

AN INVESTIGATION INTO CONTROL MECHANISMS OF DRIVING PERFORMANCE:
RESOURCE DEPLETION AND EFFORT-REGULATION

BY

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THESIS

Submitted in fulfilment of the requirement for the degree of Master of Science

Department of Human Kinetics and Ergonomics

Rhodes University, 2013

Grahamstown, South Africa

ABSTRACT

Driver fatigue is a complex phenomenon that has a range of causal factors including sleep-related and task-related factors. These manifest as different safety and performance outcomes. Extensive research has been applied to linking these factors to performance impairment. However, little research focuses on the mechanisms by which this link exists. This research project therefore focuses on the processes underlying how driving performance is controlled and maintained during the development on non-sleep-related driver fatigue. The main aim was to establish whether progressive impairment of driving control over a prolonged drive could be attributed to a depletion of attentional resources, as proposed by Resource Theory, or to a withdrawal of effort, as proposed by Effort-Regulation Theory. As a multi-component skill, driving requires perception, cognition and motor output. The secondary aim of this research was therefore to assess whether a prolonged drive impairs stage-specific information processing.

Participants (n=24) in three experimental groups performed a 90-minute simulated drive wherein they were expected to keep the bonnet of a car on a lane (tracking task). The three groups differed in terms of lane width: small, medium and large, corresponding to low, medium, and high task-demand, respectively. To assess the impacts of this task on stage-specific information processing, participants performed a set of resource specific tests before and after the prolonged drive. Each task had two difficulty variations to ensure that performance decrement was due not only to the task-characteristic, but specifically to resource depletion. The tests probing information processing were: a modified Fitts' tapping task for motor programming, a digit recall task for perception, and an object recognition reading task for cognition. Performance was measured as lateral deviation of the car. Physiological measures included heart rate frequency (HR) and various time- and frequency-domain heart rate variability (HRV) parameters, eye blink frequency and duration. The Borg CR-10 scale was used to evaluate subjective effort and fatigue during the task.

Driving control declined over time and was supplemented by HR, HRV, blink frequency and duration, indicating an increase in parasympathetic activity (or a reduction in arousal). An increase in blink frequency was considered as a sign of withdrawal of attentional resources

over time. Driving control declined to a greater extent in the large road width group and reflected a lower parasympathetic activity, whereas the inverse was observed for the small road width group. Resource tests reveal a non-specific impairment of information processing following the prolonged drive. However, this was accompanied by an increase in parasympathetic activity.

Overall, results indicate that Effort-Regulation Theory better accounts for the impairment of driving control in prolonged driving than does Resource Theory. This suggests that the impact of fatigue is guided more by task goals and intrinsic motivation than by the manner in which the fatigue state developed. Moreover, performance impairment by effort-regulation is dependant more on time on task than on task-demand.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr Swantje Zschoernack, for her guidance, trust and support, which allowed me to conduct with independence the research that has become the work presented in this thesis. The lessons I have learnt during this period will be instrumental in building my academic career. I also would like to acknowledge Professor Matthias Göbel, for his valuable insight and advice during the early conceptual development of the project.

I would like to thank Dr Candice Christie, whose support and advice during this project has been immense. Thank you.

I would like to thank all my past and present colleagues in the Department of Human Kinetics and Ergonomics for creating a friendly, engaging environment. In particular I would like to thank Dave Goble, Lee Pote, Robert Jones and Gareth Barford for their friendship and support.

I would like to thank June McDougall for always being there to help, and all the participants who willingly gave of their time to contribute to this research.

Most importantly, I would like to thank all my friends and family.

The financial assistance from the Ernst & Ethel Eriksen Trust, Rhodes University Scholarship Committee and the National Research Foundation Masters Scholarships towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to Rhodes University or the donor.

