W).
13:20 - 14:00	-	Performance test cycle 1 - 4 tests at 10 min/ test.
14:00 - 14:20	-	Moderate work intensity (40 W).
14:20 - 15:00	-	Performance test cycle 2 - 4 tests at 10 min/ test.
15:00 - 15:20	-	Moderate work intensity (40 W).
15:20 - 16:00	-	Performance test cycle 3 - 4 tests at 10 min/ test.
16:00 - 16:20	-	Moderate work intensity (40 W).
16:20 - 17:00	-	Performance test cycle 4 - 4 tests at 10 min/ test.
17:00	-	Remove instrumentation and clean up.

3.3.2 Facilities and Instrumentation

Lifestyle Management Climate Laboratory

The climate laboratory used for the experiment is situated at the Lifestyle Management offices in Verwoerdburg, Pretoria (see Figure 9 for detailed plan of facility). The laboratory consists of a GA climate chamber, 7.2 m in length, 4.2 m wide and 3.5 m in height. The air-conditioning unit is mounted on the first floor of the building and has the following system capacity:

a) Cooling: 20 kW (Freon cooling)
b) Heating: 15 kW (Electrical heating)
c) Humidification: 2 x 13 kg/h (Electrical steam damping)
d) Dehumidification: - Sensible heat 7 kW
- Latent heat 5 kW

The temperature specification for the inside of the chamber is as follows:

Max drybulb temperature 55°C Relative humidity 30 - 80%
Min drybulb temperature 18°C Relative humidity 30 - 70%
Fresh-air flow - Minimum 144 m^3/h; Maximum 220 m^3/h
Recirculation airflow - 5040 m^3/h

Up to 65 air changes per hour can be achieved by the main recirculation fan. The climate chamber is maintained at positive pressure throughout functioning. Normal functioning recirculates 90% of the air and adds 10% fresh air to the chamber. Air is

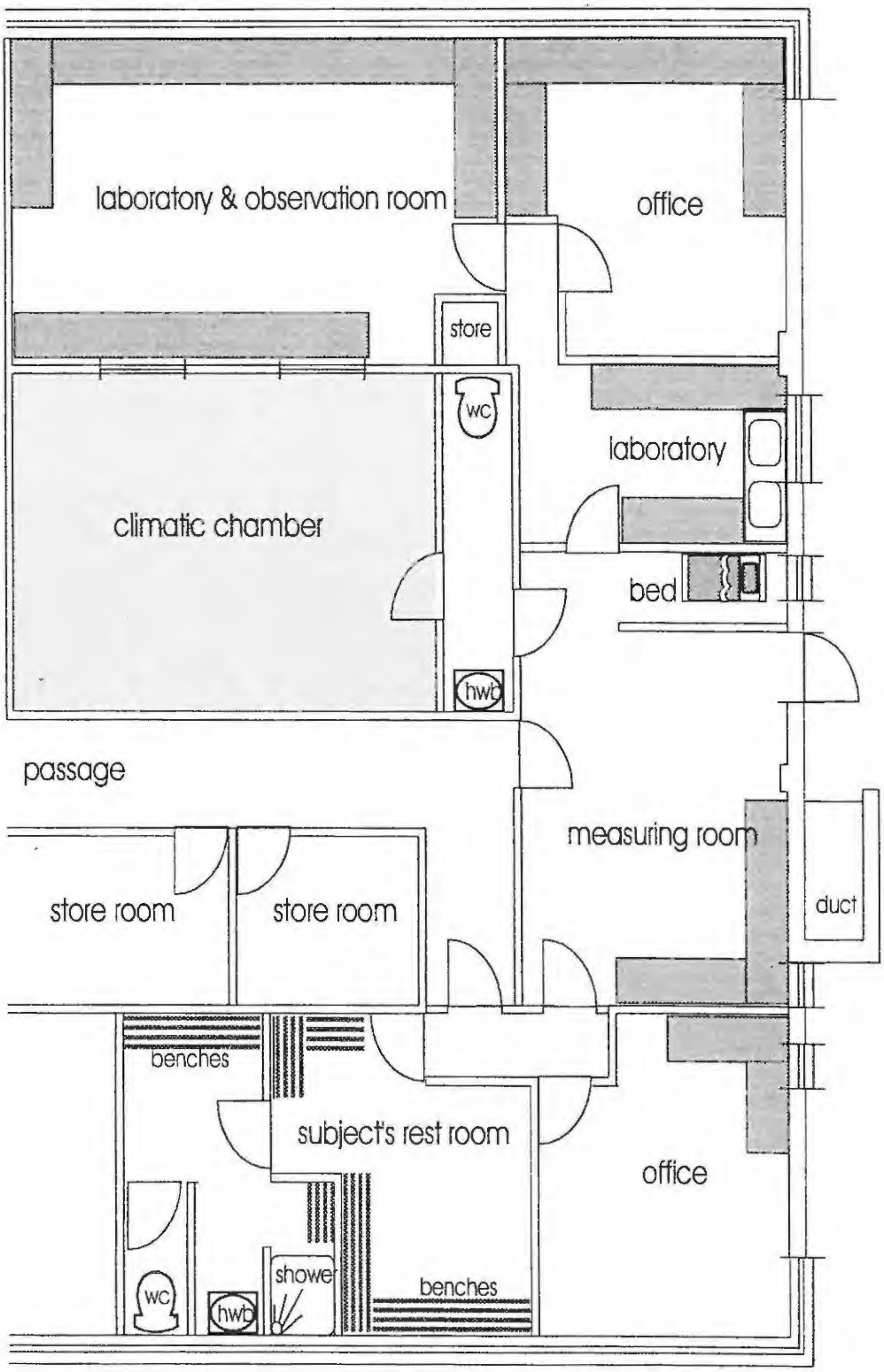


Figure 9 : Institute of Environmental Physiology

Layout of research facility

withdrawn through the two recycling ducts and circulated through the air-conditioning unit, re-entering the climate chamber through the main distribution duct in the centre of the roof via its perforated ceiling. Air velocity in the climate chamber is below 0.35 m/s.

The walls of the climate chamber consist of 75mm medium density polystyrene covered with chromadeck on both sides. The roof is a 220mm concrete structure, sealed with bitumen to prevent the absorption of moisture. The floor is a wooden structure with a drainage facility.

Dry- and wetbulb temperatures are mediated separately by means of a programmable controller to a resolution of 0.5°C from the respective setpoints. The control room is adjacent to the climate chamber (6 m x 3.5 m) with two windows in the long side of the chamber for observation. An airlock and a toilet/basin facility are situated at the entrance to the exposure chamber. The lighting inside the exposure chamber consists of double neon tubes mounted against the long sidewalls in the centre of the chamber. These lights provide a light intensity of 250 lux on the working surfaces. The electrical power in the climate chamber is provided by single-phase 220 V power supplies and the air-conditioning system is 380 V three-phase driven.

A preparation room adjacent to the airlock (entrance lobby) was provided for the subjects where they changed and where the daily fitting of instrumentation took place. Each subject was provided a locker to safeguard valuables while participating in the daily routine.

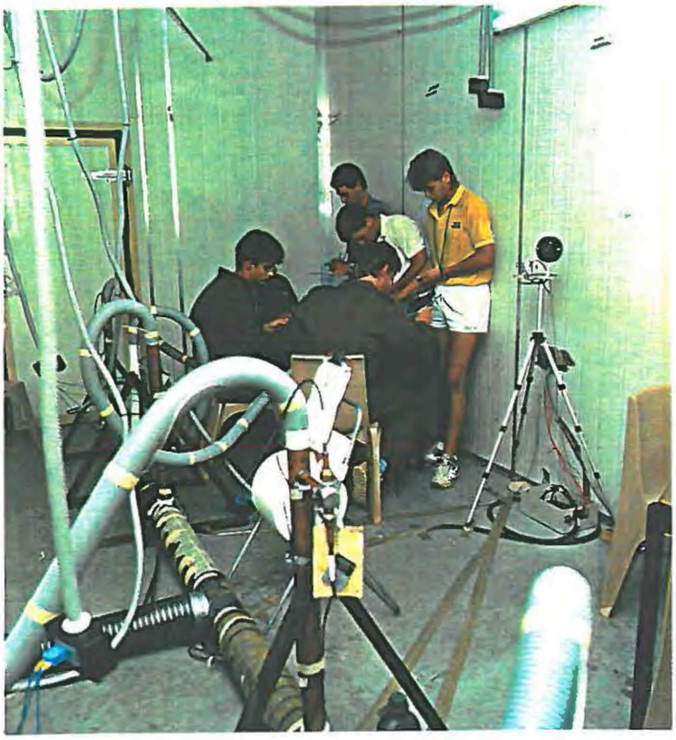
Microcooling System

The microcooling system used for this experiment was designed by Booyco Engineering (Pty.) Ltd. and consisted of a cooling unit and 8 microclimate jackets. The cooling unit was an R22 circuit with 10 kW cooling and 2.2 kW electrical heating capacity (see Figure 10). The air-flow capacity specifications of the cooling unit were as follows:

a)	Fresh-air flow	100 m^3/h	
b)	Recirculation airflow	1000 m^3/h	
c)	Total airflow	1100 m^3/h	
d)	Airflow per jacket	137.5 m^3/h	2000 ℓ/min

The 8 microcooling jackets were of the Mikroklim-type developed jointly by Booyco Engineering and the CSIR, Pretoria (see Figure 11). They were based on a Bunny-type jacket and consisted of a non-permeable outside layer, spacer tube panels (200 mm wide x 250 mm high, 10 mm diameter) and a permeable inside layer. Cool air was supplied to each jacket by means of an umbilical cord via a quick-release coupling. The jackets were worn over a cotton T-shirt and fastened by means of velcro tape on the right shoulder and hip of the subject.

(a)



(b)

Figure 10 : Microcooling System (a) external (b) internal

Instrumentation

Physiological temperature data were acquired by means of a dedicated data acquisition system consisting of a Hewlett Packard 86B desk computer and two (2) Hewlett Packard 3421A data acquisition control units with microvolt resolution transmitted to the computer. Conversion from microvolt to degrees celsius (°C) was performed by the computer and all data were stored on 360 kb disks. Each data acquisition control unit had a storage capacity of 30 channels and measurements were made at a rate of two channels per second.

The software package was developed from HP Basic and dedicated for its specific application; scanning took place at 5-minute intervals (see Figure 12). Temperature sensors were Type-T thermocouples (individual ice-referenced) with a resolution of 0.1°C.

Cardiac frequencies were measured by means of Polar Electro telemetry monitors allocated to each subject. The measurement of heart rate was monitored throughout each 4-hour schedule for each subject and the data were recorded for each condition. The sweat rate of each subject was determined by means of naked body mass measured before and after each schedule, considering the volume-monitored intake of water and of urine passed during each 4-hour schedule.

Figure 11 : Mikroklim-type microcooling jacket

Figure 12 : Data Acquisition System

The ambient temperature in the climate chamber was stabilised by the central controlling mechanism with its sensors situated in the centre of the chamber. The wet- and drybulb temperature, relative humidity and vapour pressure were constantly measured by means of an ECO CR10 Data Logger and sensors placed in the centre of the climate chamber. A Fluke 2286A Data Logger with Type-K thermocouples was used to verify the inlet temperature of each microcooling jacket at 18°C - 21°C during the microcooling condition. Four additional drybulb temperature sensors were placed next to subjects at sitting height to verify that the set environmental temperature of 40°C; 40% RH was maintained. This was done to ensure that the environmental temperature did not change due to additional volumes of cold air induced by the microcooling system.

Environmental Conditions

The study was conducted under predetermined environmental conditions. The baseline environmental condition was at a drybulb temperature of 40°C (± 1°C) at a relative humidity of 40% (± 5%). The same ambient temperature conditions pertained in the microcooling condition with the microcooling system inlet temperature controlled at 18°C - 21°C. The macrocooled environment was at a drybulb temperature of 21°C (± 1°C) with a relative humidity of 60% (± 5%). An atmospheric pressure of ≈ 842 hPa was maintained for the duration of the experiment. The lighting levels in the climate chamber were maintained at 250 lux and the monitored background noise did not exceed 80 dBA at any stage during the experiment.

Clothing and Personal Equipment of Subjects

All subjects wore the same clothing for the duration of the experiment. This consisted of a brown long-sleeved overall (boiler suit), underpants, woollen socks and running shoes. The top button of the overall was always open and the sleeves always buttoned at the wrists. Each subject was allowed to wear his own underpants, ankle length woollen socks and running shoes. Subjects were instructed not to alter their clothing configuration for the duration of the study. Each subject was supplied with his own 1-litre water bottle (see Figure 13).

Performance Tasks

Environmental stressors such as noise, vibration, gases and thermal extremes influence human performance to a great extent (Turnage et al. 1992). The main objective of this study was to quantitatively determine the difference between macro- and microcooling systems on human operator performance. The performance tasks chosen for this study were similar to those employed by other researchers for evaluating human performance in stressful environments. A critical requirement for repeated-measure of tests used in repeated-measure applications (as in the case of this study) is that alternative forms of the tests should be parallel. The requirement of parallel forms is necessary for

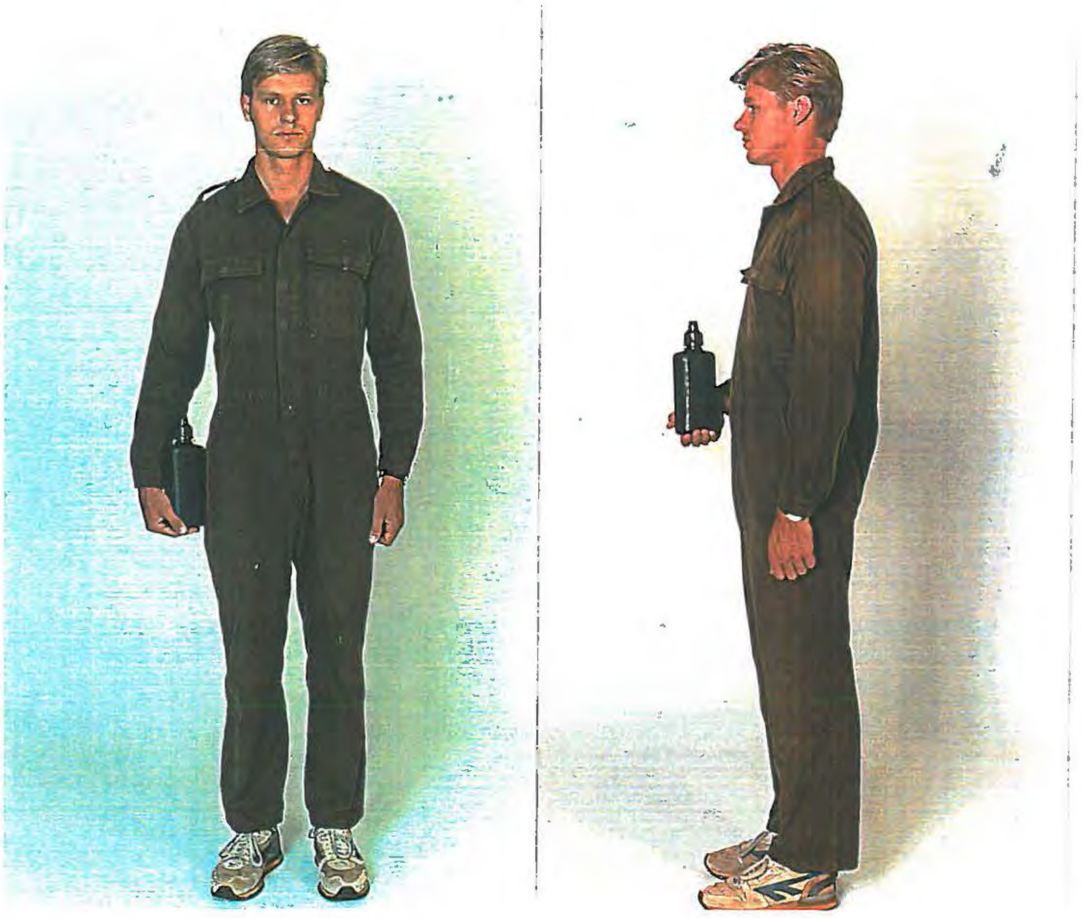


Figure 13 : Clothing worn by all subjects

proper interpretation of any change (loss or gain) in the performance parameter being measured due to the stressful environment. Turnage et al. (1992) listed the following criteria that repeated-measure testing should comply with:

a) Stability - Repeated-measures studies of environmental influences on performance require stable measures if changes in the environment are to be related meaningfully to changes in performance (Jones, 1970).

b) Reliability - The correlation between the test scores of the same test under the same conditions at two or more different points in time must be high.

c) Reliability efficiency - Facilitates judgements concerning different tests and provides an objective means for comparing the sensitivity of two separate tests.

d) Stabilization time - Good performance measures should quickly stabilize following short periods of practice without sacrificing metric qualities.

e) Task ceiling - The best tests to perform are those which stabilize early and in which no subjects will reach the maximum level of performance.

f) Validity - Performance tests should be sensitive to environmental stressors and should test the mental function(s) which they were designed for.

When the effects of environmental stressors on human performance are measured, it is desirable to sample a wide range of tasks in a very limited span time. A battery of performance tests which are not only short and quick to administer, but also valid, reliable and sensitive to the objective, is therefore necessary (Baddeley, 1968).

The performance tests identified for this study are described below and references to their previous uses are cited where appropriate. Four tests were used to measure the subjects' eye-hand coordination, reaction time, memory, attention and reasoning ability respectively. The time limit for each test was 10 min and each test was repeated four times during the 4-hour cycle. All the tasks were required to be performed as quickly and as accurately as possible. The sequence of the tests was the same for each of the four repetitions per schedule, as well as for each different temperature condition, in order to compensate for possible fatigue or arousal effect.

Grammatical Reasoning Test

This test was developed by Baddeley (1968) to determine the fall in intellectual capacity due to exposure to environmental stressors. The subjects are given a number of short sentences, each followed by a pair of letters (AB or BA). The sentences claim to describe the order of two letters.

The description can be done in several different ways, namely (1) positive or negative, (2) active or passive, (3) true or false, (4) precedes or follows, (5) A or B mentioned first. The subjects were instructed to read each sentence and decide whether it was a true or false description of the letter pair following it. If the sentence described the letter pair correctly, the subject had to make a tick in the "true" column and if the sentence described the letter pair incorrectly, the subject had to make a tick in the "false" column.

EXAMPLES		TRUE	FALSE
1.	A follows B - BA	✓	
2.	B precedes A - AB		✓
3.	A is followed by B - AB	✓	
4.	B is preceded by A - BA		✓
5.	B is not followed by A -		✓
	BA	✓	
6.	A does not precede B - BA		

Subjects had to start with the first sentence and work systematically through the test without skipping a sentence. The duration of the test was three minutes and subjects had to complete as many items as possible. If a subject finished all the sentences before the set three minutes his time was recorded.

Scoring was done by calculating an index as follows:

$$\text{Reasoning index} = \frac{\text{Total Responses}}{\text{Time Taken}} \times \text{Correct Responses}$$

The task proved easy to administer and could be used for various populations. Baddeley (1968) stated that the assumption that this task measured higher mental processes was supported by its correlation with intelligence test scores conducted by the British Army ($p < 0.002$). This test has been successfully used in other studies where the effect of environmental stressors on human performance was measured (Baddeley and Flemming, 1967;

Carter, 1979). Carter et al. (1981) evaluated this test in a repeated-measures paradigm and concluded that the grammatical reasoning test was an excellent performance test for repeated measurement and that the stable intentional correlations indicated that the test measured the same aspect on each of many repeated trials.

Three-dimensional Gross and Fine Motor Coordination Test

This test was developed by Wade et al. (1991) for use in the climate laboratory at Lifestyle Management (Pty.) Ltd. for various laboratory studies (see Figure 14).

The test apparatus consists of an electronic counter attached to a 70 cm long electrical conducting wire of which 10 cm is insulated at each end. A hand-held probe is also attached to the counter and the wire passes through the other end. The wire is bent in various directions and angles. The shape of the wire is such that tracking it involves motion in three-dimensional space. The individual is required to move the probe across the length of the wire without touching it. The following behavioural skills are evaluated by this test:

a) Gross motor coordination (arm movement).
b) Fine motor coordination (hand and finger movement).
c) Spatial orientation.
d) Concentration.
e) Hand and arm steadiness.

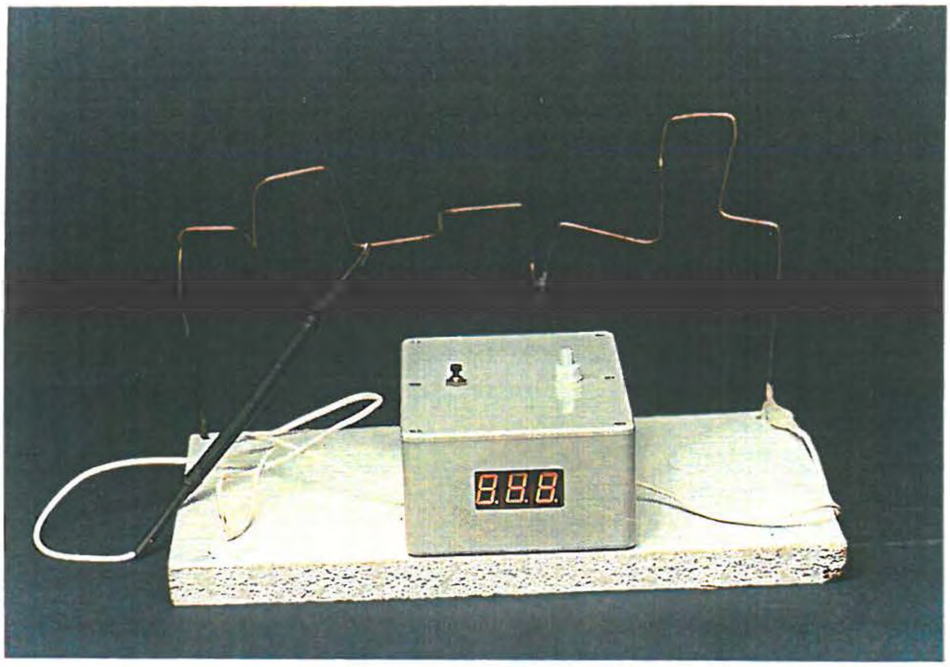


Figure 14 : Eye-hand coordination test instrument

The scoring method of the task is as follows:
Each time the wire is touched by the probe the electronic counter records it. The task is also timed, hence two performance measures are taken, namely of time and error. A performance index can also be calculated by the ratio of errors made to time taken. The task was repeated 6 times during each schedule, twice with each of the three differently-shaped wire configurations.

Scoring was done by calculating an index as follows:

$$\text{Eye-hand Index} = \frac{\text{Sum of errors}}{\text{Sum of time}}$$

This test was previously applied by Wade et al. (1991) to test differences between clothing ensembles (partial vs total encapsulation) under various thermal environments. The results showed that the test was sensitive to temperature (time) and clothing (errors).

Memory/Attention Task

This performance task was adapted from the Wechsler-Belevue Adult Intelligence Scale, Subtest number 4. A seven-digit number (randomly selected) was flashed on a microcomputer monitor for a period of five seconds.

Subjects were required to write down the seven digits in the same order within 25 s on an answering sheet provided, whereafter the second seven-digit number was flashed. This activity continued until a total number of 10 seven-digit numbers had been shown (see Figure 15).

The total number of digits recorded correctly for each of the 10 seven-digit numbers flashed was used as the subject's score. The following example illustrates the method of scoring:

NUMBER FLASHED	SUBJECT'S RESPONSE	SCORE
1. 6342157	6342157	7
2. 3426618	3426816	4
3. 1427896	1496782	2

Figure 15 : Memory/attention test

Simplified Choice Serial Reaction Task

The apparatus used by Wyon et al. (1980), was modified for this test. The apparatus consisted of 5 small red light-emitting diodes, arranged in a pentagon, spaced 15 mm apart and mounted on a 60° inclined aluminium faceplate. Five round plastic-coated pushbuttons with a 15mm diameter were arranged in a pentagon, spaced 15 mm apart and mounted horizontally at the bottom of the 5 led's (see Figure 16).

Figure 16 : Simplified choice reaction test

The subjects had to respond to whichever of the five led's was on by pushing the corresponding button with a finger of the preferred hand. The pushing of any button immediately extinguished the light and any one of the other four led's came on at random. The time elapsing between the activating of the led's was not set, but during each test cycle of 8 min the led's would come on 80 times at random. Every time a button was pressed, the following information was stored on the hard disc of a 386 microcomputer in the control room:

a) Reaction time (RT) to 0.1 ms accuracy.
b) Response time (RST) to 0.1 ms accuracy.
c) Correct response.
d) Incorrect response.

Wyon et al. (1980) noted that this performance task was used in various previous studies to measure the effects of several environmental stressors such as heat and noise on perseverance and concentration of the human operator.

Physiological Measurements

Several physiological parameters, namely rectal and skin temperature, heart rate, sweat rate and total sweat loss were measured as follows :

a) Rectal temperature

Rectal temperature was measured at 5-minute intervals by means of an indwelling sensor (resolution of 0.1°C), developed by the Institute of Environmental Physiology (IEP - Lifestyle Management), inserted to a depth of 8 - 9 cm beyond the anal sphincter. Depth of placement was maintained by the inflation with 5 mℓ of water of a section of the probe just above the sphincter (see Figure 17).

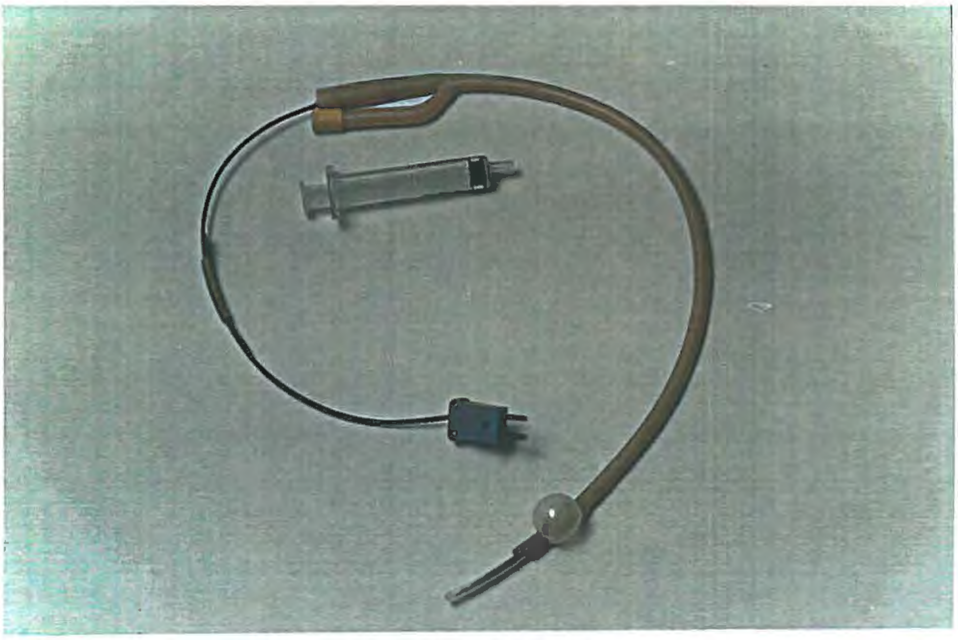


Figure 17 : Rectal temperature sensor

b) Skin temperature

Skin temperature was measured using naked T-type thermocouple junctions (resolution of 0.1°C) placed on the skin at the following sites: chest, back and thigh (Figure 18). Junctions were held in position by means of elastic bands, ensuring pressure on the skin with the least possible occlusion of skin bloodflow. The thermocouple junctions were well-insulated to prevent the cool air of the microcooling system from influencing skin temperature readings. Due to limitations in the number of temperature channels available for logging, the chest and back sensors were averaged to provide a single (equally weighted) reading for each individual. This average torso value was then combined with the average thigh value to provide the mean skin temperature.

Figure 18 : Skin temperature sensors

c) Heart rate

Heart rate was recorded using Polar Vantage XL heart-rate monitors (Polar Electro). Each subject wore a harness around the chest consisting of two 'dry' electrodes from which a miniature transmitter transferred a continuous heart rate, based on an ECG derivative to a receiver worn as a wristwatch on the subjects' arm. The receiver displayed the heart rate continuously and logged the data at preset intervals of 15 s to 1 min. For the purpose of data analysis one 5-minute mean heart rate was used (see Figure 19).

Figure 19 : Heart rate monitor (Polar Electro)

d) Total sweat loss and sweat rate

Total sweat loss and sweat rate for each subject were calculated from nude body mass measured to a resolution of 0.02 kg, before and after each exposure, taking into account any water ingested and urine voided.

Safety precautions

To ensure the safety of the subjects with regard to heat stress and/or injuries during the experiment, the following safety precautions were taken:

a) All subjects were acclimatized before the commencement of the experiment.

b) A qualified medical practitioner was physically present at the laboratory for the duration of the experiment.

c) Cold drinking-water was freely available.

d) The following criteria were applied as signals for withdrawal of subjects from exposure:

  - Rectal temperature > 39.5°C.
  - Sustained heart rate > 180 beats/min for a period of 30 min with significant subjective discomfort.
  - The presence of any symptoms of heat illness.

e) The monitoring of rectal probes was done by means of a battery-driven data acquisition system to eliminate the possibility of electrical shock.

User Perception Questionnaire

In addition to the physiological and psychological measurements taken, each subject's assessment of the two different cooling methods was recorded by means of a user perception questionnaire. The questionnaire was developed especially for this study. The aim of the instrument was to obtain subjective information on the characteristics of the two cooling methods used in the study. The following rating scale was used:

+5 Highly acceptable	-5 Highly unacceptable
+3 Acceptable	-3 Unacceptable
+1 Barely acceptable	-1 Barely unacceptable

The subjects were instructed to mark their responses with a circle around the appropriate value and, if a negative value was chosen, to explain their choice.

The questionnaire was administered after the subjects had been exposed to both types of cooling methods (see Appendix C). The perceptual parameters addressed in the questionnaire considered temperature, airflow, general ergonomics and user attitudes (10-point scale), as follows:

- Angry (0) vs Happy (10) (A)
- Uncomfortable (0) vs Comfortable (10) (B)
- Unfriendly (0) vs Friendly (10) (C)
- Bad (0) vs Good (10) (D)
- Unhealthy (0) vs Healthy (10) (E)
- Stressful (0) vs Non-stressful (10) (F)
- Dislike (0) vs Like (10) (G)

(See appendix C)

The questionnaire was scored by calculating the mean values of all the subjects' responses. These mean values were interpreted and shown in graphical form in Chapter 4.

3.4 Statistical Analysis

The experiment involved the study of two main effects: Environmental conditions (3 levels) and a rest vs work (40 W) condition (2 levels). Several measurements over time were taken on the same subject which represents repeated measurements and allows the researcher to study the effect of time under the experimental conditions. The physiological response variables (resulting in 5 analyses) were:

- Rectal temperature
- Skin temperature
- Heart rate
- Sweat rate (without a time effect)
- Sweat loss (without a time effect)

The psychological response variables (resulting in 5 analyses) were:

- Memory/attention score
- Eye-hand coordination index
- Reasoning index
- Average reaction time
- Average response time

The stated hypotheses (paragraph 1.3 refers) were evaluated using a multivariate analysis of variance procedure based on repeated measurements. In these analyses the effects of interest are:

- Between-subject effects (physiological and psychological response variables)
- Within-subject effect (time)
- Interactions between the two effects (such as environmental conditions *time)

Repeated measures analyses are distinguished from other multivariate analyses because of interest in testing hypotheses about the within-subject effect and the within-subject-by-between-subject interactions, which were of particular interest in this study. The results will be discussed in detail in the following paragraphs.

The multivariate test applied (to test for differences in means for the between-subject effect) was Duncan's Multiple-range test.

These results were compared with repeated t-tests, which were also computed in the case of unequal sample sizes. If differences occurred between the results of the two tests, the results obtained by the individual t-test were reported. This was done because repeated t-tests are easier to compute, easier to explain and specifically applicable to unequal sample sizes. (In some cases an unbalanced design occurred because of instrument failure.)

In order to test the significance of differences the 0.05 level of significance was employed throughout the statistical treatment of the data. It was felt that this was a reasonable and acceptable level of risk attached to any decisions taken regarding the hypothesis.

The output of each analysis is presented in two anovas. These anovas are discussed in different paragraphs. The reason for this approach is twofold:

- To examine the different hypotheses separately.
- To simplify the presentation of the results because two different error terms are used in the analysis of the hypotheses: One error term is used to evaluate the main effects, which is based on between-subjects differences (and which is functionally equivalent to the error term used in the analysis of a completely randomised factorial experiment). The second error term is used to evaluate differences based on repeated measures and this mean square

is usually considerably smaller than the between-subjects error term, accounting for the increased sensitivity associated with this type of experimental design (SAS/STAT User's Guide, 1990).

CHAPTER FOUR : RESULTS AND DISCUSSION

The primary aim of this study was to determine the effect of a micro- vs a macrocooling system on the physiological and psychological responses of the heat-exposed human operator. It is important for the reader to bear in mind that both cooling systems used were representative of optimal cooling systems in each category. It is furthermore important to note that the microcooling system used in the study was representative of an air-cooled system and that the results therefore are applicable only to such a system and may differ from results obtained when another type of microcooling system is used. The results discussed here are therefore applicable only to the microcooling system specified in Chapter 3.

4.1 Physiological Responses

Regarding the results of the physiological measurements it should be noted that, owing to various practical limitations such as breakage, irritation caused by sensors to parts of the subjects' anatomy and interference with readings on heart-rate monitors, some of the data could not be used for statistical analysis during different cycles.

4.1.1 Environmental Conditions: Baseline (40°C; 40% RH) vs Microcooling vs Macrocooling

The practical question regarding these results is the following:

> "After having been subjected to the three environmental conditions, are there significant differences between the physiological responses measured in these environmental conditions?"

A summary providing means and standard deviations of the respective physiological parameters for each of the environmental conditions is provided in Table XII. The means are also illustrated graphically in Figure 20.

Table XII : Summary of results of physiological responses to environmental conditions

ENVIRONMENTAL CONDITIONS	PHYSIOLOGICAL RESPONSES				
	RECTAL TEMP (°C)	SKIN TEMP (°C)	HEART RATE (BEATS/MIN)	SWEAT	
				SWEAT RATE (ℓ/h)	TOTAL SWEAT LOSS (ℓ)
Baseline	37.41 (0.39)	35.68 (0.58)	92.26 (20.34)	0.50 (0.21)	2.02 (0.85)
Microcooling	36.93 (0.46)	27.46 (2.14)	77.78 (17.22)	0.19 (0.11)	0.74 (0.44)
Macrocooling	36.83 (0.39)	32.33 (1.14)	79.95 (16.26)	0.12 (0.06)	0.48 (0.24)

Note: Standard deviations are provided in brackets.

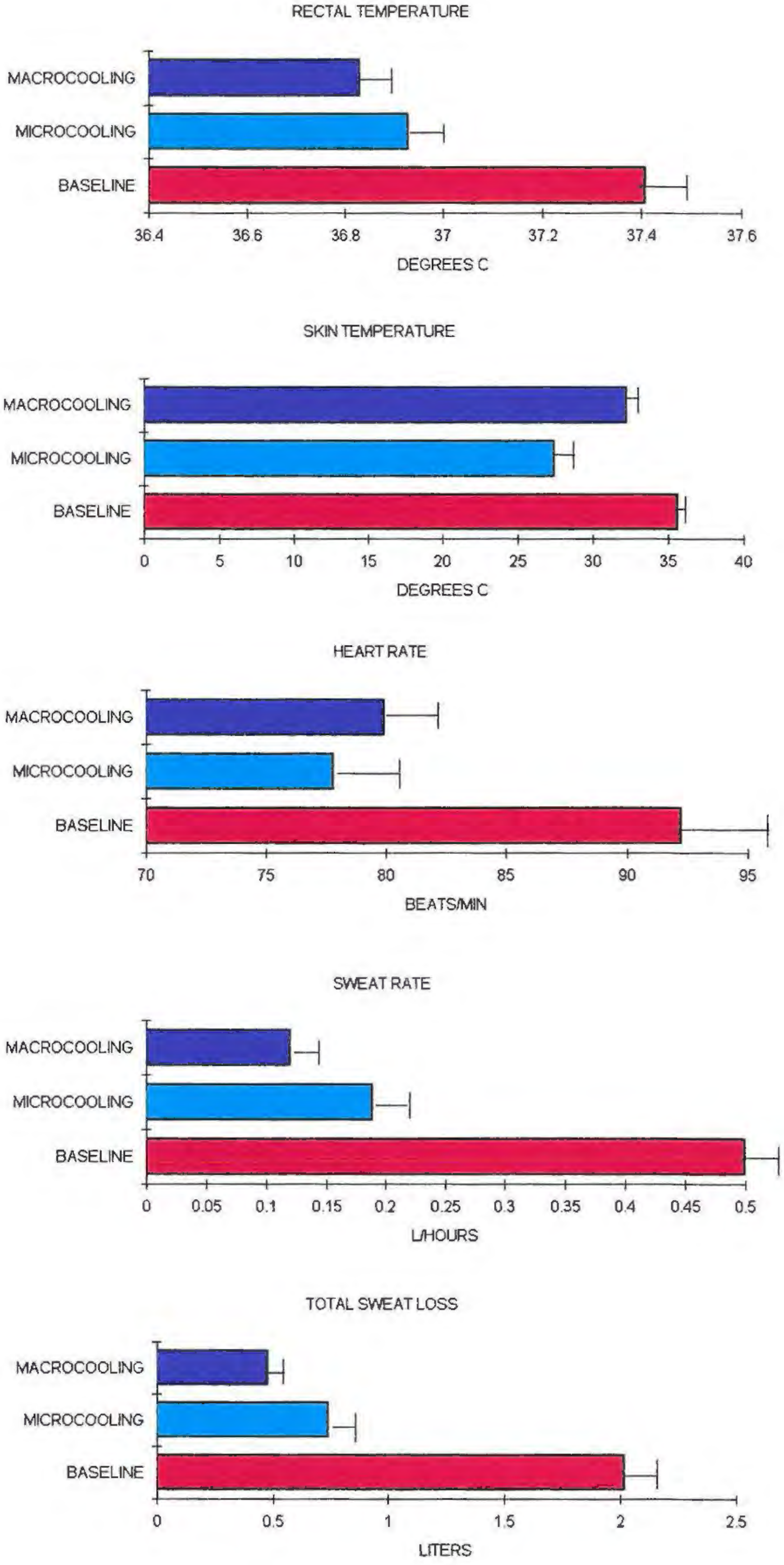


Figure 20: Results (mean values) of Physiological Responses Environmental Conditions

As can be seen from the results in Table XII the mean values that were measured between the physiological responses are different for each environmental condition. It was clear from the results that the baseline condition (40°C) resulted in the highest mean values for all physiological parameters. In order to identify whether there were significant differences between the physiological responses for the three environmental conditions these responses were individually evaluated using analysis of variance. A summary of the results is given in Tables XIII - XVI.

Rectal Temperature Responses

Table XIII : Repeated measures analysis of variance - Rectal temperature tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	180.75	2	90.38	53.96	0.0001
V_2: Rest vs Work	146.97	1	146.97	87.75	0.0001
Interaction					
$V_1{}^*V_2$	0.607	2	0.303	0.18	0.83
Residual	226.11	135	1.68		

Note: F-ratios are based on the residual mean square error.

The results of the analysis of variance (Table XIII) demonstrate a significant difference between the rectal temperature results of the three environmental conditions ($p < 0.05$). There were also significant differences between the rectal temperature results ($p < 0.05$) of the rest and work conditions, which will be discussed in detail in paragraph 4.1.2. However, no significant interaction between the two main effects was established. This means that differences between levels of environmental conditions can be indicated directly without reference to the specific levels of the rest vs the work condition.

The results regarding the deep-body or rectal temperatures confirmed results of various studies over the years. Nielsen (1938) showed that the rectal temperature in the steady state was independent of the environmental stress but that internal regulation failed if the environmental conditions were severe. Konz (1979) stated that at lower environmental temperatures the body remained in thermal equilibrium and that the point at which rectal temperatures began to rise was a function of metabolic rate as well as the environment. McIntyre's (1980) opinion, namely that rectal temperature was influenced only by environmental temperatures of 30°C and higher, is supported by the findings in this study in that the mean rectal temperature in the baseline condition (40°C) differed significantly from the macrocooling conditions over the measured time interval. In view of the primary objective of this study, namely to evaluate an optimal microcooling vs an optimal macrocooling system, it was clear that the findings supported the fact that cooling in general was beneficial to a heat-exposed human operator. Kok et al. (1989) found in their laboratory experiments that rectal temperatures in the cooled state did not exceed 38°C and on average the microcooling condition resulted in a 0.6°C - 0.7°C reduction as compared to the non-cooled condition. Van Rensburg et al. (1972) found in their experiment, which involved two types of microcooling systems, those provided protection physiologically equivalent to removing the entire environmental heat stress even at wetbulb temperatures of 33.9°C. With reference to the above, the findings of the present study confirmed the fact that differences between the environmental conditions existed. However, it is important to note that it was also evident that the effect of time had a major impact on the results. This effect will be discussed in depth in paragraph 4.1.3.

Skin Temperature Responses

Table XIV : Repeated measures analysis of variance - Skin temperature tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects V_1: Environmental Conditions	29 545.75	2	14 772.88	482.29	0.0001
V_2: Rest vs Work	278.29	1	278.29	9.10	0.0031
Interactions V_1*V_2	118.19	2	59.10	1.93	0.1497
Residual	3 736.92	122	30.63		

Note: F-ratios are based on the residual mean square error.

The results of the analysis of variance (Table XIV) demonstrate a significant difference between the skin temperature results of the three environmental conditions ($p < 0.05$). There was also a significant difference between the skin temperature results ($p < 0.05$) of the rest and work conditions, which will be discussed in detail in paragraph 4.1.2. Again no significant interaction between the two main effects was established which means that differences between environmental conditions can be indicated directly without reference to the specific levels of the rest vs the work condition.

These findings were hardly surprising since microcooling was directed at the thorax area of the subjects with cool air (18°C - 21°C) being supplied at a rate of 1 500 ℓ/min. From a physiological point of view this indicated that microcooling, although only directed at approximately 30% of the body-surface area (thorax), resulted in a benefit that was equivalent to that obtained by means of an ideal working environment (macrocooling, 21°C).