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CHAPTER I

INTRODUCTION

1.1 ROAD ACCIDENT CONTEXT

Driving is a common activity, making driving safety an important issue in everyday life. In South Africa and the world over, road accidents are the main cause of premature deaths in people 45 years and below. The burden of crashes is counted not only in lives, and handicaps, but also as a cost to society. In the 20 years from 1990 to 2010, the number of licensed vehicles in South Africa increased by 23.7%, from about 5.25 million to 9.59 million, while in the same period the total annual mileage travelled increased by 27.5 % to reach 129 million kilometres in 2010 (Road Traffic Management Corporation, 2011). Despite safety improvements in road and vehicle design, the number of fatal crashes still increases. Motor vehicle-related fatalities increased from 11,157 in 1990 to 14,627 in 2009 (Road Traffic Management Corporation, 2011), with a social cost rising to an estimated R306 Billion¹ in 2012, approximately 10% of South Africa's gross domestic product (Ensor and West, 2013). This figure dwarfs estimates from other developing countries, where the cost of accidents is said to consume an average of 2% of GDP.

Based on the 2006 Millennium Development Goals, one of the aims of the 2015 Road Traffic Safety Management Plan is to reduce by half the rate of accident fatalities arising from road and other transport by 2015 (Road Traffic Management Corporation, 2011). Taken together, these figures demonstrate that driving safety represents a persistent and important issue in transport in South Africa. Reducing crash involvement would benefit millions of people across South Africa and the world.

Reducing the road toll requires a deep understanding of the factors that contribute to accidents. Typically, these are ascribed to three factors: human (driver) error, environmental factors and vehicular defects (Figure 1). Of these, driver error is reported to contribute to 92.9%, while road and vehicle factors contribute roughly 30 and 10%, respectively (Treat *et*

¹ R306 Billion $\approx$ \$34.3 Billion

² The fact that the participants may have anticipated that it was the same tasks that were being repeated the

al., 1977; Shinar, 1978). Thus it is clear that the focus of the major efforts to reduce the road toll should be on the human factor, and on understanding how it relates to the development of fatigue.

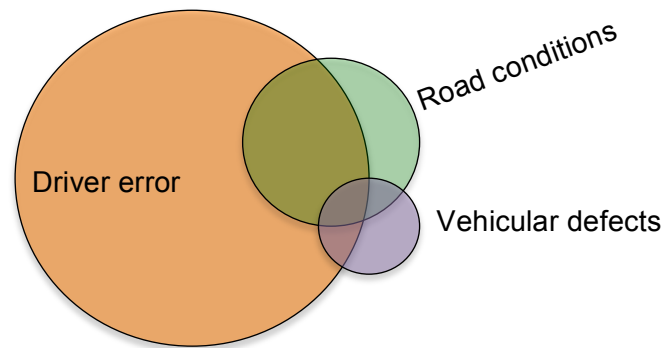


Figure 1: Contributions of the three categories of contributing factors.

According to Lee (2006), these performance breakdowns can be grouped in four major categories: alcohol, fatigue, aging, and distraction. By some accounts, fatigue plays a role in up to 20% of vehicle accidents (Maycock, 1996; Horne and Reyner, 1995; Dobbie, 2002). Williamson *et al.* (2011) argue that this proportion is likely to be underestimated, as the evidence used to link fatigue to crashes is often based on the exclusion of other factors rather than trying to specifically identify fatigue as a causal agent. This underestimation is likely to be due to the lack of a proper definition of crashes due to fatigue, our inability to measure and quantify fatigue in the same way that we can for other causal factors, and an inability on the part of the driver to accurately assess their level of fatigue and thus failing to report on it (Horne and Reyner, 1995).

Fatigue is a complex, partly hypothetical construct that itself has a range of causal factors related to sleep task-related factors; these manifest as different performance and safety-related outcomes (May and Baldwin, 2009). What compounds this complexity further is that these fatigue states can appear simultaneously and can also be exacerbated in the presence of other endogenous factors such as age, personality, race, and exogenous factors such as education, motivation, and medication (Sirevaag and Stern, 2000; Di Milla *et al.*, 2011). These combine to form a driver fatigue state, which results in impaired information processing and poorer driver performance (Thiffault and Bergeron, 2003b).