Webb (1969) stated that a comfort level for mean skin temperature was in the range of 32°C - 34°C. At temperatures higher than this level sweating would occur and at temperatures lower than this level discomfort and shivering would occur. However, it is also important to note that when humans are not in a steady state and part of the heat stress is caused by internally generated metabolic rate, such as the workrate of 40 W as used in this project, the meaning of skin temperature changes. If cooling is applied by means of cold ambient air, micro- or macrocooling, the skin temperature should be lowered below the nominal comfort level in order to cool enough (Webb and Annis, 1967). The results of this study clearly demonstrated that the mean skin temperature during the macrocooling condition corresponded with Webb's (1969) comfort level. It also confirmed the fact that with the use of an air microcooling system a lower skin temperature is necessary to ensure the same comfort level, especially when exercising. Kok et al. (1989) found that the wearing of a microcooling system brought about a 6°C - 7°C reduction in skin temperature, which is also strongly supported by the findings of this study.

The statistical results regarding skin temperature as physiological response again showed that there were significant differences between the environmental conditions. Yet, the effect of rest vs work and time, as in the case of rectal temperatures, has a definite effect on the interpretation of the results and will be discussed further in paragraphs 4.1.2 and 4.1.3.

Heart Rate Responses

Table XV : Repeated measures analysis of variance - Heart rate tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	98 727.42	2	49 363.71	17.90	0.0001
V_2: Rest vs Work	169 534.85	1	169 534.85	61.46	0.0001
Interactions					
V_1*V_2	12 314.50	2	6 157.25	2.23	0.1122
Residual	297 916.26	108	2 758.48		

Note: F-ratios are based on the residual mean square error.

The results of the analysis of variance (Table XV) demonstrate a significant difference between the heart rate results of the three environmental conditions ($p < 0.05$). There was also a significant difference between the heart rate results ($p < 0.05$) of the rest and work conditions, which will be discussed in detail in paragraph 4.1.2. No significant interaction between the two main effects was established, which enhances the validity of the analysis of variance process.

The mean heart rate results of the different environmental conditions indicated that a significant difference existed only between the baseline condition and the two cooling conditions, and not between the micro- and macrocooling conditions. Heart rate as an indication of heat stress is found in many studies (Brouha, 1960; Lienhard et al., 1964; Webb, 1969). According to Webb (1969) heart rate may be the most meaningful single measurement to take in order to evaluate physiological effects of heat stress. This statement may be valid in the real working environment or other practical applications, but not for experimental situations like the present study. This can be attributed to the fact that subjects are placed in an artificial and unfamiliar situation that may cause stress in many other ways, all of which may influence heart rates (Parsons, 1993). Meese (1988) stated that heart rate was primarily a response to workload, but that high thermal environments could place greater strain on the heart. This conclusion of Meese (1988) was supported in both instances by the findings of the present study. Kok et al. (1982) found in their study on the effect of heat stress on the potential work performance of industrial workers an increase of about 15 beats/min between temperatures of 20°C and 38°C for white males. This compares favourably to the findings of this study of an increase of 12 beats/min between temperatures of 21°C (macrocooling) and 40°C (baseline environment). Owing to the fact that metabolic rate or workload and exposure time play such an important role in heart rate, this matter will be discussed in more detail in paragraphs 4.1.2 and 4.1.3.

Sweat Rate and Total Sweat Loss

The results for the physiological responses of sweat rate and total sweat loss demonstrated significant differences for the results of the three environmental conditions, as well as for the rest and work conditions ($p < 0.05$). Furthermore, a significant interaction existed between the two main effects ($V_1{}^*V_2$: $p < 0.05$). Owing to this interaction the significant differences found between the environmental conditions can only be interpreted at the specific levels of the rest and work conditions. The detailed results will be discussed in paragraph 4.1.2

4.1.2 Rest and Work Conditions

The practical question regarding these results is the following:

> "After having been subjected to two different conditions in metabolic workrate, namely rest vs work (40 W) under similar ambient thermal conditions, are there significant differences between the physiological responses measured in these two work conditions?"

A summary providing the means and standard deviations of the respective physiological parameters for each of the two work conditions is provided in Table XVI. The means are also illustrated graphically in Figure 21.

Table XVI : Summary of results of physiological responses: rest and work conditions

Physiological Responses Work Condition	Rectal Temperature (°C)	Skin Temperature (°C)	Heart Rate (HR) (beats/min)	Sweat Rate (SR) (ℓ/h)	Total Sweat Loss (TSL) (ℓ)
Rest	36.83 (0.45)	31.97 (3.35)	75.13 (14.33)	0.19 (0.14)	0.76 (0.56)
Work (40 W)	37.28 (0.41)	31.43 (3.85)	91.49 (19.67)	0.35 (0.25)	1.40 (1.02)

Note: Standard deviations are provided in brackets.

As can be seen from the results in Table XVI there were differences between the physiological responses measured for the different working conditions (rest vs work). In order to determine whether these differences between the physiological responses were significant, each physiological response was individually evaluated, using analysis of variance. A summary of the results is given in Tables XIII to XVI (V_2: rest vs work - main effect).

Rectal Temperature Responses

The results of the analysis of variance (Table XIII) demonstrate a significant difference between the rectal temperature results

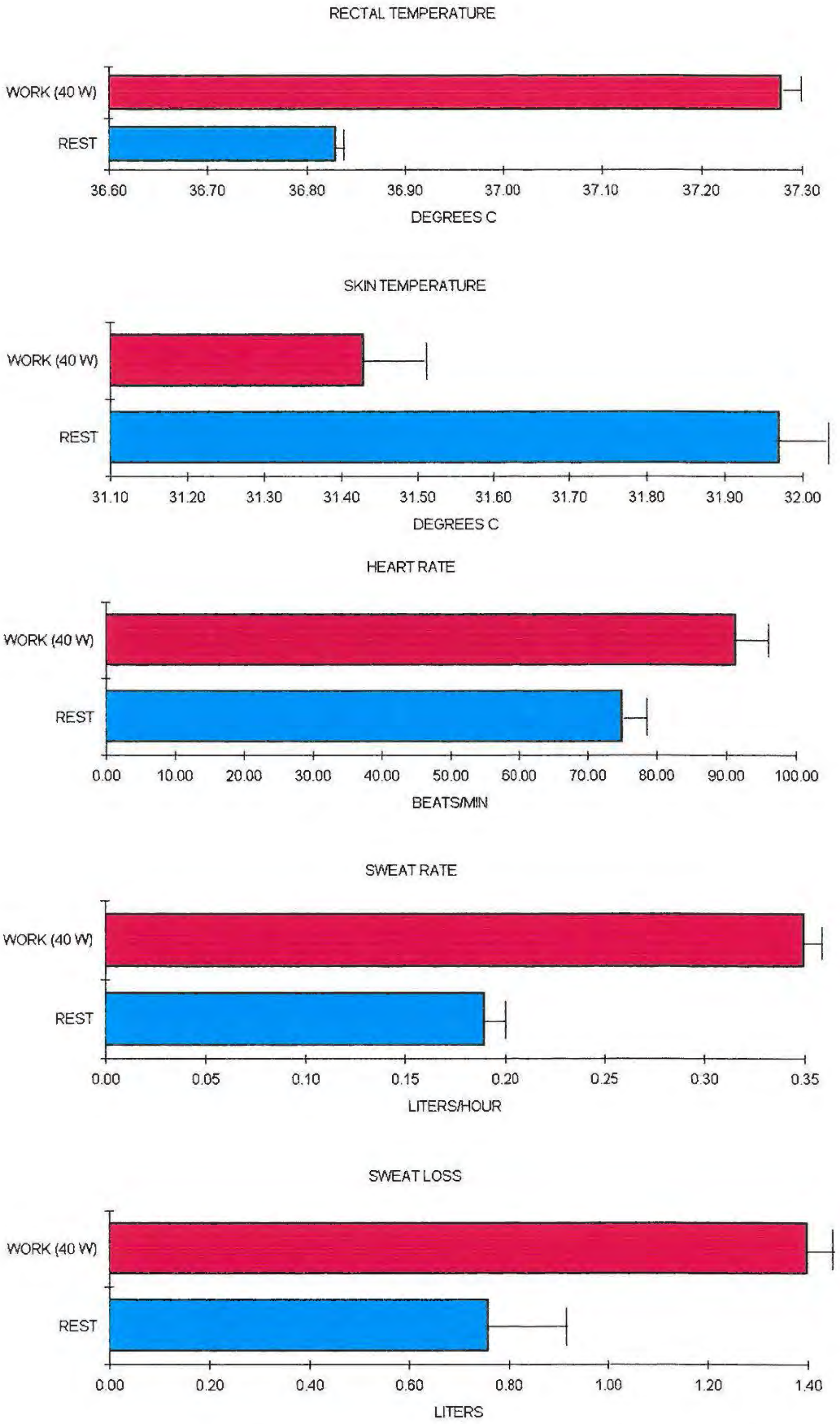


Figure 21: Results (mean values) of Physiological Responses
Rest vs Work

for the two conditions, viz rest and work ($p < 0.05$). The above findings support the findings in numerous other studies. Lind (1963) showed that the point at which rectal temperature began to rise was a function of metabolic rate and at this higher metabolic rate rectal temperature would easily reach 38°C. Meese (1988) concluded that the sensitivity of the core temperature to the workrate emphasized the interaction between the various factors which were involved in thermal control. It is therefore clear that, as in the study conducted by Kok et al. (1989), rectal temperatures decreased, but still remained between the narrow limits of 36.1 - 37.2°C throughout the exposure when the two cooling methods were used during the work (40 W) condition. McIntyre (1980) had observed that during exercise the core temperature would rise and the skin would normally sweat to maintain equilibrium. This study confirmed this observation and showed that although the mean rectal temperature rose in all three environmental conditions, from the steady state to the work (40 W) condition, the effect of both cooling methods was to reduce the rectal temperature rise rates. The effect of rest vs work over time will be discussed further in paragraph 4.1.3.

Skin Temperature Responses

The results in Table XIV (V_2: rest vs work - main effect) demonstrate a significant difference between skin temperatures for the rest and work conditions ($p < 0.05$). These findings confirm results in earlier studies, as summarized by Kerslake

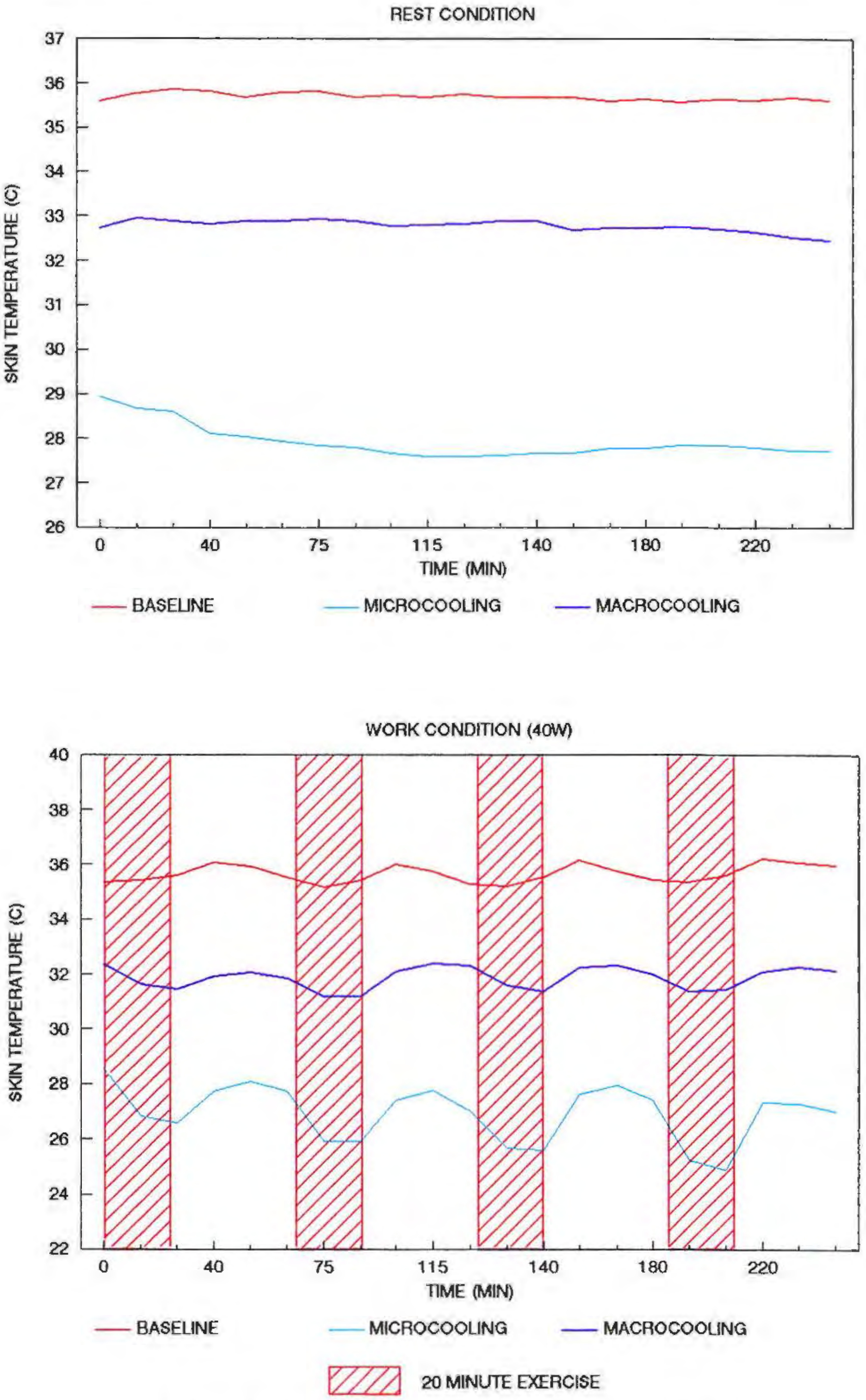


Figure 22 : Mean skin temperature over time

(1972), that mean skin temperature is independent of the workrate but depends on the environment. Figure 22 illustrates the mean skin temperatures for the three environmental conditions for both the rest and work (40 W) conditions. The difference in mean skin temperatures for the rest and work conditions are demonstrated in Figure 23.

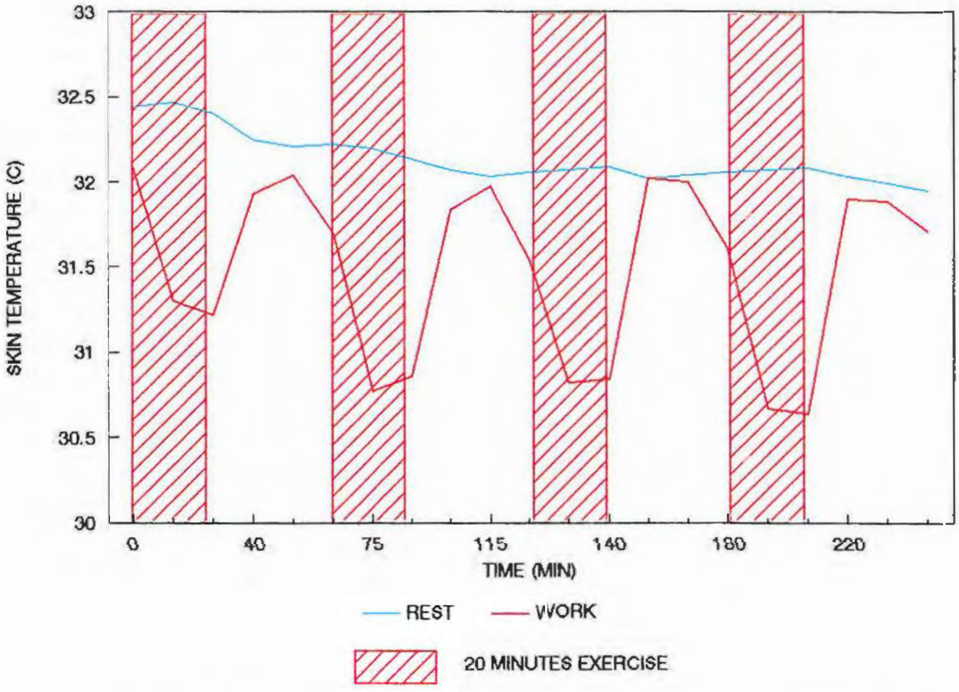


Figure 23 : Mean skin temperature : Rest vs work conditions

Kerslake (1972) reported on experiments where subjects rode a bicycle mounted on a treadmill where it was found that skin temperature degraded by 1°C for each 100 W/m^2 increase in heat production. In the present study it was clear that during each of the 20 min moderate work (40 W) periods the mean skin temperatures dropped on average 0.9°C, which confirms the above findings by Kerslake (1972).

An interesting observation was, however, that the mean skin temperature during the baseline condition showed a slight rise during the 20 min work period. This tendency confirmed the report by Kerslake (1972) that skin temperature in warm environments was more uniform and the effect of work rate on it was less marked. It was furthermore also noted that the skin temperatures, at the end of each 1-hour cycle, were very close to those values at the same time intervals for the rest condition. The effect of time will be discussed in further detail in paragraph 4.1.3.

Heart Rate Responses

As shown in Table XV a significant difference exists between the rest and work conditions for the physiological response of heart rate. Figure 24 shows the mean heart rate over time for these two conditions.

The mean heart rate over time for the rest condition stays fairly constant over the 4-hour time interval with a minimum of 73 and a maximum of 78 beats/min. As expected, for the work condition it was found that the heart rate increased every time during the 20-minute work period of each 1-hour cycle. On average the increase was 16 - 20 beats/min. These findings again support the accepted trend that an increase in heart rate is primarily a

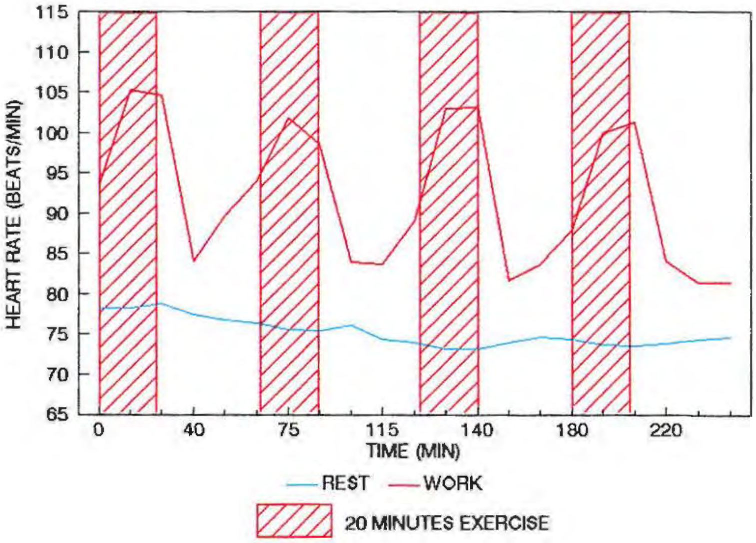


Figure 24 : Mean heart rate over time : Rest vs work conditions

response to workload. However, a combination of workload and heat stress will place a greater strain on the heart and will result in an increase in heart rate. Parsons (1993) noted that during exercise an initial sympathetic vasoconstriction occurs so that blood may flow to the active muscles. The central nervous blood volume decreases as the cutaneous vessels dilate, which causes the stroke volume to fall and the heart rate must increase to maintain cardiac output.

Sweat Rate and Total Sweat Loss

A summary of the results for sweat rate and total sweat loss as physiological responses is given in Tables XVII and XVIII. It is, however, important to note that after the data had been analysed, it was discovered that sweat rate and total sweat loss showed similar results and can therefore actually be regarded as being one and the same.

Table XVII : Repeated measures analysis of variance - Sweat rate tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	65.27	2	32.63	181.08	0.0001
V_2: Rest vs Work	14.69	1	14.69	81.50	0.0001
Interactions					
V_1*V_2	6.51	2	3.26	18.06	0.0001
Residual	24.87	138	0.18		

Note: F-ratios are based on the residual mean square error.

The results in Table XVII demonstrate a significant interaction between the two main effects (V_1*V_2). These results are shown in Figure 25. A significant difference was found for sweat rate between the three environmental conditions. The mean values for sweat rate were 0.505 ℓ/h, 0.187 ℓ/h and 0.12 ℓ/h for the baseline (40°C; 40% RH), microcooling and macrocooling conditions respectively (Figure 26). A significant difference also existed for sweat rate between the rest and work conditions. These results are shown in Figure 27. The mean values for sweat rate in this case were 0.35 ℓ/h and 0.19 ℓ/h for the rest and work (40 W) conditions respectively.

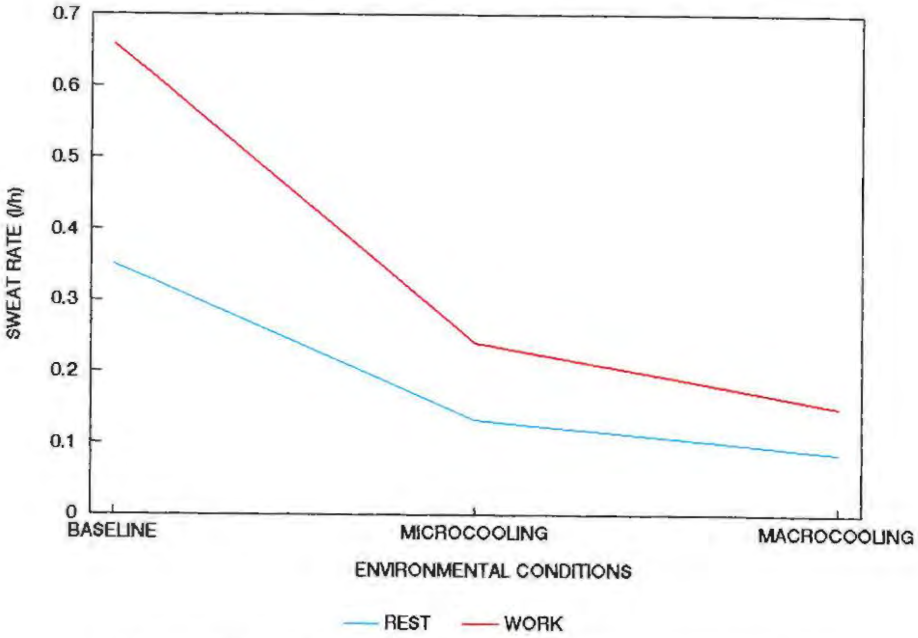


Figure 25 : Sweat rate interaction between main effects

Table XVIII : Repeated measures analysis of variance - Total sweat loss tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	4.08	2	2.04	181.08	0.0001
V_2: Rest vs Work	0.92	1	0.92	81.50	0.0001
Interactions					
V_1*V_2	0.41	2	0.20	18.06	0.0001
Residual	1.55	138	0.11		

Note: **F-ratios are based on the residual mean square error.**

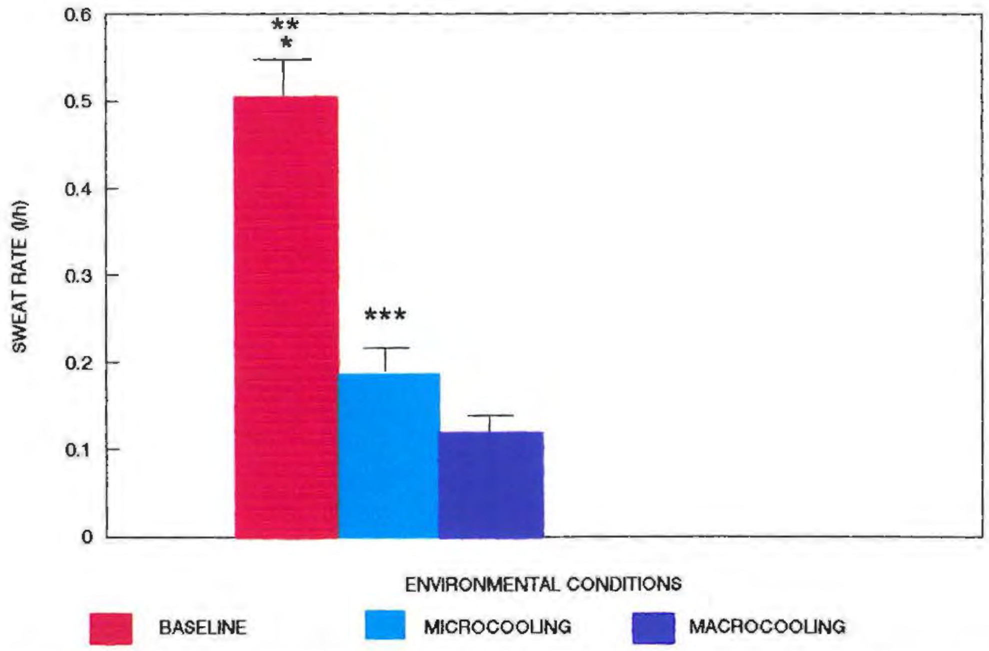


Figure 26 : Mean sweat rate : Difference between environmental conditions

* Represents significant differences between baseline and micro

** Represents significant differences between baseline and macro

*** Represents significant differences between micro and macro

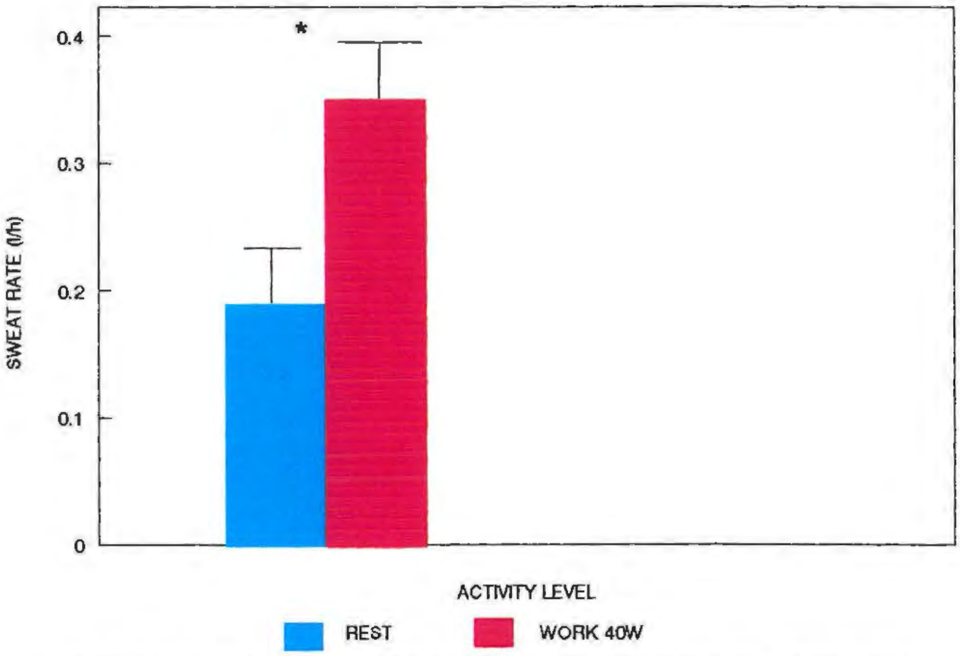


Figure 27 : Mean sweat rate : Difference between rest and work

* Represents significant differences between rest and work

The results in Table XVIII demonstrate a significant interaction between the two main effects ($V_1{}^*V_2$). This interaction is shown in Figure 28. A significant difference was found for total sweat loss between the three environmental conditions. The mean values for total sweat loss for the environmental conditions were 2.02 ℓ for the baseline condition (40°C; 40% RH), 0.75 ℓ for the microcooling condition and 0.48 ℓ for the macrocooling

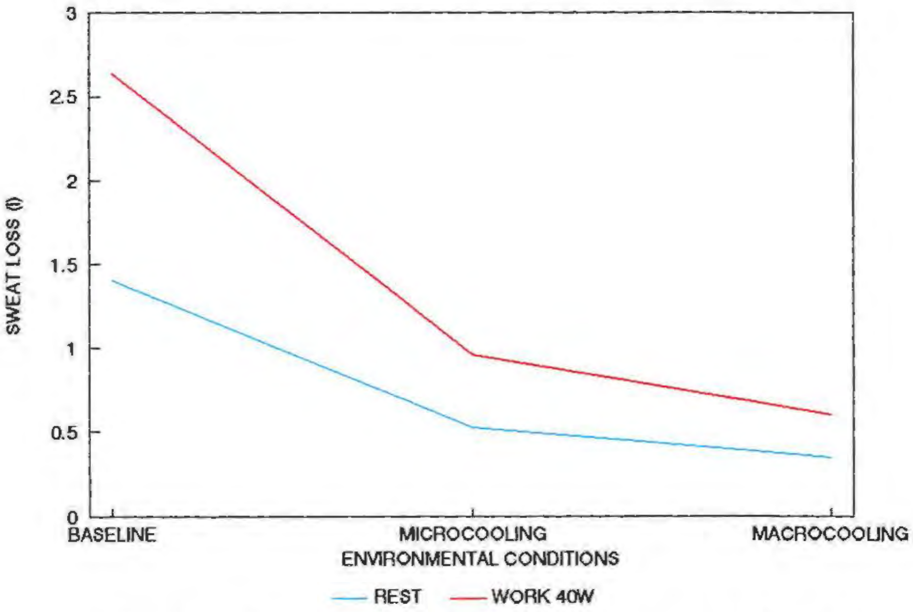


Figure 28 : Sweat loss interaction between main effects

condition. The results are shown in Figure 29. A significant difference also existed for total sweat loss between the rest and work conditions (Table XVIII). The mean values for total sweat loss were 1.40 ℓ for the rest condition and 0.76 ℓ for the work condition (Figure 30).

The Duncan's Multiple Range Test was used to determine whether all these differences were significant. It was found that for both sweat rate and total sweat loss responses a significant difference existed between the baseline condition and the two cooling conditions, as well as between the micro- and macrocooling conditions. It was furthermore found that for both sweat rate and total sweat loss a significant difference existed between the rest and work conditions. Pandolf et al. (1988) stated that for a given person the sweating rate was dependent on environmental conditions, clothing and the physical activity level. In the case of this study the clothing factor was kept constant, therefore a clear comparison could be drawn between the environmental conditions and rest vs work. Both the sweat rate and total sweat loss indicated that the greatest benefit was derived from the macrocooling condition. Chato and Hertig (1969) stated that the maximum loss of weight due to sweat loss and breathing should be 0.1 ℓ/h. This finding was confirmed by Trautman (1969) and Santamaria (1970). Weaver et al. (1982) suggested a sweat rate of 0.05 - 0.1 ℓ/h for thermal comfort. The results of this study confirmed the above findings where the mean sweat rate of 0.12 ℓ/h during the macrocooling condition produced a comfortable environment for the subjects. The higher

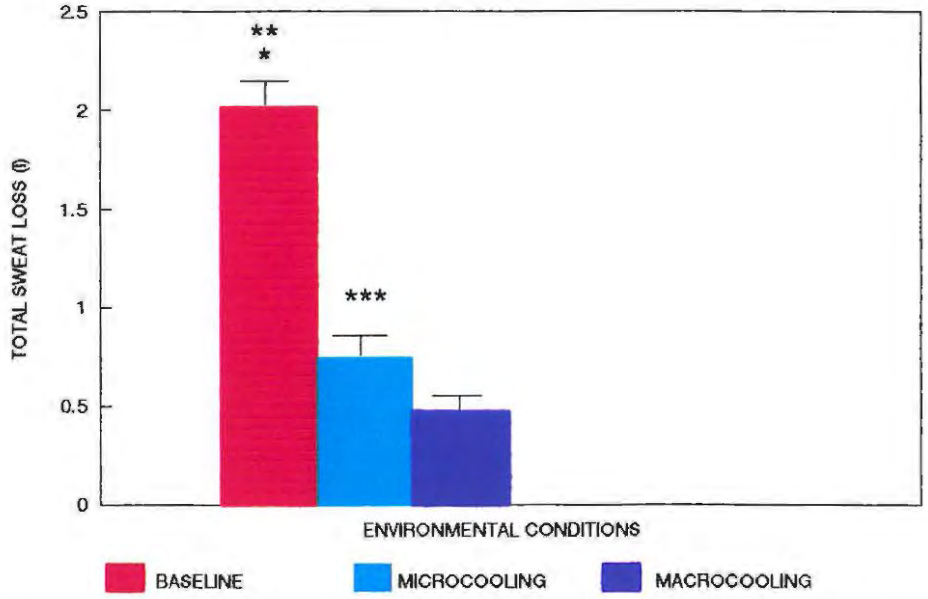


Figure 29 : Mean total sweat loss : Difference between environmental conditions

* Represents significant differences between baseline and micro
** Represents significant differences between baseline and macro
*** Represent significant differences between micro and macro

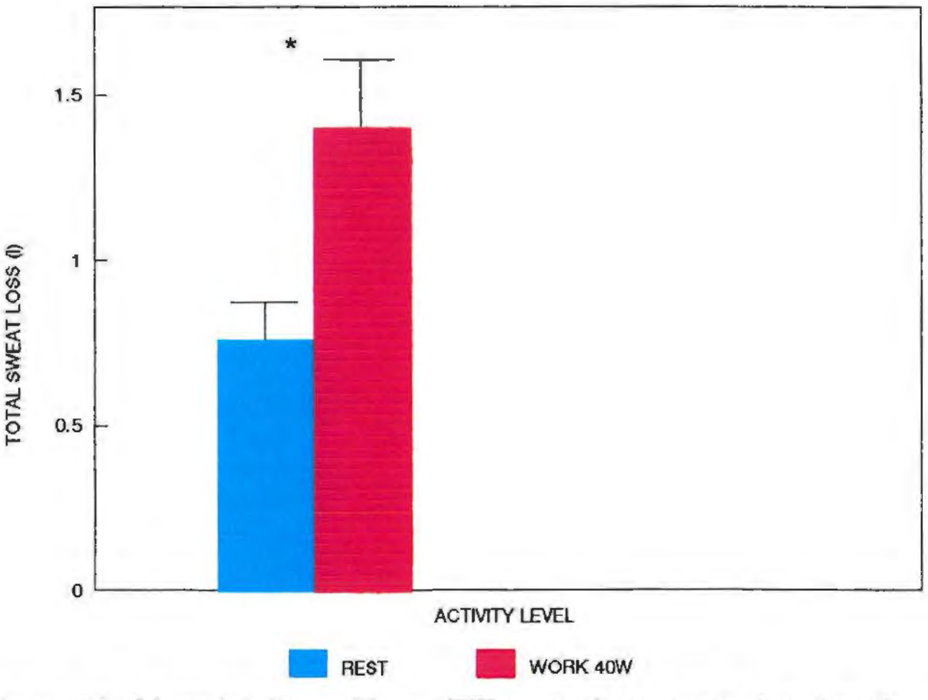


Figure 30 : Mean total sweat loss : Difference between rest and work

* Represents significant differences between rest and work

sweat rate and total sweat loss during the microcooling and baseline conditions, although not posing an extremely detrimental effect, would indeed enhance the discomfort of operators in hot environments.

Although some research has indicated that sweat rate can successfully be suppressed to below 0.1 ℓ/h at reasonable workrates by the use of a water-cooled suit (Webb and Annis, 1967), the results obtained with the microcooling used in this study (air cooling) showed a higher sweat rate (0.18 ℓ/h). It can therefore be concluded that different microcooling systems will affect the sweat rate and total sweat loss of humans differently.

4.1.3 The Effect of Time

The practical question regarding these results is the following:

> "After having been subjected to the three environmental conditions over a period of time (4 hours), are there significant differences between the physiological responses measured over the set time?"

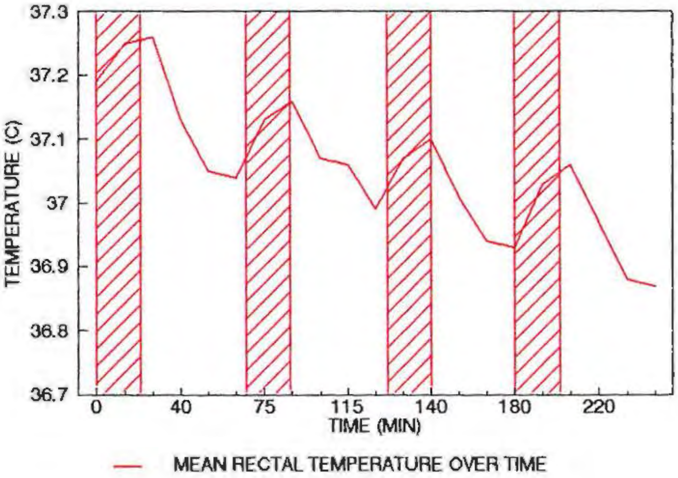
A summary providing the means and standard deviations of the respective physiological responses over time (T_0 - T_{240}) is provided in Table XIX. The means are also illustrated graphically in Figure 31.

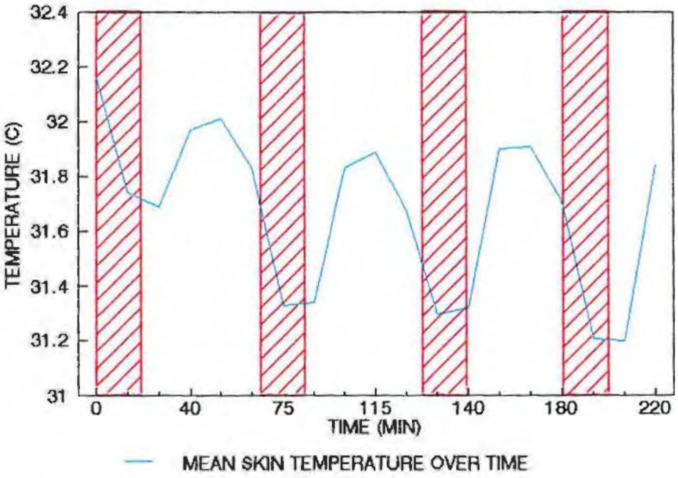
In order to identify whether there were significant differences between the physiological responses for the three environmental conditions over time, these responses were again individually evaluated using analysis of variance.

Table XIX : Summary of results of physiological responses - Time effect

Physiological Responses Time	Rectal Temperature (°C)	Skin Temperature (°C)	Heart Rate (HR) (beats/min)
Time interval			
T_0	37.19 (0.33)	32.16 (3.04)	85.62 (13.90)
T_{15}	37.25 (0.30)	31.74 (3.51)	90.98 (18.89)
T_{20}	37.26 (0.38)	31.69 (3.64)	90.66 (21.71)
T_{40}	37.13 (0.36)	31.97 (3.50)	80.18 (14.88)
T_{55}	37.05 (0.36)	32.01 (3.39)	82.62 (15.63)
T_{60}	37.04 (0.37)	31.83 (3.39)	84.45 (17.56)
T_{75}	37.13 (0.43)	31.33 (3.84)	87.69 (19.23)
T_{80}	37.16 (0.46)	31.34 (3.86)	86.06 (19.03)
T_{100}	37.07 (0.45)	31.83 (3.60)	79.23 (18.51)
T_{115}	37.00 (0.45)	31.89 (3.47)	78.40 (15.90)
T_{120}	36.99 (0.45)	31.68 (3.58)	80.89 (16.18)
T_{135}	37.07 (0.51)	31.30 (3.88)	86.95 (21.85)
T_{140}	37.10 (0.53)	31.32 (3.97)	86.70 (23.69)
T_{160}	37.01 (0.52)	31.90 (3.54)	76.92 (17.29)
T_{175}	36.94 (0.51)	31.91 (3.36)	78.50 (16.44)
T_{180}	36.93 (0.52)	31.71 (3.43)	80.48 (16.90)
T_{195}	37.03 (0.54)	31.21 (3.99)	85.72 (20.87)
T_{200}	37.06 (0.58)	31.20 (4.18)	86.03 (23.35)
T_{220}	36.97 (0.57)	31.84 (3.63)	77.95 (18.44)
T_{235}	36.88 (0.57)	31.82 (3.65)	77.15 (17.02)
T_{240}	36.87 (0.57)	31.71 (3.69)	77.30 (16.62)

Note: Standard deviations are provided in brackets.





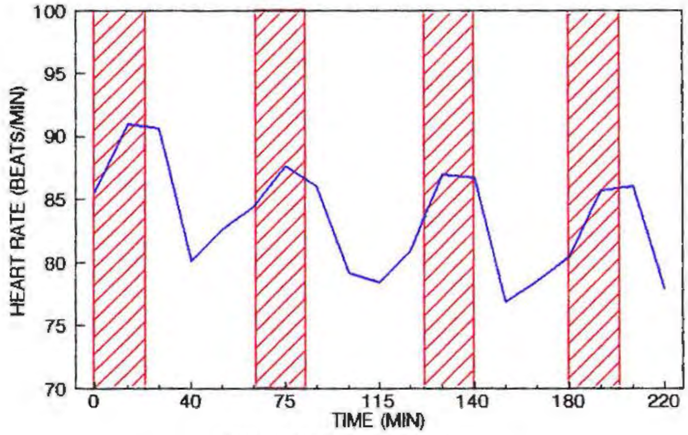


Figure 31 : Mean physiological responses over time
Combination of rest and work

▨ 20 MINUTE EXERCISE

A summary of the results is given in Tables XX to XXII. The significant interactions that were found between the main effects for the physiological responses are shown in Figures 32 to 34.

Rectal Temperature Responses

Table XX : Summary of analysis of variance - Rectal temperature : univariate tests of hypotheses for within-subject effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Within-subject effect					
Time	31.91	20	1.60	99.62	0.0001
Between-subjects effect					
Time $^*V_1$	48.18	40	1.21	75.22	0.0001
Time $^*V_2$	12.38	20	0.62	38.66	0.0001
Time $^*V_1{}^*V_2$	2.63	40	0.07	4.11	0.0001
Residual	43.24	2700	0.02		

Note: F-ratios are based on the residual mean square error.

The results of the analysis of variance as shown in Table XX reveal a significant interaction between the within-subject effect time and both the three environmental conditions (V_1) and the rest and work conditions (V_2) ($p < 0.05$). A detailed analysis was done where rectal temperature for each environmental condition was compared firstly by using both the rest and work conditions' data and secondly by using the data of the rest and work conditions separately.