The research community has focused on understanding the impact of these factors on performance, both in isolation and in concert (Horne and Reyner, 1995; Williamson *et al.*, 2011; Thiffault and Bergeron, 2003b). However, little research focuses on the processes underlying the control and maintenance of driving performance in these conditions. From a safety perspective, this understanding is vital as these same mechanisms control the extent to which, and rate at which fatigue develops. If we can understand how performance is controlled, we will be better able to predict performance breakdowns in different situations and under different stresses, which will inform more effective fatigue management strategies and countermeasures.

1.2 RESEARCH PROBLEM

1.2.1 Thesis Objectives

The main objectives of this research are to:

- provide analyses of driving performance in a prolonged simulated driving task from a behavioural, psychophysiological and subjective perspective
- assess the validity of two leading candidate mechanisms proposed to control driving performance
- design an experiment that is able to identify whether the impacts of prolonged driving differentially tax information processing stages

By achieving the objectives, this thesis will provide greater insight into control mechanisms of driver performance, how they relate to the development of fatigue with time on task, and whether they impact on the ability to mobilise resources at the different information processing stages.

1.2.2 Theoretical Background of the Research Problem

This research uses and extends current knowledge on factors contributing to fatigue-related driver performance decrements. Such factors are classified to understand the mechanisms controlling driving performance with time on task.

Driving for prolonged periods, with the ability to maintain adequate control of the vehicle on the road in relation to others requires a top-down control of attention (Henderson and Dittrich, 1998). However, as these attentional control processes are transient (Smallwood and Schooler, 2006), prolonged driving performance requires a mechanism that stabilises or reactivates these processes to ensure that drivers are able to maintain attention (Banich *et al.*, 2000).

Attentional Resource Theory posits that prolonged exertion of goal-directed attention will deplete attentional resources (Matthews *et al.*, 2000). Because attentional resources exist in a fixed capacity, depletion will result in a reduced ability to implement task-specific information processing (Kahneman, 1973), at which point performance will break down (Warm *et al.*, 2008). Thus performance is impaired because resources are depleted.

However, this resource depletion account has been criticised by Hancock and Warm (1989), who propose an alternative account based on Effort-Regulation Theory. This model attributes performance decrements to either a failure on the part of the driver to maintain a stable allocation of cognitive resources, or effort, to the driving task (Hockey, 1997), or to the driver misperceiving the demands of the task (Matthews and Desmond, 2002). Thus, in this model, performance is not impaired because resources are depleted, but rather because there is a misallocation of cognitive resources.

Therefore, accumulating resource depletion and effort-regulation emerge as two candidate mechanisms that may be active during the decrement of driving performance with time on task.

While there are discrepant views regarding the nature of the relationship between time on task and driving performance, it is generally accepted that fatigue acts through both mechanisms (Matthews, 2001). However, to what extent performance decrements with time on task can be attributed to either is yet to be established and therefore requires further investigation (Williamson *et al.*, 2011). The aim of this study was to assess the validity of these models as foundations for understanding performance decrement while attending to a prolonged driving task.

The understanding of how these processes function in the presence of sleep-related fatigue is a difficult human factors issue and is beyond the scope of this study.

1.2.3 Approach

Fatigue is a general psychophysiological state wherein an individual's ability to perform the driving task is severely diminished (Thiffault and Bergeron, 2003b). Such a state can develop as a result of variances in the body's natural sleep/wake cycle, the amount of time an individual has been awake, and in response to a combination of task characteristics (Williamson *et al.*, 2011). Fatigue impairs perceptual, cognitive and motor performance, which is concerning given that driving is a complex multi-component skill (Angell *et al.*, 2006).

Although the concept is usually associated in the literature with prolonged or effortful work, fatigue can be observed in other, less obvious settings. The consequence of fatigue is a breakdown of driver performance, which is known to be a key factor leading up to an accident. Unfortunately, fatigue cannot be measured or observed directly, only through its behavioural and physiological manifestations.

Consequently, it is important to design a research study that separates the effects of resource depletion and effort-regulation in the control of driver performance, and account for the extent to which a prolonged drive impacts on the perceptual, cognitive and motor performance aspects of information processing.

To address these questions, this study will manipulate road width in a prolonged driving task to observe the effect of high versus low task demand on the time-related changes in behavioural, psychophysiological and subjective measures to deduce the contributions of resource depletion and effort-regulation. In addition, pre- and post-tasks will be introduced to probe the impairment of attentional resources. The changes in performance between the pre- and post-maximal driving tests can be attributed to resource depletion.

1.3 RESEARCH HYPOTHESES

The two performance theories described previously make differing predictions regarding the effects of drive task-demand on indices of driver performance, psychophysiological measures and information processing capacities.

Resource theory predicts that fatigue responses would be lowest under the experimental group with the smaller drive task-demand (i.e., the large road width group) and highest under the higher drive task-demand (i.e., small road width group). Further, Resource Theory predicts that the prolonged drive will negatively impact on the allocation of the various cognitive resources. If the allocation is not affected, Resource Theory predicts that there would be an increase in psychophysiological responses to compensate for the depletion of resources.

By contrast, Effort-Regulation Theory predicts that fatigue responses would be lowest under the experimental group with the higher drive task-demand (i.e., the small road width group) and highest under the smaller task-demand (i.e., large road width group). Further, Effort-Regulation Theory predicts that the prolonged drive will not selectively impair resources at any of the information processing stages, however the performance will be impaired, which will reflect as a decrease in psychophysiological responses, due to a withdrawal of effort.

1.4 THESIS OUTLINE

Chapter 2: Review of Literature

Chapter 2 covers the background to the relationship between fatigue and task performance, which is necessary to understand the work presented later in this thesis. It details the main sources of fatigue before unpacking the concepts of resource depletion, effort-regulation and information processing. It concludes with an outline of the various types of measures used to assess fatigue and performance breakdown.

Chapter 3: Methodology

Chapter 3 focuses on the concept and design of the current study using the literature presented in earlier chapters. Its implementation is then presented.

Chapter 4: Results

Chapter 4 analyses the data collected on the driving simulator and during the pre- and post-tests.

Chapter 5: Discussion

With the experiment in place, Chapter 6 proceeds to discuss the effects of time on task task-demand (road width) on fatigue development observed throughout the experiment. It goes on to discuss the he impact of the prolonged driving task on the resources used in various information processing stages.

Chapter 6: Conclusion

Chapter 7 concludes the thesis with a summary of the work presented in previous chapters and goes on to discuss issues and insights that have been identified in this work, along with paths for future research.

CHAPTER II

REVIEW OF LITERATURE

INTRODUCTION

This chapter aims to provide the necessary background for understanding and assessing the relationship between fatigue and driving performance, as well as the factors that are known to influence it.

The first section examines the concept of fatigue and how it applies to the driving context before coming to a definition of fatigue for current research. Section 2.2 unpacks the various sources of fatigue, including sleep-related factors, task-related factors and individual differences. Section 2.3 clarifies some of the basic concepts required to understand how humans interact with information in their environment, followed by a description of the human information processing system. The next section outlines two candidate mechanisms proposed to underlie the development of fatigue with time on task, as well as how each accounts for performance impairment. Section 2.4 outlines the various types of measures used to assess the breakdown of performance. These include behavioural measures, psychophysiological assessments and subjective assessments. Advantages and disadvantages of each method are also discussed before concluding the chapter with a summary of the findings.

2.1 WHAT IS FATIGUE?

2.1.1 Grappling with Our Understanding

In any attempt to understand and define fatigue it is useful to acknowledge that at the most basic level it is an overarching term that accounts for a myriad of mental and physical responses to taxing or prolonged work (Hitchcock and Matthews, 2005). Outside of this, there exists little agreement on a succinct and universally acceptable definition of the construct of fatigue (Dawson *et al.*, 2011; Desmond and Hancock, 2001), and no widely satisfactory biological marker for it has yet emerged (Kohl *et al.*, 2009). This is not surprising, as fatigue

has a non-specific aetiology, there are vast individual differences in susceptibility and adaptations to it, and there is no consensus regarding its measurement (Dawson *et al.*, 2011). To compound these factors, the mechanisms underlying how this phenomenon affects cognitive and task performance are complex and poorly understood (Boksem and Tops, 2008). This is especially startling when one realises that reference to a fatigue framework was first made in 1875 (Rabinbach, 1990).