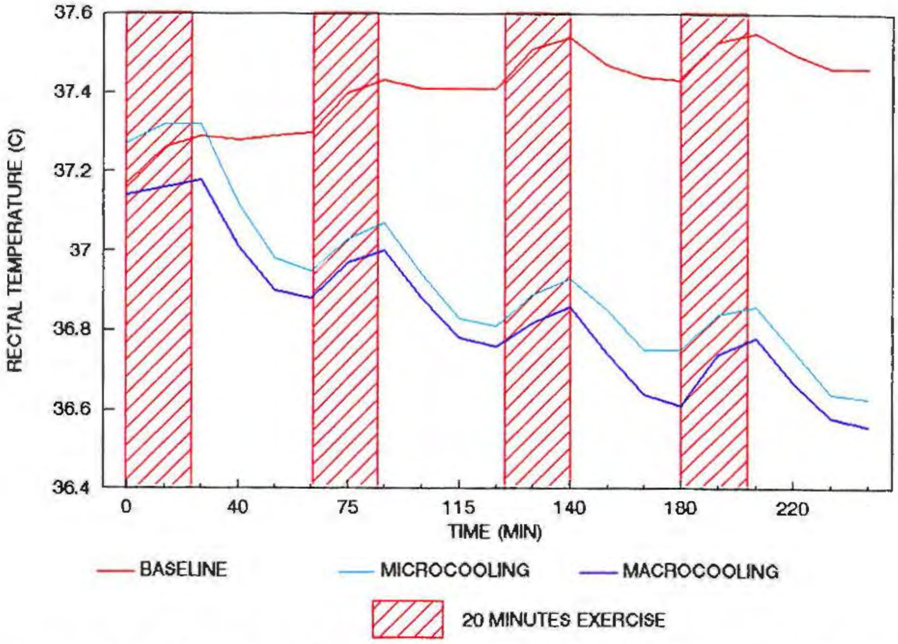
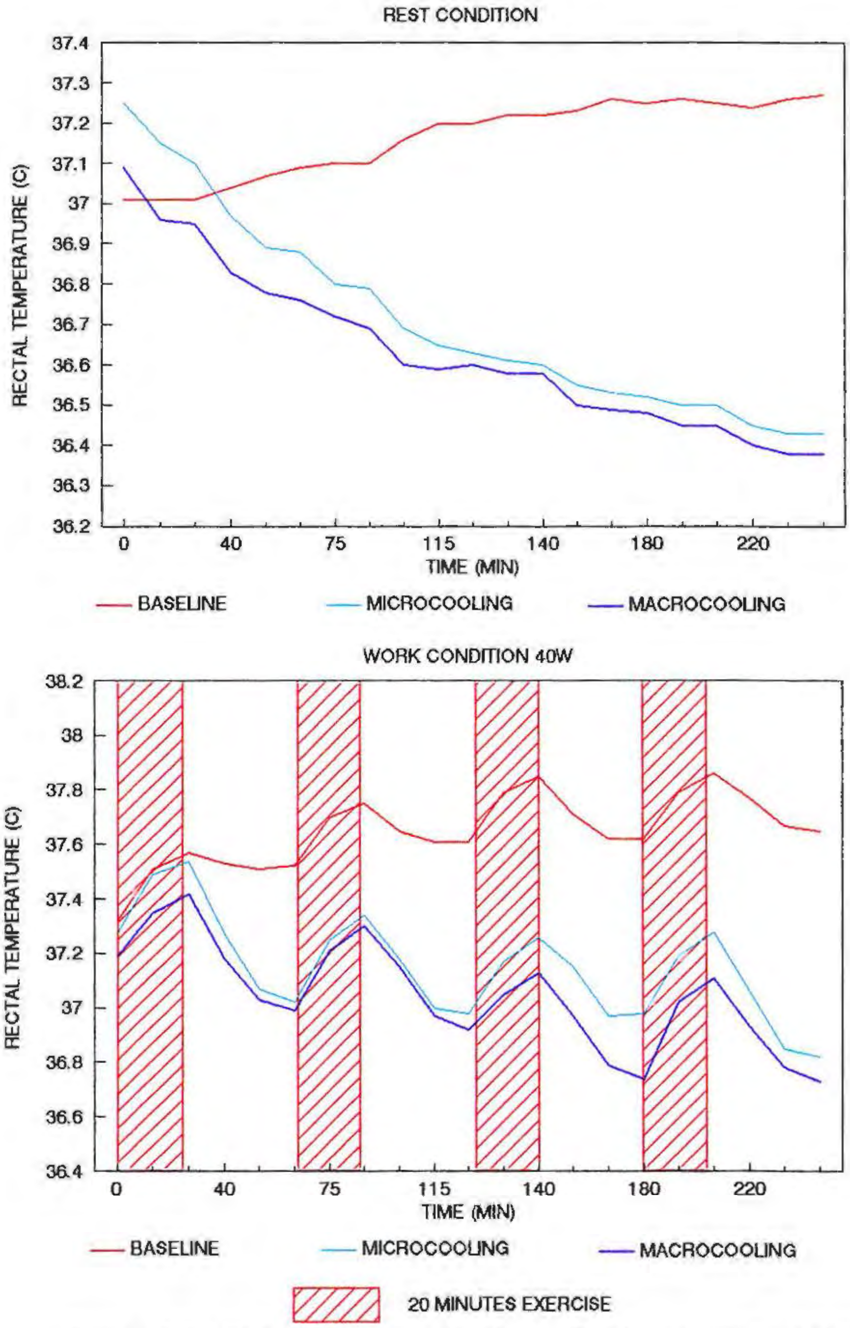


Figure 32 : Mean rectal temperature : Combination of rest and work

Figure 32 shows the mean rectal temperature over time where the rest and work conditions' data were combined. It was found that at the beginning of the 4-hour time interval (T_0 - T_{20min}) no significant difference existed between the baseline condition and the two cooling conditions. However, an interesting observation was the fact that for the first 20 min (T_0 - T_{20min}) a significant difference was found between micro- and macrocooling where the mean rectal temperature for microcooling was higher than that for macrocooling. This occurrence is difficult to explain owing to the fact that every condition's start-up procedures remained exactly the same. However, the author is of the opinion that this aspect did not affect the results in any significant way. Thereafter no significant difference was observed between the two cooling conditions.

Another interesting observation from the results was the constant rise in rectal temperature during the baseline condition and a constant drop in rectal temperature over time for both cooling conditions. Du Bois (1937) stated that under ordinary resting conditions the internal or core temperature of the human body would be maintained within the narrow limits of between 36.1°C and 37.2°C. In this study it was found that both cooling methods were able to keep the mean rectal temperatures between the above-mentioned limits and that the mean rectal temperatures measured in the baseline environment constantly exceeded the maximum of 37.2°C.

Figure 33 shows the mean rectal temperature for the three environmental conditions separately for the rest and work conditions. It is interesting to note that similar tendencies were found in the analysis of the combined rest and work data. It can therefore be concluded that the rectal temperatures for both cooling conditions were kept within the recommended comfort and safety levels and that subjects benefited substantially from both micro- and macrocooling. Webb (1969) stated that humans would reach a physiological endpoint or thermal tolerance limit if exposed to severe environmental conditions for long periods.


REST CONDITION

WORK CONDITION 40W

Figure 33 : Mean rectal temperature : Rest and work conditions

These findings were similar to those of earlier reports by Blockley et al. (1954) and Leithead and Lind (1964). The fact that rectal temperatures were reduced over time when the two cooling systems were used in the present study is reflective of the same trend observed in studies conducted on the development of a micro climate-conditioning system for tanks (Kok et al. 1989).

Figure 34 shows the mean rectal temperatures measured for rest and work over time. It is significant to note that the rectal temperatures for the work condition fluctuated in sequence with the 20-minute work (40 W); 40-minute seated intervals for each hour. The rectal temperatures rose on average 0.27°C during each 20-minute work cycle and dropped on average 0.32°C during each 40-minute testing (seated) cycle. Again these findings support the findings of earlier studies as discussed in paragraph 4.1.1 under rectal temperature (Lind, 1963; Meese, 1988). The mean rectal temperature for the rest condition showed a constant degradation over the time period from a highest value of 37.12°C at the beginning of the period (T_0) to 36.69°C at the end of the cycle (T_{240}). These results therefore emphasize the fact that body temperature will increase with an increase in metabolic rate and will be constant during steady state conditions.

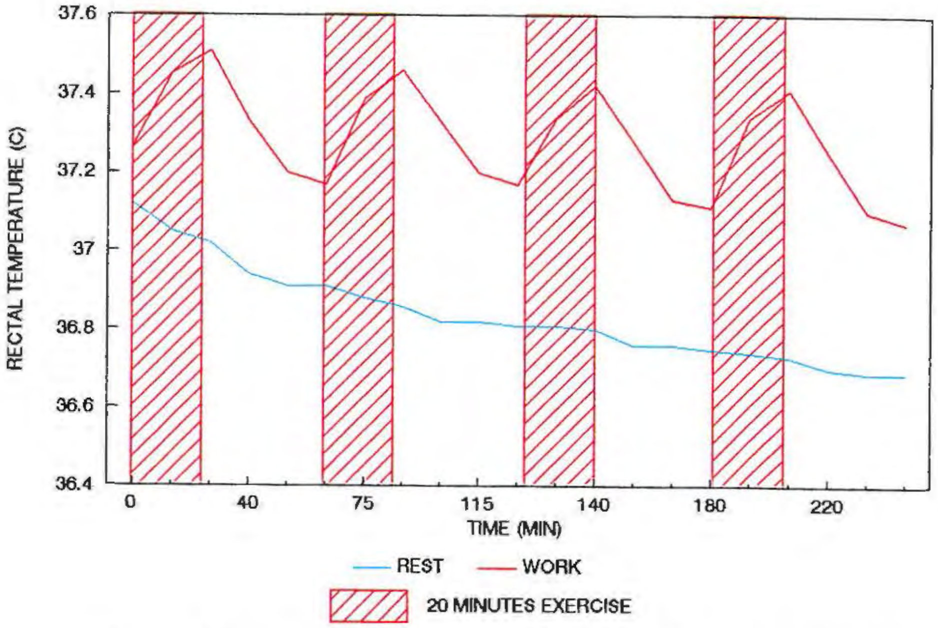


Figure 34 : Mean rectal temperature : Rest vs work conditions

The practical implications of these results are as follows:

Cooling, whether by means of a micro- or macrocooling system, results in a significant benefit to the human operator when compared to a condition without cooling. This was shown by the declining, but still within the acceptable limits of 36.1 - 37.2°C, rectal temperature during exposure where cooling was supplied.

Cooling by either the micro- or macrocooling method minimizes the effect of physical work on rectal temperature as was illustrated by the fact that physical work resulted in significantly higher rectal temperatures during the baseline condition (40°C; 40% RH), whereas these differences during cooling (micro and macro) were not found to be significant.

The four-hour exposure to harsh conditions (40°C; 40% RH) resulted in a significant increase in rectal temperature, while that was not the case when either micro- or macrocooling was applied. These results indicate that body temperature responses are unlikely to be affected when harsh environmental conditions are mitigated by effective cooling, regardless of the manner of cooling.

Skin Temperature Responses

Table XXI : Summary of analysis of variance - Skin temperature: univariate tests of hypotheses for within-subject effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Within-subject effect					
Time	182.80	20	9.14	29.47	0.0001
Between-subjects effect					
Time $^{*}V_1$	154.68	40	3.87	12.47	0.0001
Time $^{*}V_2$	192.28	20	9.61	31.00	0.0001
Time $^{*}V_1{}^{*}V_2$	90.81	40	2.27	7.32	0.0001
Residual	756.62	2440	0.31		

Note: **F-ratios are based on the residual mean square error.**

The results of the analysis of variance as shown in Table XXI reveal a significant interaction between the within-subject effect time and both the three environmental conditions (V_1) and the rest and work conditions (V_2) ($p < 0.05$). Again a detailed analysis was done where skin temperatures for each environmental condition were compared firstly by using both the rest and work conditions' data and secondly by using the data of the rest and work conditions separately. Figure 35 shows the mean skin temperature over time where the rest and work conditions' data were combined. An important fact to bear in mind is that skin temperatures were measured on the chest, back and thigh of each subject. The chest and back measurements were averaged to provide a single equally weighted reading which was again equally weighted with the thigh skin measurement to obtain the mean skin temperature for each subject.

The results in Figure 35 show that the skin temperature during the various environmental conditions stayed fairly stable over the 4-hour measurement period. It is, however, interesting to note that the mean skin temperature in the baseline environmental condition fluctuated between 35.5°C and 35.8°C with an average of 35.7°C. As discussed in paragraph 4.1.1 the skin temperature during this specific environmental condition was higher than the preferred comfort level for the entire 4-hour measurement period. This caused definite discomfort for the subjects, which was also confirmed by the sweat rate and total sweat loss physiological responses.

During the macrocooling condition, however, the environment was kept at a desired comfortable level for the duration of the 4-hour measurement period, with skin temperatures of between 31.2°C and 32.9°C. These results support findings of earlier studies on skin temperature and comfort (Webb, 1969). The microcooling

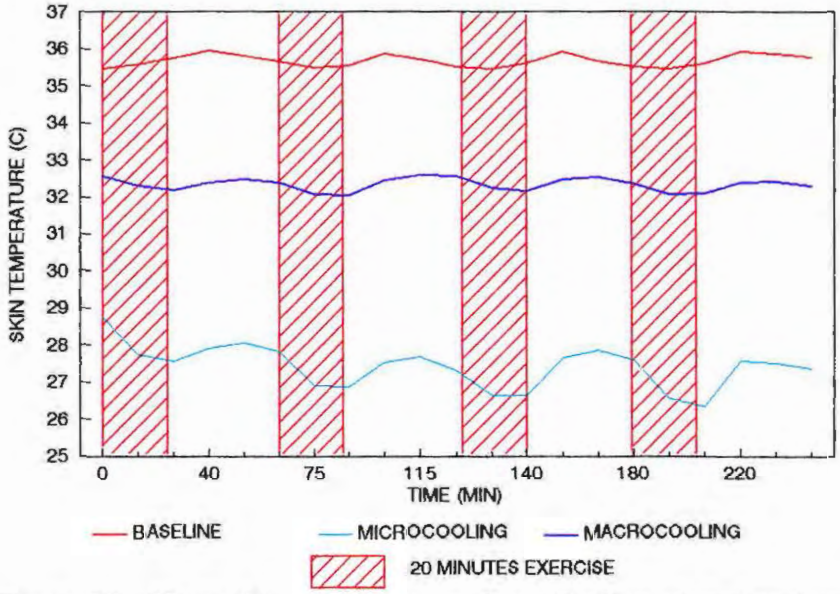


Figure 35 : Mean skin temperature : Combination of rest and work

condition on the other hand produced constant mean skin temperatures of between 24.88°C and 28.9°C over the 4-hour period. These results were obtained despite the fact that the thermocouples on the chests and backs of the subjects were insulated properly. Allowing the skin temperature to drop too low will result in discomfort and an irritation, and may cause local constriction of the skin blood vessels, especially over long periods such as the exposure time of 4 hours in this study.

In practical terms it is therefore clear that both cooling systems were of great benefit to the human operator in keeping him comfortable for a long period of exposure. The macrocooling system especially kept the human operator at a constant comfortable skin temperature (32°C - 34°C) in both the steady state and working conditions. From a purely physiological perspective the microcooling system, although the results obtained were lower than the recommended comfort level, will ensure that the human operator is able to perform his task in severe environmental conditions for long periods of exposure without any detrimental effects to his health.

Heart Rate Responses

Table XXII : Summary of analysis of variance - Heart rate: univariate tests of hypotheses for within-subject effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Within-subject effect					
Time	49 089.39	20	2 454.47	29.88	0.0001
Between-subjects effect					
Time $\times V_1$	16 141.09	40	403.53	4.91	0.0001
Time $\times V_2$	42 586.27	20	2 129.31	25.92	0.0001
Time $\times V_1 \times V_2$	7 886.58	40	197.16	2.40	0.0001
Residual	177 421.77	2166	82.14		

Note: F-ratios are based on the residual mean square error.

The results of the analysis of variance as shown in Table XXII reveal a significant interaction between time and both the three environmental conditions (V_1) and the rest and work conditions (V_2) ($p < 0.05$). Again a detailed analysis was done where heart rate, for each environmental condition, was compared by using both the rest and work data. Figure 36 shows the mean heart rate over time where the rest and work data were combined. The results clearly indicated similar trends for all three environmental conditions with reference to the rising of heart rate for the first 20 min of each 1-hour cycle when the subjects were exercising, and the falling in heart rate for the 40 minutes while sitting down and performing the psychological tests.

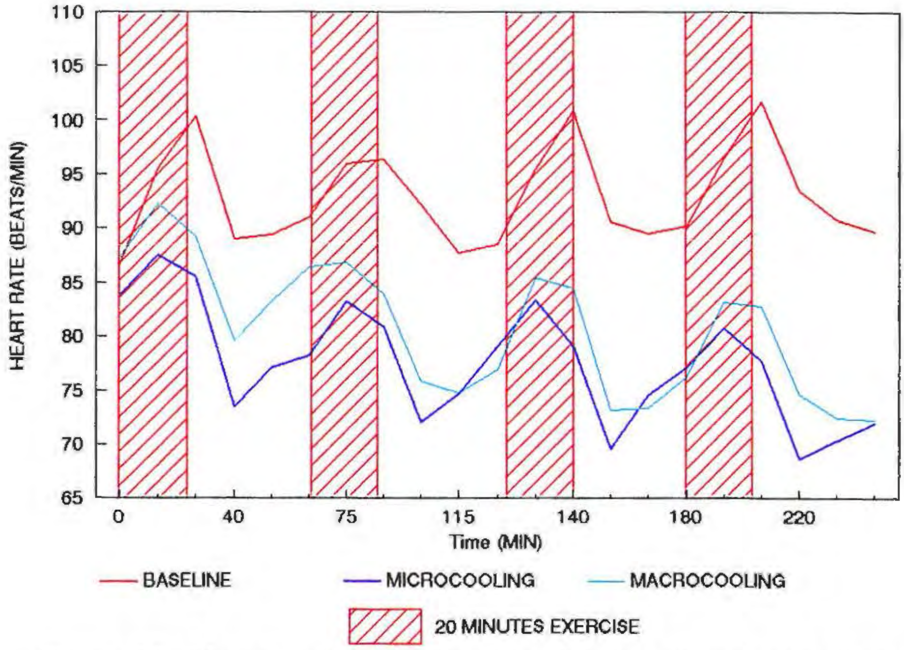


Figure 36 : Mean heart rate : Combined rest and work conditions

The results again showed that heart rate in the baseline condition was significantly higher than when cooling was applied. Furthermore it is clear that micro- and macrocooling had a similar effect on heart rate over time, with no significant difference between the two cooling methods. For continuous exposure to a hot ambient environment it is necessary for the heat to be dissipated, which will result in an increased cutaneous blood flow. This will cause the stroke volume to fall and the heart rate must increase to maintain cardiac output (Parsons, 1993).

In summarizing the results of the physiological responses the following was found in this study:

For rectal temperature it was found that both cooling conditions (micro- and macrocooling) were beneficial to heat-exposed human operators. Rectal temperatures measured during the baseline conditions were significantly higher than those measured during the two cooling conditions, and the results of the two cooling conditions did not differ significantly. It was furthermore found that rectal temperature results also differed significantly between the rest and work conditions, indicating that increased metabolic rate generated a higher mean rectal temperature.

Regarding skin temperature it was found that both the micro- and macrocooling were beneficial to heat-exposed human operators and produced a comfortable ambient environment. A significant difference was found between mean skin temperatures for the rest and work conditions where higher skin temperatures were measured during the rest conditions. Skin temperatures measured during the baseline condition indicated that the subjects experienced discomfort for the duration of this condition.

Heart rate as physiological response showed a difference between the baseline condition and the two cooling conditions. A significant difference was found between rest and work, with higher heart rates occurring during the work condition.

For sweat rate and total sweat loss as physiological responses it was found that a significant difference existed between the environmental conditions with the baseline condition > microcooling > macrocooling. It was furthermore found that sweat rate and total sweat loss were higher for the work than for the rest condition.

In summary it can be stated that the physiological responses differed significantly between the environmental conditions, the rest and work conditions and over time.

4.2 Psychological Responses

4.2.1 Environmental Conditions (Baseline vs Microcooling vs Macrocooling

The practical question regarding these results is the following:

> "After having been subjected to the three environmental conditions, are there significant differences between the

psychological responses measured in these environmental conditions?"

A summary providing the means and standard deviations of the respective psychological parameters for each of the three environmental conditions is provided in Table XXIII. The means are also illustrated graphically in Figure 37.

Table XXIII : Summary of results of psychological responses to environmental conditions

ENVIRONMENTAL CONDITIONS	PSYCHOLOGICAL RESPONSES				
	MEMORY/ ATTENTION	EYE-HAND COORDINATION	REASONING	AVERAGE REACTION TIME	AVERAGE RESPONSE TIME
Baseline 40°C; 40% RH	68.46 (2.99)	1.33 (0.72)	12.31 (4.90)	0.33 (0.05)	0.20 (0.02)
Microcooling	69.03 (2.50)	1.00 (0.57)	14.65 (6.14)	0.33 (0.06)	0.21 (0.02)
Macrocooling	69.03 (0.39)	0.89 (0.55)	17.05 (6.65)	0.33 (0.05)	0.21 (0.02)

Note: Standard deviations are provided in brackets.

As can be seen from the results in Table XXIII and Figure 37 there were numerical differences between the psychological responses measured under each environmental condition. In order to identify whether there were significant differences between the psychological responses for the three environmental conditions these responses were individually evaluated using analysis of variance. A summary of the results is given in Tables XXIV - XXVII.