Fatigue therefore appears to be multi-faceted, with the various sources all eliciting subjective tiredness, but also differing in their performance effects and the mechanisms through which they impact on information processing. This suggests that if a “gold standard” for its measurement were ever established, it would be a useful tool only insofar as it could account for the interaction effects of each of its causal agents (Di Milia *et al.*, 2011; Hancock and Scallen, 1999). Some argue that given our limited understanding, fatigue should be viewed merely as the mechanism by which the link between causal factors and performance outcomes exists (Williamson *et al.*, 2011). What is important to note, however, is that while discrepant views on a definition exist, each carries value when considered against a backdrop of the research in which it is being applied. Accordingly, before coming to our own definition of fatigue it is relevant to first consider the context in which it is being examined.

2.1.2 The Driving Context

Driver fatigue has long been identified as a major contributing factor to road accidents, representing a serious and persistent problem in transportation. Performance decrements and subjective feelings of sleepiness during extended driving durations may develop due to fatigue or boredom – this distinction will be unpacked in Section 2.6. Long-distance heavy-vehicle truck drivers are at significant risk due to the potential for sleep restriction created by their long and irregular hours, which neglect the influence of the circadian rhythm and the benefits of adequate rest breaks (Horne and Reyner, 1999; Lal and Craig, 2001). These factors are discussed further in Section 2.2.

Driving is predominantly a cognitive task, but more precisely a vigilance task (Dinges, 1995). Therefore, many of the definitions around driver fatigue focus on cognitive fatigue, the concept of vigilance, and the factors known to influence them. A principle factor in vigilance

performance is cognitive effort, which is an umbrella term pertaining to attention, selective attention, complex decision-making, and automatised perceptual-motor skills (Lal and Craig, 2001). Therefore, by linking vigilance performance to the driving task, driver fatigue emerges as a phenomenon characterised by inhibited alertness associated with reduced cognitive and motor performance. Eoh *et al.* (2005) also class fatigued drivers as having impaired levels of information processing speed and memory capacity, which results in a poorer task performance. This has the concerning implication that fatigued drivers are in a state where they are unable to maintain visual vigilance and to react timeously to unique, emergency situations. Williamson *et al.* (2011) describe how these states vary according to the driver's level of arousal and are most prevalent at night or early morning due to the fluctuation of the circadian rhythm (see Section 2.2 for details). The extent of the effect of fatigue on performance outcomes is further exacerbated by task-related factors such as prolonged driving and monotonous environments, as well as time since last sleep (Thiffault and Bergeron, 2003b; Lal and Craig, 2001). These sources of fatigue are discussed in greater detail in the following sections.

2.1.3 Defining Fatigue

“Fatigue”, “sleepiness” and “drowsiness” are often used interchangeably and inconsistently in the literature (Jackson *et al.*, 2011). They refer to three different neurobiological processes through which circadian rhythm and the need to rest is controlled. In general terms, fatigue is the transition between being awake and falling asleep (Brown, 1994). An important distinguishing factor of fatigue is that it is usually manifested as physiological sleepiness, which results in a decrement in task performance via cognitive and psychomotor impairment. Brown (1994) distinguishes fatigue in terms of physical fatigue and mental fatigue. Both types of fatigue can result in decrements in task performance (Davies and Parasuraman, 1982).

Physical fatigue is related to dynamic and/or static muscular work and is synonymous with muscle fatigue. Such fatigue results in a loss of muscle strength, pain, discomfort, headaches, nausea and blurred eyes. Therefore, it contributes to impaired coordination and increased chances of errors and accidents during driving (Lal and Craig, 2001). On the other hand, mental fatigue is used to describe a gradual development of fatigue in relation to decreased efficacy and motivation, and decreased alertness and performance with time on task

(Grandjean, 1979). In some cases prolonged work does not always result in a fatigue state (Park *et al.*, 2001). Nevertheless, performance deterioration due to mental fatigue increases the risk of accidents while performing a task, which is especially notable in the driving context, as it requires greater cognitive effort than physical effort (Brown, 1994).

Fatigue can be further categorised as either active or passive fatigue states (Hancock and Desmond, 2001). Active fatigue derives from continuous and prolonged high perceptual motor demands, while passive fatigue appears over time, conditions of underload, and where stimulation and perceptual motor demands are low. Some studies have attempted to link the passive fatigue state with the underload aspect of effort-regulation (Saxby *et al.*, 2005). However, the active/passive distinction rather seems to attribute performance impairments to task characteristics without acknowledging behavioural mechanisms, an element Hancock and Scallen (1999) assert is vital in modelling human performance. The active/passive distinction has some parallels with the inverted-U relationship between arousal and performance (Brown, 1994), discussed below.

Thus, fatigue emerges as a general state of reduced efficiency and, as Brown (1994) puts it, a “disinclination to continue performing the task at hand”. However, as this study is particularly focused on exploring the mechanisms underlying the psychophysiological manifestations of fatigue, as opposed to focusing on its behavioural manifestations, fatigue in the current study is defined as “a general psychophysiological phenomenon, which diminishes the ability of the individual to perform the driving task” (Adapted from Thiffault and Bergeron, 2003a). Together with this understanding is due cognizance of the changes in motivational and subjective states that occur during this transition.

To understand the context in which fatigue is understood in this research, it is relevant to acknowledge the multiple domains of fatigue research by discriminating the various sources of fatigue, their underlying processes, and types of fatigue responses (Matthews *et al.*, 2000).

2.2 SOURCES OF FATIGUE

As previously stated, while fatigue is a familiar state for drivers, it is generally hard to define and measure with any rigor (Gawron *et al.*, 2001). Nevertheless, among attempts to define

fatigue are those from an operational perspective, such as the ones outlined above. Another way to view fatigue is to consider it according to its sources or causal factors. Williamson *et al.* (2011) identify types of fatigue in terms of causal factors, including circadian-related factors, sleep homeostasis and task-related factors (Figure 2). May and Baldwin (2009) group the sources of fatigue into sleep-related factors and task-related factors – the distinction is followed in this section. Though individual differences are often described as factors that merely compound the extent of the fatigue, some dimensions do show a causal link (Thiffault and Bergeron, 2003a).

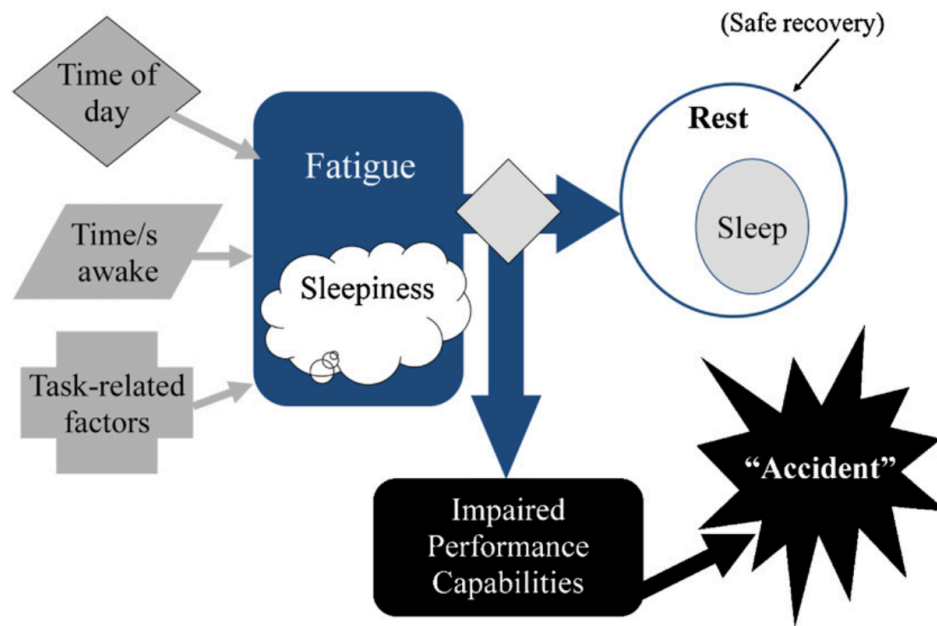


Figure 2: Framework for examining the relationship between fatigue and safety (adapted from Williamson *et al.*, 2011, pg. 499).