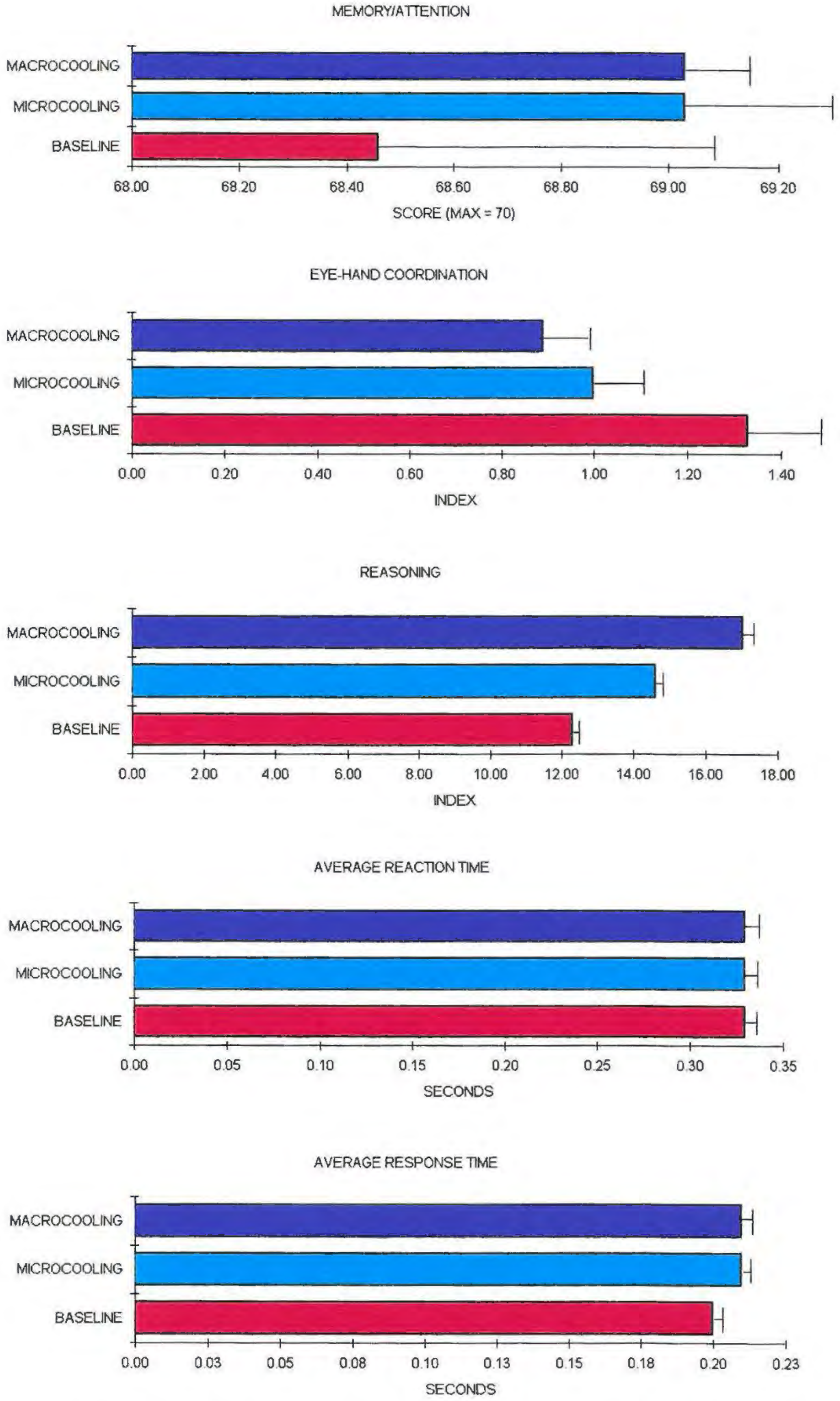


Figure 37: Results (mean values) of Psychological Responses
Environmental conditions

Memory/Attention Test

Table XXIV : Repeated measures analysis of variance - Memory/ attention test: tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	41.25	2	20.62	2.15	0.12
V_2: Rest vs Work	29.79	1	29.80	3.10	0.08
Interactions					
$V_1{}^*V_2$	9.65	2	4.83	0.50	0.60
Residual	1 324.67	138	9.60		

Note: **F-ratios are based on the residual mean square error.**

The results of the analysis of variance (Table XXIV) showed no significant difference between the memory/attention test results under the three environmental conditions. This confirmed the results obtained by Meese et al. (1981) wherein the overall effect of different temperatures on short-term memory tended to increase at higher temperatures, but the effects were not usually significant. However, Nunneley et al. (1978) had found in their investigation that subjects would experience a decrement in efficiency in most tasks, in particular learning tasks, at temperatures as low as 28.7°C. In another study on the effect of temperature on learning Mayo (1955) found no difference in results between the temperatures of 24°C and 33.6°C. It should, however, also be noted that the complexity of the learning task would play a role in the effect of different temperatures (Schaer and Shaffran, 1973). It is therefore clear that neither cooling conditions benefitted the subjects in any significant way to enhance their memory/attention ability.

Eye-Hand Coordination Test

An eye-hand coordination performance index was determined by calculating the sum of the errors over all the runs for all three apparatus used, divided by the sum of all the times over all the runs for all three apparatus, thus:

$$\text{Performance Index} = \frac{\text{Sum of errors}}{\text{Sum of time}}$$

Table XXV : Repeated measures analysis of variance - Eye-hand coordination test: tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	19.68	2	9.84	6.99	0.0013
V_2: Rest vs Work	0.22	1	0.22	0.15	0.690
Interactions					
V_1*V_2	0.66	2	0.33	0.23	0.790
Residual	194.18	138	1.407		

Note: F-ratios are based on the residual mean square error.

The results of the analysis of variance (Table XXV) showed a significant difference between the eye-hand coordination test results of the three environmental conditions. The Duncan's Multiple Range Test was used to determine whether these differences were significant. It was found that for the eye-hand coordination responses a significant difference existed between the baseline condition and both cooling conditions, but no significant difference was found between the micro- and macrocooling conditions. These results are shown in Figure 38.

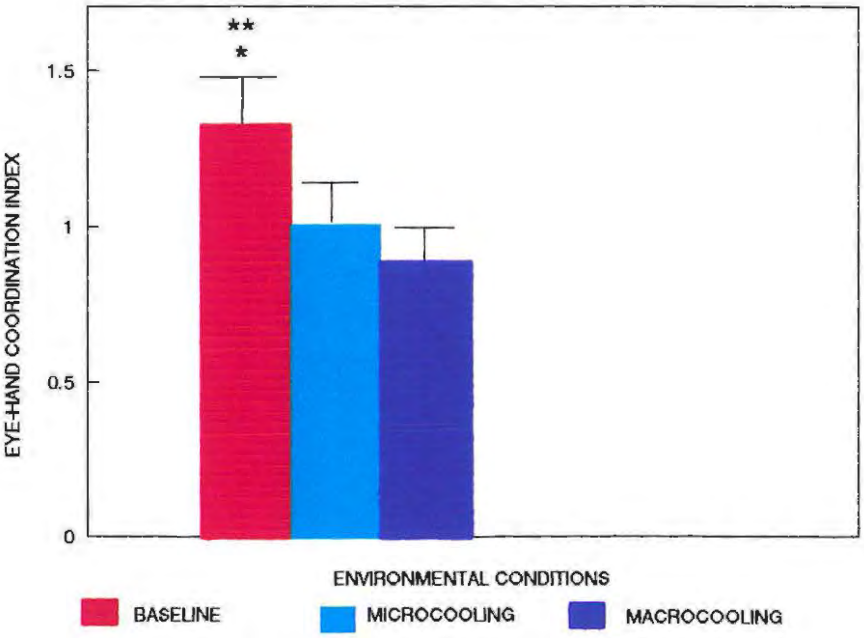


Figure 38 : Mean eye-hand coordination responses

* Represents significant differences between baseline and micro

** Represents differences between baseline and macro

From the results of this study it was evident that changes in the environmental temperature had an effect on gross and fine eye-hand coordination. When applying the performance index to incorporate both errors and speed it was found that the mean index value during the baseline condition was significantly higher than for both the cooling conditions, thus indicating a deterioration in performance. Ramsey (1975) conducted various eye-hand coordination tests in different thermal environments.

With all his tweezer manipulation tests he found no change in performance between 21°C and 40°C. In his stylus tracking tests he often found an improvement in performance in the hotter environments. The results of this study are therefore contradictory to previous findings because better performances were measured under the cooler and more comfortable environmental conditions.

Reasoning Test

For the reasoning test an index was determined by calculating the product of the amount of correct responses and the speed in which the test was completed, thus:

$$\text{Index} = \text{Correct responses} \times \text{Speed}$$

$$\text{where Speed} = \frac{\text{Total responses}}{\text{Time taken}}$$

Table XXVI : Repeated measures analysis of variance - Reasoning test: tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	2 161.12	2	1 080.56	8.08	0.0005
V_2: Rest vs Work	332.07	1	332.07	2.48	0.1173
Interactions					
$V_1{}^*V_2$	23.35	2	11.67	0.09	0.9164
Residual	18 453.05	138	133.71		

Note: F-ratios are based on the residual mean square error.

A detailed analysis of the data showed a difference between the environmental conditions ($p < 0.05$). The univariate tests of hypotheses for within-subject effects showed that the effect of time had an influence on the significance of the differences. These results are explained in paragraph 4.2.3 where the effect of time is discussed in more detail.

Reaction and Response Time

Summaries of the reaction and response time results are shown in Tables XXVII and XXVIII.

Table XXVII : Repeated measures analysis of variance - Reaction time: tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	0.0005	2	0.0002	0.02	0.98
V_2: Rest vs Work	0.0027	1	0.0027	0.24	0.63
Interactions					
$V_1{}^*V_2$	0.005	2	0.0025	0.21	0.81
Residual	1.6315	138	0.0118		

Note: F-ratios are based on the residual mean square error.

Table XXVIII : Repeated measures analysis of variance - Response time: tests of hypothesis for between-subjects effects

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main effects					
V_1: Environmental Conditions	0.002	2	0.001	0.15	0.87
V_2: Rest vs Work	0.001	1	0.001	0.12	0.73
Interactions					
$V_1{}^*V_2$	0.007	2	0.004	0.59	0.56
Residual	0.88	138	0.006		

Note: F-ratios are based on the residual mean square error.

The results of the analysis of variance revealed no significant difference ($p < 0.05$) between the environmental conditions (V_1) or the rest and work conditions (V_2) for both average reaction and response times. The mean values as shown in Table XXIII show an average reaction time of 0.3 s and an average response time of 0.20 s for each environmental condition. In the literature conflicting results are found regarding reaction time responses. Teichner (1954) stated that reaction time was unchanged in a range of -45°C to +47°C. This statement was confirmed by this study. On the other hand Meese _et al_. (1981) noted a peak in reaction time at 32°C, followed by a significant deterioration at 38°C. More contradicting results were obtained by Hancock and Dirkin (1982) who suggested that an increase of 4.9°C in rectal temperature would bring about an increase in reaction time and a decrease in errors. In this study the increase in rectal temperature between the environmental conditions was only 0.6°C and can therefore not be compared with the results of Hancock and Dirkin (1982). Bell _et al_. (1982) in their study on the effects of heat on reaction time found no statistically significant results at all. Nunneley _et al_. (1982) found that elevated head temperature resulted in shortened reaction time and an increase in errors. Again the present study could not support these findings in that no differences in response times were found between the three temperature conditions.

The practical implication of the present findings is that reaction and response time as psychological performance parameters are not influenced by heat and therefore the usage of micro- or macrocooling would be equally beneficial to human operators when such tasks are to be carried out.

4.2.2 Rest vs Work Condition

The practical question regarding these results is the following:

> "After having been subjected to two different conditions in metabolic workrate, namely rest vs work (40 W) under similar ambient thermal conditions, are there significant differences between the psychological responses measured in these two conditions?"

A summary providing the means and standard deviations of the respective psychological parameters for each of the two conditions is provided in Table XXIX. The means are also illustrated graphically in Figure 39.

Table XXIX : Summary of results of psychological responses: rest vs work

REST VS WORK	PSYCHOLOGICAL RESPONSES				
	MEMORY/ ATTENTION	EYE-HAND COORDINATION	REASONING	AVERAGE REACTION TIME	AVERAGE RESPONSE TIME
Rest	68.614 (2.972)	1.056 (0.67)	13.917 (6.01)	0.330 (0.05)	0.207 (0.001)
Work	69.07 (2.39)	1.095 (0.634)	15.435 (6.388)	0.326 (0.057)	0.204 (0.003)

Note: Standard deviations are provided in brackets.

As can be seen from the results in Table XXIX and Figure 39 numerical differences existed between the psychological responses measured at rest vs work under the different environmental conditions. However, no significant differences were found when each response was evaluated individually using analysis of

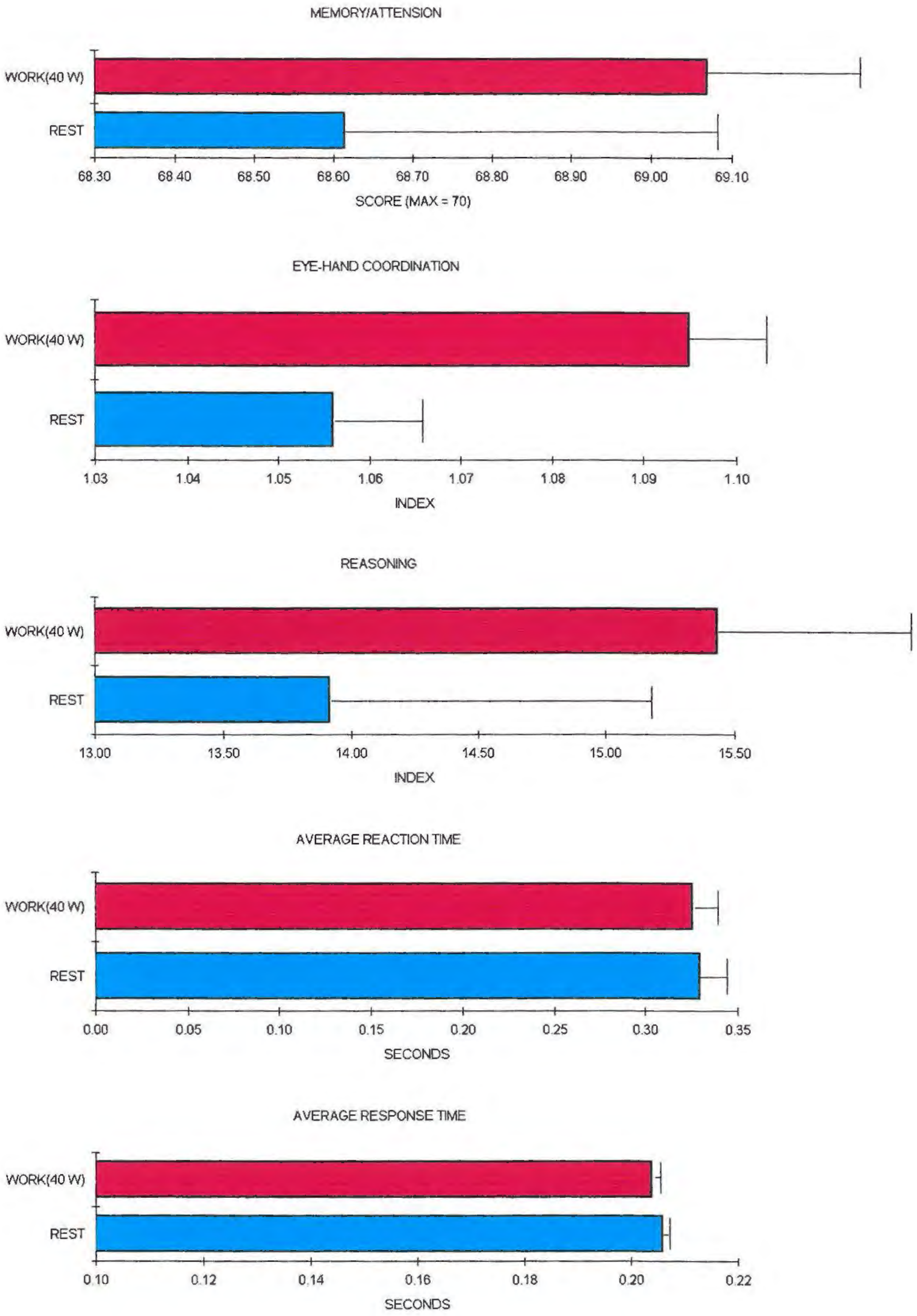


Figure 39: Results (mean values) of Psychological Responses
Rest vs Work

variance. (See Tables XXIV to XXVIII.) Although these differences were not statistically significant, it was interesting to note that for three of the tests, namely the memory/attention, eye-hand coordination and reasoning tests, the subjects performed better after the work cycle of 20 min than after the rest cycles.

This phenomenon may be attributed to the fact that the state of alertness could have been higher after the work cycle than after a 20-min period of rest where most of the subjects may have been sleepier. The aspect of boredom could also have played a role in this result. During the 20-min rest cycle the subjects were not compelled to do anything in particular, which could have caused boredom and might have influenced their responses towards the performance tasks in a negative way. In practical terms this could mean that human operators, whose primary tasks involve attention/memory, eye-hand coordination or reasoning skills, should be kept at a relatively high alertness level in order to prevent boredom influencing their performance of the specific primary task.

For the eye-hand coordination test the opposite was found in that better performances were obtained after the rest condition. This phenomenon could be explained by the fact that after exercising the hand movements of subjects may not have been that steady due to an increase in muscle activity, heart rate and bloodflow. In practice it will therefore be desirable that operators responsible for tasks where eye-hand coordination is of critical importance be physically less active for optimal performance.

4.2.3 The Effect of Time

The practical question regarding these results is the following:

> "After having been subjected to the three environmental conditions over a period of time (4 hours), are there significant differences between the psychological responses measured over the set time?"

A summary providing the means and standard deviations of the respective psychological responses over time is provided in Table XXX. The means are also illustrated graphically in Figure 40. Each test was measured 4 times, once every hour at the same time interval in each hour.

Table XXX : Summary of results of psychological responses
Time effect

TIME INTERVAL	PSYCHOLOGICAL RESPONSES				
	MEMORY/ ATTENTION	EYE-HAND COORDINATION	REASONING	AVERAGE REACTION TIME	AVERAGE RESPONSE TIME
T_1	68.743 (2.871)	1.046 (0.603)	14.283 (6.281)	0.323 (0.055)	0.20 (0.001)
T_2	68.368 (3.350)	1.088 (0.667)	14.641 (6.137)	0.326 (0.058)	0.21 (0.005)
T_3	69.013 (2.423)	1.102 (0.691)	14.680 (6.344)	0.331 (0.055	0.21 (0.004)
T_4	69.243 (1.918)	1.066 (0.639)	15.099 (6.244)	0.33126 (0.0587)	0.21 (0.003)

Note: Standard deviations are provided in brackets.

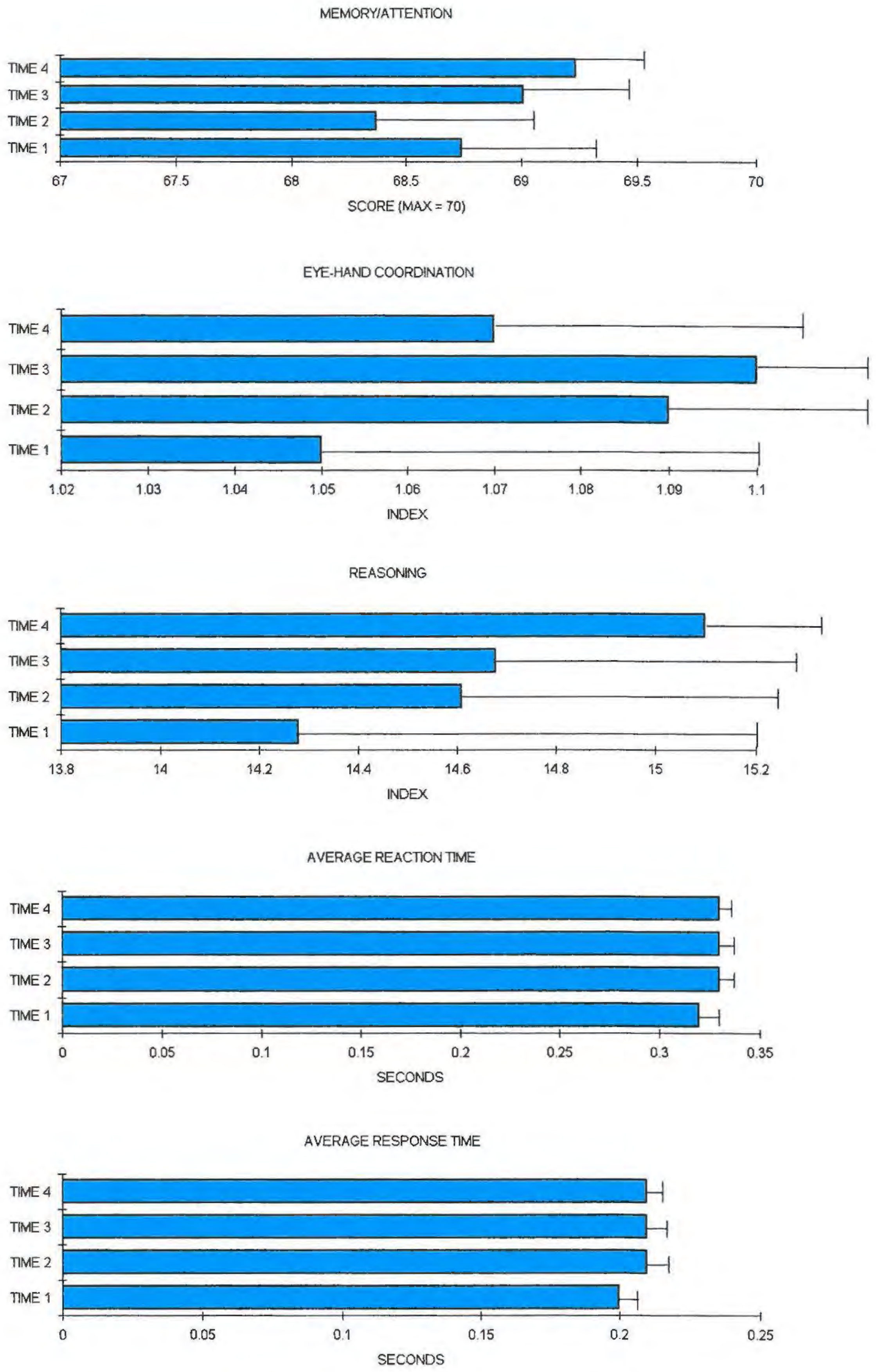


Figure 40: Results (mean values) of Psychological Responses
Effect of time

The results as shown in Table XXX and Figure 39 showed that differences existed between the psychological responses measured over time during the three environmental conditions. However, the analysis of variance test done on each individual response showed no significant difference over the time interval for three of the psychological parameters, namely memory/attention, eye-hand coordination and average reaction and response times.