2.2.1 Sleep-Related Factors Affecting Fatigue

Circadian and homeostatic factors combine to govern the body’s natural sleep/wake cycle, or internal clock. Sleep homeostasis relates to the neurobiological need to sleep, therefore, the longer one remains awake the greater the desire to sleep and the more difficult it is to resist (Dinges 1995). In these states, the driver suffers impaired alertness and performance (Williamson and Friswell, 2011). The drive of sleep homeostasis to initiate sleep is also very much dependent on the extent and quality of prior sleep or wakefulness, and in this way

attempts to balance the time an individual spends awake with the time an individual spends asleep (Williamson *et al.*, 2011). As the drive for sleep increases relative to time awake (this is usually linked to the progression of the day), we typically see peaks between 10pm and midnight (Porter, 2011). The concept of sleep homeostasis implies that sleepiness may be akin to mental fatigue, however they are fundamentally distinct in terms of how they are both generated, and what is required to overcome or recover from their effects (Jackson *et al.*, 2011). While rest alone is sufficient to alleviate mental fatigue, only adequate sleep can reduce sleepiness and restore performance (Figure 2).

However, a sleep-driver linked more strongly with the body's internal processes is the circadian pacemaker, which is an internal clock located in the suprachiasmatic nucleus (SCN) of the hypothalamus (Dijk and Lockley, 2002) and regulates physiological and behavioural functions on a 24-hour basis. The distinction between the circadian pacemaker and sleep homeostasis is that the drive to sleep from the circadian rhythm is independent of time awake. Evidenced from neurobehavioural measures, light is reported to provide the principle time cue or "zeitgeber" for the SCN (Wirz-Justice, 2006), thus the circadian wakefulness drive increases in power during the day and dissipates after melatonin is secreted during the night (Edgar *et al.*, 1993). There is evidence that the circadian rhythm is synchronized by other zeitgebers such as knowledge of clock time, and work time (Kroemer and Grandjean 1997). In addition to the circadian co-variation of neurobehavioural variables with light-factor zeitgebers, there appears also to be a short-term dip in these variables in the afternoon, which has been referred to as the mid-afternoon, siesta, post-lunch, or post-prandial dip (Dinges, 1995). This function has reportedly received mixed support, with some finding the effect both in the field (Bjerner *et al.*, 1955) and in the laboratory (Monk *et al.*, 1997), but some finding it inconsistent (Folkard, 1983). The relationship between driver performance and circadian fluctuations has been studied extensively (see Folkard, 1997 for a review). However, few have studied the functioning of fatigue processes in the context of circadian factors. This is pertinent to note, as the various sources of fatigue outlined in this section may produce very different responses when occurring simultaneously (Williamson *et al.*, 2011).

2.2.2 Task-Related Factors Affecting Fatigue

Task-related factors are further broken down into time on task factors and task-demand factors.

Time on task

In the workplace, time on task is usually used to refer to time on duty or time into the work shift. In the context of driving, time on task is also known as drive duration (Williamson *et al.*, 2011). Time on task typically has a strong correlation with fatigue, with many authors arguing that there is a direct causal link between the two. The deleterious effects of time on task on driving are widely reported, both from the point of view of subjective reports and objective performance impairments in field and laboratory settings (Williamston *et al.*, 2011). Folkard (1997) conducted a meta-analysis showing that there is an increased risk of being in a drowsy driving crash during the first two hours of driving, followed by a decrease for the next two hours before increasing again. Maycock (1996) noticed a greater risk of being involved in a fatigue-related crash when driving for a longer time without taking a break, specifically when driving three hours or longer. The impact of time on task on fatigue can also be compounded by the other sources of fatigue described in this section. However, this interaction is complex and not very well understood.