For the reasoning test significant differences were found for the three environmental conditions over the four time intervals. These differences are illustrated in Figure 41. It is interesting to note that for the first two hours (T_1 and T_2) significant differences existed between the baseline condition

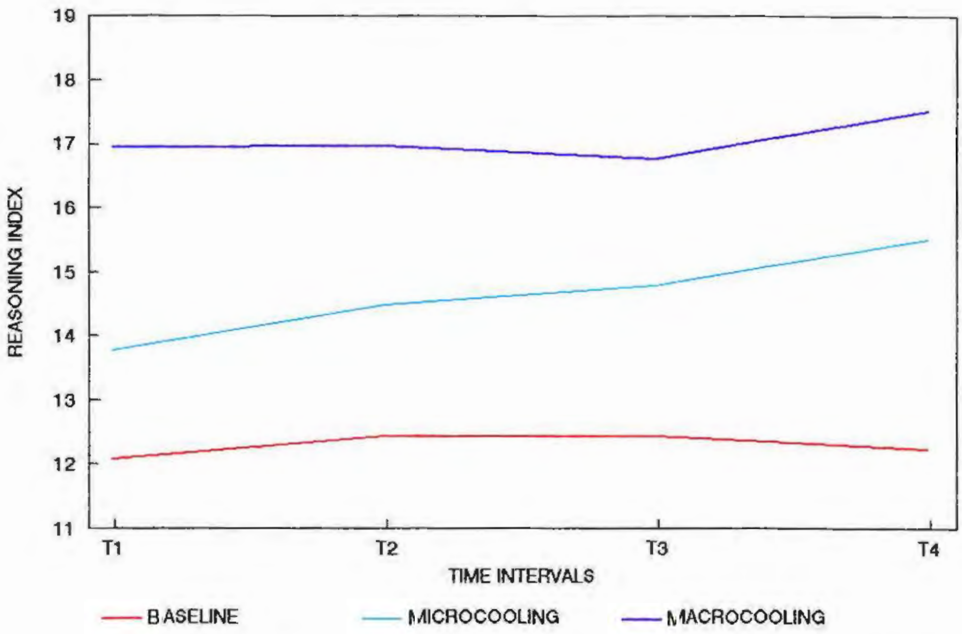


Figure 41 : Mean reasoning test responses for environmental conditions

and macrocooling, as well as between microcooling and macrocooling. For both these two time periods the highest score was measured for the macrocooling condition (index = 16.9) and the lowest for the baseline environment (index = 12.76) For the next two time intervals (T_3 and T_4) the only significant difference was found between the baseline environment and macrocooling. In practical terms it appears that the macrocooling initially is more beneficial to the human operator with reference to his reasoning ability. For the last two hours, however, the reasoning ability during microcooling improved to such an extent that no significant difference existed between micro- and macrocooling. The results of this study confirm the findings of Wing (1965) that cognitive performance degradation becomes visible much quicker at higher temperatures and that nearly no degradation will take place in a constant comfortable environment. The general conclusion is that some deterioration in performance of mental or cognitive tasks may occur at about 29°C and that a macrocooled environment is most suitable for a human to perform a reasoning task in.

In summarizing the results of the psychological responses, the following were found in this study:

For memory/attention as psychological response no significant differences were found between either the environmental conditions or the rest vs work sessions. Therefore neither cooling method benefitted the subjects in any significant way. Regarding eye-hand coordination it was found that a significant difference existed between the baseline environment and both cooling conditions, with the better performances measured during the cooling conditions.

With reference to reasoning ability as psychological response it was found that significant differences did not exist for either the environmental conditions or the rest vs work condition. The mean values, however, showed that subjects performed better after the work condition than in the rest condition. The effect of time was noticed in that the macrocooling results were better than those of both the microcooling and the baseline conditions for the first two measurement periods (T_1 and T_2). For the latter two time periods, however, no difference existed between the two cooling conditions. Regarding the average reaction and response time, as psychological responses, no significant differences were found.

4.3 User Perception

The results of the physiological and psychological responses, as discussed in the preceding paragraphs, are very important measurements for the evaluation of the two cooling methods described in this study. However, thermal conditions will directly affect thermal sensation and comfort, as well as the mood and behaviour of a human operator in his work environment (Parsons, 1993). The results obtained from evaluating the physiological and psychological responses reveal that both cooling methods provided a significant benefit for the human operator in comparison with a hot, uncooled environment. The way in which human operators experience their work environment would indeed influence their mood, attitude and behaviour, which will determine the degree of task performance. A very important part of this study therefore was the measurement of user perception regarding the two cooling methods by means of a user perception questionnaire specifically designed for this purpose. (See Appendix C for questionnaire.) This questionnaire was administered to the subjects after they had been exposed to both types of cooling methods. The subjects' perception of the two cooling systems was measured in the following categories:

- Temperature
- Airflow
- General ergonomics
- User attitudes.

With reference to the categories temperature, airflow and general ergonomics the general subjective opinions of the subjects are summarized below. The mean values of the user attitudes were calculated on a 10-point scale and they are shown in Table XXXI and in graphical form (see Figure 42) for each cooling method.

4.3.1 Microcooling

Regarding the user perception towards microcooling, it should be borne in mind that the users in this instance were only exposed to the one particular microcooling system used for the experiment and the perception is therefore not applicable to microcooling in general.

With reference to temperature, the majority of subjects felt that several parts of their bodies were not cooled at all; these included the head, arms, hands, legs and feet. The fact that these body parts were not cooled down caused discomfort to the subjects due to a higher sweat rate and higher skin temperatures. On the other hand the concentration of cold air at the inlet of the jackets resulted in numbness of the skin in that area, especially when the subjects were not exercising. This also caused a degree of discomfort to the subjects and could have a direct influence on attitudes, moods, behaviour and even performance.

Regarding the airflow of 1 500 ℓ/min presented to the subjects, the general opinion was that it was a little too high, especially when being delivered at a single concentrated point at the inlet of the jacket. It was felt that an airflow of approximately 1 000 ℓ/min at 18°C - 21°C would have been ideal or, alternatively, higher air temperature at 1 500 ℓ/min. It was therefore clear that the balance between the air temperature and airflow delivered at the jacket inlets are important factors to consider when applying air-microcooling.

The following comments were made with reference to the general ergonomics of the microcooling system: Firstly the subjects felt that the connections between the pipe and jackets were not effective since they came loose frequently during the experiment, especially while moving around and exercising. This interference of the umbilical cord or pipe caused irritation to some subjects, more so during the latter part of each daily cycle. Secondly the subjects felt that the jackets had a deleterious influence on their performance due to the fact that they were not adjustable according to size. This problem was experienced mainly by the larger subjects. A third comment concerned the regulation of the airflow. The subjects in general felt that each individual should have been able to regulate his own airflow according to preference. Finally the subjects stated that a number of them experienced symptoms of colds and influenza while exposed to the microcooling. They felt that the sharp contrast between the hot ambient environment that existed in the climatic chamber and the directional cold air of the microcooling system could have caused these symptoms.

4.3.2 Macrocooling

The macrocooling condition was found to be highly acceptable to all the subjects who participated in the experiment. There were no negative comments regarding any of the perception parameters set and all subjects agreed that the macrocooling system prevented them from sweating and that their bodies as a whole were cooled effectively. This comfortable environment created by the macrocooling system resulted in an ability to concentrate to a higher degree and made effective task execution possible. Both the controlled temperature of 21°C and the airflow that constantly existed during the macrocooling environment were rated by the subjects as highly acceptable and ideal. The fact that no additional equipment, as in the case of microcooling, was required, also weighted in favour of macrocooling.

4.3.3 User Attitudes

The seven subjective user attitudes that were used expressed the subjects' feelings and moods towards each of the cooling methods. The subjects had to indicate on a scale of 10 how they felt about each cooling condition. On the 10-point scale 0 reflected the negative side of the scale and 10 the positive side, e.g. Angry (0) vs Happy (10).

The user attitudes used were the following:

A: Angry (0) vs Happy (10)
B: Uncomfortable (0) vs Comfortable (10)
C: Unfriendly (0) vs Friendly (10)
D: Bad (0) vs Good (10)
E: Unhealthy (0) vs Healthy (10)
F: Stressful (0) vs Not stressful (10)
G: Do not like (0) vs Like (10)

The results for the user attitudes as described above (A - G) are shown in Figure 42 and Table XXXI.

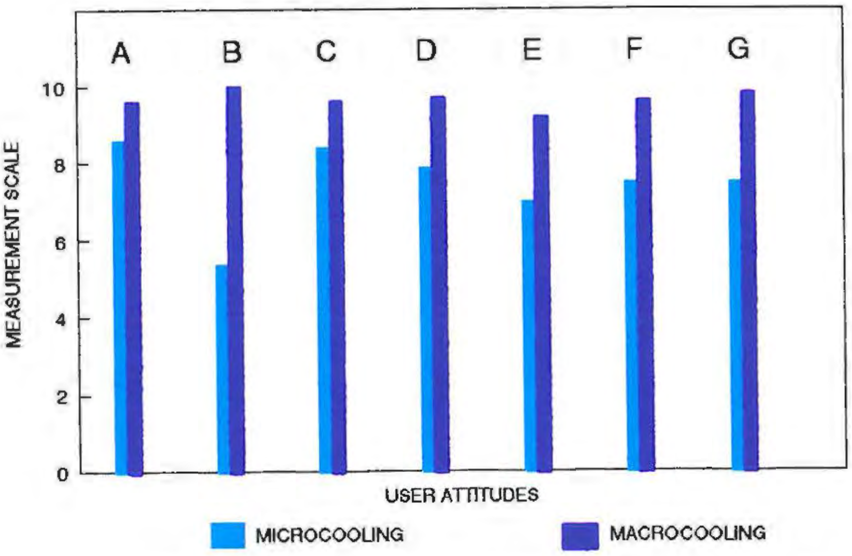


Figure 42 : User perception of micro- vs macrocooling
User attitudes measured on a 10-point scale

Table XXXI : Summary of mean values for user attitudes

USER ATTITUDE	COOLING CONDITION	
	MICROCOOLING	MACROCOOLING
A: Angry vs Happy	8.61 (1.76)	9.67 (1.41)
B: Uncomfortable vs Comfortable	5.43 (2.64)	10.00 (1.13)
C: Unfriendly vs Friendly	8.43 (1.95)	9.64 (1.45)
D: Bad vs Good	7.88 (2.42)	9.67 (1.51)
E: Unhealthy vs Healthy	7.00 (3.14)	9.19 (1.90)
F: Stressful vs Not stressful	7.57 (2.29)	9.64 (1.43)
G: Do not like vs Like	7.48 (2.66)	9.79 (1.30)

Note: Standard deviations are provided in brackets.

These subjective results clearly showed that macrocooling was found to be more acceptable than microcooling for all seven user attitudes. The biggest difference between the subjective ratings was found for user attitude B: uncomfortable vs comfortable, where the subjects found the macrocooling significantly more comfortable than the microcooling.

The present project proposed that the issue of thermal comfort plays an important role in the comparison of micro- vs macrocooling. However, Parsons (1993) stated that while general comfort is a psychological phenomenon it is not directly related to the physical environment or the psychological state of the human operator. The results of this study clearly demonstrate that a correlation does exist between favourable physiological data and subjective comfort ratings. Although no dangerous levels of any of the physiological responses were measured during any of the three environmental conditions, the results clearly indicated that the macrocooling environment was the most beneficial to the subjects. These objective measurements were confirmed by the subjects' subjective comfort rating of the two cooling conditions.

In summary, it is evident that the three main aspects discussed in this chapter, namely physiological responses, psychological responses and user perception, should be integrated when conclusions are made. When reviewing the results presented, it was found that a cooled environment, whether micro- or macrocooled, were significantly beneficial to the human operator.

The results of this study furthermore indicated that macrocooling kept the physiological responses of the human operator closer within specified parameters than microcooling. Subjectively macrocooling was judged significantly more favourable than microcooling, especially regarding thermal comfort. As far as the psychological responses are concerned, no significant differences could be found, although both cooling methods produced a significant advantage to the human operator in performing certain psychological tasks.

CHAPTER FIVE : SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The effect of heat on the physiological and psychological performance of the human operator has been researched extensively worldwide with reference to different practical applications. Although conflicting findings have been made by the various researchers, it is generally agreed that environmental temperatures of 28.5°C and higher will have an influence on physical and mental work performance. The human operator, as an integral part of modern highly technological systems, is often pressured to perform physically and mentally under harsh environmental conditions, with specific reference to heat. To improve this uncomfortable working environment certain control measures can be applied, namely ventilation, air-conditioning and use of protective clothing. One of these control measures, air-conditioning, is used to ensure a safer and more comfortable environment for the human operator in many industrial and other practical applications. These air-conditioning systems may be either micro- or macrocooling devices. In some of these applications factors such as space, weight, logistics and finance play an important role in the selection of an effective air-conditioning system. When regarding the human operator as the least efficient link in the total system the question whether macro- or microcooling is the most effective system for optimal physiological and psychological performance appears to have been the focus of very little research.

The objective of this study was to evaluate the effect of an optimal micro- vs an optimal macrocooling system on certain physiological and psychological parameters of the human operator in his working environment.

5.1 Hypotheses

It was hypothesized that:

5.1.1 The physiological and psychological (cognitive and psychomotor) performance of the human operator in a hot ambient environment (40°C; 40% RH) is equal to that under macro- and microcooling conditions.

5.1.2 The physiological and psychological (cognitive and psychomotor) performance of the human operator is equal under non-physical (resting) and moderate workrate (40 W) conditions.

5.1.3 The physiological and psychological (cognitive and psychomotor) performance of the human operator is equal when repeated four times over a period of four hours, once per hour.

5.2 Summary of Procedure

This study was conducted in a climate laboratory under controlled environmental conditions. Healthy young adult male subjects (n = 24) volunteered to participate in the study which was scheduled over a period of thirteen days.

The subjects went through an acclimatization period of four days which consisted of a daily exposure (4 hours per day) to the experimental environmental conditions (40°C, ±1°C; 40%, ±5% RH). The workrate of the subjects was progressively increased each day to ensure a gradual increase of stress intensity over the acclimatization period. During this acclimatization period the subjects were instrumented as for the experiment. The performance tests chosen for this experiment were also thoroughly rehearsed during the acclimatization period of four days. The reason for training the subjects in the four performance tests was to eliminate the effects of learning.

The subjects were divided into two groups, namely a morning group (n = 12) and an afternoon group (n = 12) which did not change for the duration of the study. Each subject was exposed to three environmental conditions:

> The baseline condition was a constant hot environment of 40°C (±1°C) at 40% (±5%) relative humidity. The second was a similar environment to that of the first condition, but one in which the subjects used a microcooling system at 18°C -

21°C. In the third condition the environment was controlled by a macrocooling system at 21°C (±1°C) at 60% (±5%) relative humidity.

Each of the above environmental conditions was repeated twice for both the morning and afternoon groups; once while the subjects remained at rest for the full duration of exposure and once while a physical workload of 40 W (positive component) was simulated. During each exposure of 4 h the performance tests were conducted once every hour for 40 min at a time after either a rest period or physical workout of 20 min. The physiological measurements were monitored continuously throughout the 4-hour exposure. The physiological measurements taken were rectal temperature (Tre), skin temperature (Tsk), heart rate, total sweat loss (TSL) and sweat rate (SWR). The four performance tests conducted were a grammatical reasoning test, a three-dimensional gross and fine motor coordination test, a memory task and a simplified choice serial reaction task.

The subjects were all dressed in the same type of clothing for the study and were instructed not to alter their clothing configuration for the duration of the study. Subjects were allowed to drink as much liquid as they wanted to, but the liquid intake and urine passed were strictly monitored.

The daily procedure started at 07:00 each morning with the arrival of the morning group at the laboratory. The first hour before each exposure was used to prepare the subjects for the day's session which included the weighing and instrumenting of subjects. The afternoon group arrived at 12:00 for their preparation and started their session at 13:00 daily. The sequence in which the performance tests was conducted remained the same throughout the experiment to ensure that each subject performed the same test at the same point in time every hour. The daily procedure ended at 18:00 every day. At the end of the experiment each subject completed a user perception questionnaire which had been developed especially for this study (see Appendix C). Through his responses to this questionnaire each subject expressed his subjective feelings towards the different environmental conditions, as well as towards macro- and microcooling as integrated cooling systems.

The physiological measurements were acquired by means of a dedicated acquisition computer system, Polar Electro heart rate monitors and manual weighing calculations for total sweat loss and sweat rate. The psychological performance tests were administered manually, except in the case of the reaction time test which was computerized.

Statistical analysis of the collected data was performed by using a repeated measures analysis of variance procedure. A repeated-measures factorial design (3 x 2 x 4) was used with the following factors:

- environmental conditions (3 levels)
- rest vs work (2 levels)

- time (4 levels)

It was furthermore possible to test for significant interactions between factors since $n > 1$. In all cases a significant level of $p < 0.05$ was used to indicate differences. When analysis of variance indicated that factors differed, the multiple comparison methods known as Duncan and Paired t-tests were used. These methods enabled the researcher to discover differences between individual levels of the factor means.

5.3 Summary of Results

5.3.1 Physiological Measurements

There was a significant difference between the physiological responses under the baseline condition (40°C; 40% RH) and both cooling conditions that were tested. It is clear for all five physiological parameters (rectal temperature, skin temperature, heart rate, sweat rate and total sweat loss) that the human operator benefits substantially whatever the cooling condition. Rectal temperature serves as the most important indicator of the state of thermoregulation which is ideal at approximately 36°C - 37°C. Should a rectal temperature of 39°C - 40°C be reached, it may pose serious dangers to the human as heat stress and even death may occur. During the experiment it was observed that the average rectal temperature for the baseline condition (40°C; 40% RH) was significantly higher than in the case of either cooling condition. Cooling, whether micro- or macrocooling, therefore ensures that the core temperature of the human operator remains within the ideal temperature range of 36.1 - 37.2°C.

Although the rectal temperature of the subjects did not rise particularly high during the baseline condition, definite discomfort was experienced, which was not observed during the cooling conditions. Although a slight numerical difference was observed between the micro- and macrocooling conditions in terms of mean rectal temperature, it was not significant and therefore the advantages of both systems were equal.

With reference to skin temperature, it is known from a variety of studies that a comfortable skin temperature for the human is in the vicinity of 33.5°C. From the results of this study it would appear that there was a significant difference between the mean skin temperature of the three environmental conditions. The mean skin temperature of 32.3°C maintained by the macrocooling system indicated that it was very comfortable for the subjects throughout this condition. Although the mean skin temperature of 27.4°C observed during the microcooling condition is not regarded as detrimental, it is likely to result in a certain degree of discomfort for some individuals. Though it would be possible to regulate the temperature of certain microcooling systems, it was not possible for the specific microcooling system used in this experiment. The mean skin temperature of 35.68°C during the baseline condition (40°C; 40% RH) did indeed cause discomfort and increased sweat rate among the subjects.

The physiological variable of heart rate indicated that increased temperatures did indeed lead to an increase in heart rate. The results indicated that the average heart rate was higher during the baseline condition than during the two cooling conditions, with no significant difference between the two cooling conditions. However, it should be borne in mind that heart rate is highly variable between individuals owing to various factors such as work capacity, weight and anxiety levels.

The total sweat loss and sweat rate results indicated that the highest values were measured during the baseline condition (40°C; 40% RH) and the lowest values during the macrocooling condition in the case of both variables. However, from the literature it appears once again that the changes in total sweat loss and sweat rate which occurred, even during the baseline condition, were not particularly high and therefore did not pose any health risk to the subjects. The higher sweat rates elicited in the baseline and microcooling conditions will, however, increase the discomfort of human operators in hot environments. This statement applies to both the rest and work conditions which were performed.

With reference to the rest and work conditions, it was clear that the rectal temperature, heart rate, total sweat loss and sweat rate increased when workload increased, regardless of the environmental conditions. The fact that none of these physiological variables indicated extreme values, not even during the working condition, suggests that the intermittent very moderate workload of 40 W did not make any extreme physical demands on the subjects.

5.3.2 Psychological Performance Measurements

Short-term memory/attention responses indicated no significant differences between any of the environmental conditions, nor between the rest and work conditions. From this it appeared that even though the subjects experienced significant discomfort during the baseline condition, this did not deleteriously affect their ability to concentrate.

With regard to eye-hand coordination, two strategies could be used by the subjects utilizing the test instrument. One approach was to complete each run with as few errors as possible, thus sacrificing speed. The other approach regarded the speed of completion of each run as priority, regardless of the number of errors thus caused. In order to accommodate both these approaches a performance index was worked out where both these dimensions were weighted equally. The results of this study indicated a significant difference between the baseline condition and both the cooling conditions, but no such difference was observed between the micro- and macrocooling conditions. No difference was observed between the rest condition and the intermittent work condition for the eye-hand coordination performance.

The third psychological variable measured was verbal reasoning ability. The results indicated that there was a significant difference between the baseline condition and both cooling methods. However, an interesting phenomenon was the fact that better reasoning results were obtained after the work condition than after the rest condition. As discussed, this phenomenon may be attributed to the greater state of alertness of the subjects after physical exercise, as opposed to sitting idle for the rest period. This phenomenon may also be attributed to the fact that the subjects were very relaxed during the rest conditions, as some even slept, and that they therefore would have been much less alert than in the case of physical exercise.

The reaction time test results were analyzed in two ways. Firstly, with reference to average reaction time, there was no significant difference between the various environmental conditions, nor between the work and rest conditions. Secondly, the mean response time as variable showed no significant difference between both the environmental conditions on the one hand and the rest vs work condition on the other.

It is clear from the discussion of the psychological performance results that the analysis of performance data is very difficult to interpret owing to various external factors that may influence the subjects' responses. One of the most important, yet most difficult, factors to account for was the motivational drive of the subjects when performing the tasks. Since this study was conducted over a period of approximately three weeks, it may be assumed that the repetitive nature of the tests may have led to boredom and a lack of motivation among the subjects, especially during the later phases of the experiment. Although the subjects were remunerated for their participation, this would not necessarily lead to continuous optimal performance as remuneration is generally not regarded as a consistent motivator. Another important factor which might have had an influence on the performance of the subjects was the discomfort caused during testing, especially by the rectal temperature sensors. Although the sensors used in the study were state of the art equipment, the whole idea of a rectal temperature sensor remained difficult for subjects naive to this sort of procedure to get used to and the unnaturalness of the situation would, in all probability, have influenced the attitudes of the subjects negatively.

5.3.3 User Perception

In a study of this nature, especially where psychological measurements are involved, the subjective user perception can definitely not be ignored and should therefore play an extremely important role in the evaluation of the two cooling methods. It is furthermore important to bear in mind that this study was conducted under controlled laboratory conditions which added unnatural stressors on the subjects, such as the previously mentioned rectal sensors. From the user perception questionnaire developed specifically for this study it was clear that all subjects gave preference to the macrocooling system mainly from a comfort point of view.

The microcooling system was generally accepted as a welcome alternative to a macrocooled environment, but several shortcomings were noted by the subjects. Firstly, the fact that parts of the body, namely the arms, hands, legs, feet and especially the head, were not cooled effectively; a major point of discomfort. Secondly, it was noted that the single inlet of the cold air caused discomfort on one side of the body; a more even distribution of the cold air would definitely enhance the effectiveness of the system. Owing to the fact that the so-called comfort zone differs between people, the ability to regulate the inlet air would further contribute to a more effective system. Another negative aspect of the microcooling system used in this study was the fact that the subjects were connected to the system by means of a tube which limited their freedom of movement.

On the other hand the macrocooling ambience was found highly acceptable by all the subjects. They felt comfortable throughout the exposure to this condition and were always able to concentrate fully on the tasks given to them. It was therefore clear that the macrocooling was perceived to be the optimal method of cooling in a severe thermal environment.

5.4 Conclusions

Hypothesis 1 is rejected. The physiological and psychological (cognitive and psychomotor) responses of the human operator in a hot ambient environment (40°C; 40% RH) are not equal to those under the macro- or microcooling conditions tested.

Hypothesis 2 is rejected. The physiological and psychological (cognitive and psychomotor) responses of the human operator are not equal under resting and intermittent moderate workrate (40 W) conditions, under the environmental conditions tested.

Hypothesis 3 is rejected. The physiological and psychological (cognitive and psychomotor) performance parameters of the human operator were altered when repeated four times over a period of four hours, once per hour under the environmental conditions tested.

The following practical conclusions can be drawn from the results obtained in this study:

- A cooled environment, whether by means of micro- or macrocooling, produces a significant physiological benefit for the human operator in comparison with a hot, uncooled environment as simulated during the baseline condition. This physiological benefit includes lower core and skin temperatures, heart rate, total sweat loss and sweat rate.

- An effective air microcooling system, such as the one used in this study, is able to maintain the human body in an acceptable physiological state for at least a 4-hour exposure in a severe thermal environment.

- Macrocooling has significant advantages over an effective microcooling system with reference to certain physiological and psychological performance parameters.

- If the psychological performance parameter of reasoning is a critical component in a specific task which is to be performed in a severe thermal environment, a macrocooling system should be considered as the first choice for a cooling method.

- A macrocooled environment ensures a much higher degree of perceived comfort for the human operator than a microcooling system in which parts of the human anatomy are still exposed to the high thermal environment. User perception indicates that a macrocooled environment is more acceptable for the human to operate in owing to a variety of practical limitations created by a microcooling system.

- The principle of air microcooling is definitely a useful alternative for macrocooling, especially where factors such as cost, engineering feasibility and available space need to be considered. It also has the added advantage of it being possible to adjust the temperature to individual preferences.

- Thermal comfort is a factor that should always be considered when choosing a cooling system for a particular work environment, since comfort influences factors such as motivation and productivity.

Finally, as far as it could be established in the literature no studies similar to this one have been conducted to evaluate the difference between macro- and microcooling with specific reference to physiological and psychological performance. The question originally posed by the researcher, namely whether a microcooling system would be able to maintain optimal performance in what is often regarded as the weakest link in the modern technological chain - the human operator - is a step closer to an answer. It is also clear that a macrocooling system is still the superior cooling method. However, this study did demonstrate that an effective microcooling system is a viable alternative to macrocooling when it is impossible to use the latter for specific practical design or cost-effective reasons.

5.5 Recommendations for Further Studies

For each possible application there are factors to be considered and research still needs to be done in various areas regarding the subject of macro- vs microcooling. The following recommendations are therefore made for further studies:

- The user population should be widened to include subjects from both sexes as well as people of diverse ethnic groups.

- Regarding the psychological performance tasks, further studies should include a broader spectrum of dimensions to be evaluated.

- The effect of microcooling on the general health of human operators has not yet been clearly investigated and should be addressed more thoroughly.

- Determining the optimal effective airflow rate for an air-cooled microcooling system is another factor which still needs to be investigated.

- In order to try and eliminate the effects of learning, habituation and boredom during long investigative periods, future researchers should consider randomly exposing individual subjects to experimental conditions.

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APPENDICES

APPENDIX A

BIOGRAPHICAL DATA OF SUBJECTS

SUBJECT NR.	AGE y	MASS kg	STATURE cm	BODYFAT %	BODY SURFACE AREA m^2
1	22	80.52	178.4	8.64	1.99
2	22	85.88	182.6	9.78	2.08
3	25	81.76	181.5	6.96	2.02
4	19	76.26	176.0	9.92	1.92
5	23	70.72	173.0	10.40	1.84
6	23	99.82	179.0	16.78	2.21
7	21	78.26	177.0	8.80	1.95
8	21	70.12	173.0	7.78	1.83
9	21	62.56	174.6	5.81	1.74
10	21	81.86	185.0	8.64	2.04
11	21	71.74	187.0	7.61	1.93
12	19	74.34	180.0	9.71	1.92
13	22	72.40	172.4	8.24	1.86
14	22	72.20	170.0	10.06	1.82
15	20	79.46	174.0	10.35	1.95
16	21	88.7	186.0	9.94	2.13
17	20	67.88	173.9	6.14	1.81
18	20	74.40	176.4	9.06	1.90
19	19	110.74	190.5	16.67	2.40
20	19	93.4	175.0	18.07	2.12
21	21	95.10	177.4	10.64	2.15
22	21	77.30	181.0	9.75	1.96
23	21	74.40	173.7	11.26	1.89
24	21	69.80	180.5	6.92	1.87
$\overline{X}$	21.04	79.48	178.24	9.92	1.97
SD	1.398	11.06	5.114	3.08	0.14

Note: Body fat percentage calculated according to Durnin and Womersley, 1974.

APPENDIX B

SUBJECT CONSENT FORM

I, ____, having full capacity to consent and having been fully informed of the nature of the proposed experiment entitled "Influence of macro- versus microcooling on human performance" under the supervision of Mr. G.J. Heyns, hereby volunteer and give my consent to participate as a subject in the above-mentioned research project. I understand that the consent of a parent or my legal guardian should also be obtained if I am under the age of 21 years. I am aware of the fact that I should undergo a preliminary medical examination to ensure that my standard of health is acceptable for participation in the experiment.

I understand the implications of any voluntary participation and declare that I have received verbal and written instructions concerning the nature, duration and purpose of, as well as methods and physical activities involved in the project. I am fully aware of the fact that participation in this experiment is at my own risk and that neither the researchers nor the companies and/or organizations they represent will be held liable for any personal damage or injuries sustained. I am aware of the fact that a medical doctor will be present for the duration of the experiment and that I should report any signs or symptoms indicating any abnormality or stress. I understand that I may at any time during the course of this research project withdraw my consent to and participation in the project without prejudice. I agree that the data collected during the course of this research may be used and published for statistical or scientific purposes.

I, ____, declare that:

I have read the foregoing information and that I fully understand the contents thereof. I furthermore declare that I was afforded the opportunity to ask questions and that my questions were answered to my satisfaction. My signature indicates that I have decided to voluntarily participate in this research project.

Subject:

NAME IN PRINT SIGNATURE DATE

Parent/Legal guardian (In case of subject being under 21 years of age):

NAME IN PRINT SIGNATURE DATE

Witness: I was present during the explanation of the conditions of participation, I witnessed the subject's opportunity for questions and I hereby witness the signature.

NAME IN PRINT SIGNATURE DATE

Researcher: G. J. Heyns

SIGNATURE DATE

APPENDIX C

USER PERCEPTION QUESTIONNAIRE: MICRO- vs MACROCOOLING

INSTRUCTIONS

SECTION A

The purpose of this questionnaire is to determine your perception with regard to a number of characteristics of the two cooling systems (micro vs macro) you were exposed to for the duration of the experiment. Please evaluate the acceptability of each characteristic by making a cross next to the appropriate value provided for every characteristic. The following evaluation scale is used:

+ 5	Highly acceptable
+ 3	Acceptable
+ 1	Barely acceptable
- 1	Barely unacceptable
- 3	Unacceptable
- 5	Highly unacceptable

When you award a point of -1, -3 of -5, you must please furnish reasons for your decision in the space provided. You must complete this section as objectively and honestly as possible.

Thank you for your cooperation.

+ 5	Highly acceptable	- 1	Barely unacceptable
+ 3	Acceptable	- 3	Unacceptable
+ 1	Barely acceptable	- 5	Highly unacceptable

Name: ______________________ Subject no.: ____________________

Date: ______________________

A1: MICROCOOLING SYSTEM

A. ERGONOMICS

1.	Comfortableness to get dressed.	-5 -3 -1 +1 +3 +5
2.	How does the jacket fit your body?	-5 -3 -1 +1 +3 +5
3.	Adjustability to your size.	-5 -3 -1 +1 +3 +5
4.	Connection of airpipe.	-5 -3 -1 +1 +3 +5
5.	Fitting of airpipe to jacket.	-5 -3 -1 +1 +3 +5
6.	Disconnection of airpipe.	-5 -3 -1 +1 +3 +5

COMMENTS

____

____

____

+ 5 Highly acceptable
+ 3 Acceptable
+ 1 Barely acceptable

- 1 Barely unacceptable
- 3 Unacceptable
- 5 Highly unacceptable

B. AIRFLOW AND TEMPERATURES

1. How did you find the airflow through the jacket:

1.1	During the first hour	-5 -3 -1 +1 +3 +5
1.2	During the second hour	-5 -3 -1 +1 +3 +5
1.3	During the third hour	-5 -3 -1 +1 +3 +5
1.4	During the fourth hour	-5 -3 -1 +1 +3 +5

2. How did you find the air temperature blown into the jacket:

2.1	During the first hour	-5 -3 -1 +1 +3 +5
2.2	During the second hour	-5 -3 -1 +1 +3 +5
2.3	During the third hour	-5 -3 -1 +1 +3 +5
2.4	During the fourth hour	-5 -3 -1 +1 +3 +5

COMMENTS

C. GENERAL

1. How effectively were the following parts of the body cooled:

1.1	Head	-5 -3 -1 +1 +3 +5
1.2	Neck and Chest	-5 -3 -1 +1 +3 +5
1.3	Arms	-5 -3 -1 +1 +3 +5
1.4	Legs	-5 -3 -1 +1 +3 +5
1.5	Feet	-5 -3 -1 +1 +3 +5

COMMENTS

+ 5 Highly acceptable
+ 3 Acceptable
+ 1 Barely acceptable

- 1 Barely unacceptable
- 3 Unacceptable
- 5 Highly unacceptable

---

2. How effectively did the microcooling system remove sweat from the following parts of the body:

2.1	Head	-5 -3 -1 +1 +3 +5
2.2	Neck and Chest	-5 -3 -1 +1 +3 +5
2.3	Arms	-5 -3 -1 +1 +3 +5
2.4	Legs	-5 -3 -1 +1 +3 +5
2.5	Feet	-5 -3 -1 +1 +3 +5

COMMENTS

3. How did you experience the air distribution through the jacket?

-5 -3 -1 +1 +3 +5

COMMENTS

4. How did you experience microcooling as cooling mechanism?

-5 -3 -1 +1 +3 +5

COMMENTS

5. How did the other subjects in your group experience microcooling?
-5 -3 -1 +1 +3 +5

COMMENTS

6. Write down the three most positive aspects of the microcooling system as you experienced it:

6.1
6.2
6.3

+ 5	Highly acceptable	- 1	Barely unacceptable
+ 3	Acceptable	- 3	Unacceptable
+ 1	Barely acceptable	- 5	Highly unacceptable

---

7. Write down the three most negative aspects of the microcooling system as you experienced it:

7.1 ____________________

7.2 ____________________

7.3 ____________________

<u>A2: MACROCOOLING SYSTEM</u> (21°C)

1. How did you find the temperature of the environment at 21°C:

1.1	During the first hour	-5 -3 -1 +1 +3 +5
1.2	During the second hour	-5 -3 -1 +1 +3 +5
1.3	During the third hour	-5 -3 -1 +1 +3 +5
1.4	During the fourth hour	-5 -3 -1 +1 +3 +5

<u>COMMENTS</u>

____

____

____

2. How effectively were the following parts of the body cooled:

2.1	Head	-5 -3 -1 +1 +3 +5
2.2	Neck and Chest	-5 -3 -1 +1 +3 +5
2.3	Arms	-5 -3 -1 +1 +3 +5
2.4	Legs	-5 -3 -1 +1 +3 +5
2.5	Feet	-5 -3 -1 +1 +3 +5

<u>COMMENTS</u>

____

____

____

3. How effectively did the macrocooling system remove sweat at the following parts of the body:

3.1	Head	-5 -3 -1 +1 +3 +5
3.2	Neck and Chest	-5 -3 -1 +1 +3 +5
3.3	Arms	-5 -3 -1 +1 +3 +5
3.4	Legs	-5 -3 -1 +1 +3 +5
3.5	Feet	-5 -3 -1 +1 +3 +5

<u>COMMENTS</u>

____

____

____

+ 5	Highly acceptable	- 1	Barely unacceptable
+ 3	Acceptable	- 3	Unacceptable
+ 1	Barely acceptable	- 5	Highly unacceptable

---

4. How did you experience macrocooling as cooling mechanism?
   -5 -3 -1 +1 +3 +5

COMMENTS

5. How did the other subjects in your group experience macrocooling?
   -5 -3 -1 +1 +3 +5

COMMENTS

6. Write down the three most positive aspects of the macrocooling system as you experienced it:

6.1 ______________________
6.2 ______________________
6.3 ______________________

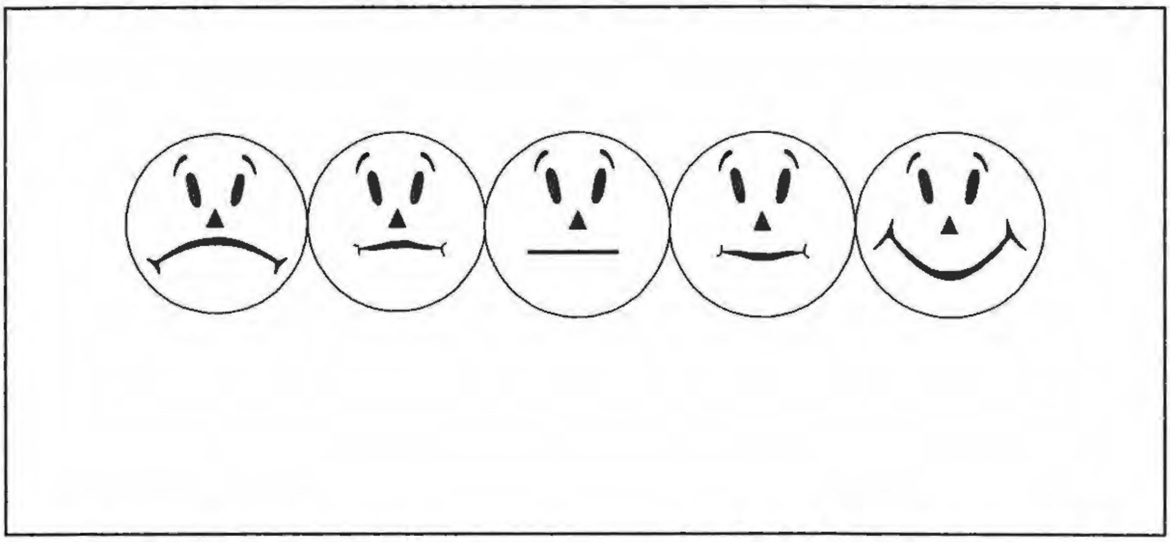
7. Write down the three most negative aspects of the macrocooling system as you experienced it:

7.1 ______________________
7.2 ______________________
7.3 ______________________

SECTION B

1. Which of the faces below describe your feelings the best when the concept of microcooling is mentioned?

2. Below you will find a number of expressions of feeling described by words of opposite meaning. Indicate by means of a cross (x) on the line your feelings with regard to microcooling at a chosen point of the scale.



<u>Example</u> Angry ____________________x____________________ Happy

Angry ____ Happy

Uncomfortable ____ Comfortable

Unfriendly ____ Friendly

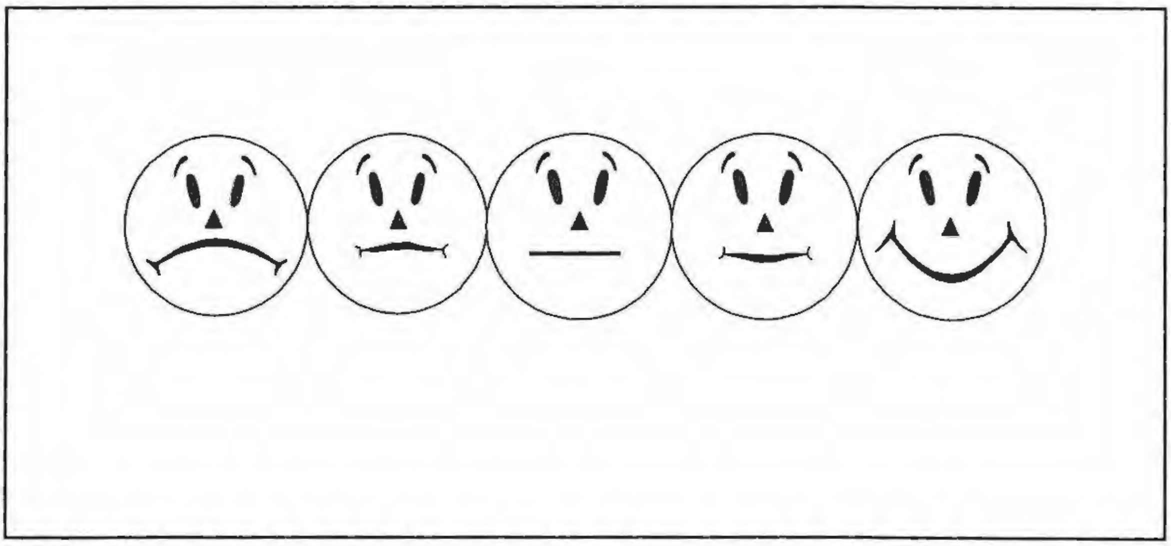
Bad ____ Good

Unhealthy ____ Healthy

Stressful ____ Not stressful

Do not like ____ Like

3. Which of the faces below describe your feelings the best when the concept of macrocooling is mentioned?



4. Below you will find a number of expressions of feeling described by words of opposite meaning. Indicate by means of a cross (x) on the line your feelings with regard to macrocooling at a chosen point of the scale.

Angry	____	Happy
Uncomfortable	____	Comfortable
Unfriendly	____	Friendly
Bad	____	Good
Unhealthy	____	Healthy
Stressful	____	Not stressful
Do not like	____	Like