The different fatigue processes discussed in Section 2.4 offer alternative accounts of why time on task, or drive duration, impacts on driving performance. Some suggest that the prolonged duration leads to a depletion of attentional resources required to maintain adequate performance, while others assume that extended duration leads to monotony which in turn leads to an inability to exert executive control over the allocation of attentional resources, also known as effort. In either case, time on task has a deleterious effect on task performance.

Task demand

Boredom, monotony and under-stimulation may also contribute to the development of fatigue and performance decrement. One way to conceptualise this is to consider it within the framework of Arousal Theory (Figure 3; Thiffault and Bergeron, 2003b). The inverted-U relationship between performance and arousal, or Arousal Theory, holds that fatigue will

develop in conditions of under-stimulation, or low task-demand. Associated with this is low performance efficiency, decreased attention and diminished cortical arousal (Grandjean, 1977). As per the suggestion of Carskadon and Dement (1987), it is likely that these conditions may in fact “unmask” any latent sleepiness. Hancock and Verwey (1997) argue that high levels of stimulation or high task-demand can also bring about fatigue. A further assumption of this model is that the optimal level of arousal is dependant on individual differences discussed below (Zuckerman, 1972).

Authors have differing views as to the mechanism that underlies performance decrements in these situations. Some attribute the decrement to a resource account, while others relate it to an effort account. As indicated above, these distinctions will be unpacked in Section 2.4. Though the inverted U relationship of Arousal Theory has been discredited on many fronts in terms of its ability to predict performance impairments (Matthews *et al.*, 2000), what is important to remember about task demand is that it is a critical factor in the aetiology and evolution of fatigue states.

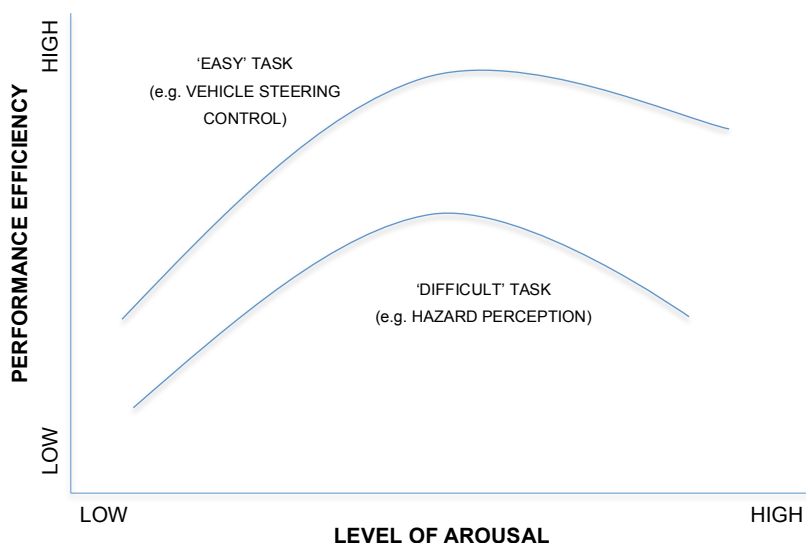


Figure 3: Performance as a function of arousal (Inverted-U/Arousal Theory; adapted from Brown, 1982, pg. 86).

2.2.3 Individual Differences

Individuals vary in terms of their capacity to resist fatigue. In their profiling of susceptibility to monotony and fatigue, Thiffault and Bergeron (2003a) identified three different mediating factors that have been shown to amplify performance decline. The first ranges across the extremes of the introversion/extraversion dimension. Extraverts appear to require more stimulation from the driving environment to stave off vigilance decline, which translates as a diminished capacity to cope with prolonged, monotonous driving. In contrast, introverts tend not to require such stimulation and thus may be resistant to certain forms of fatigue. The second factor, sensation seeking, shares many similarities with extraversion. However, it extends its reach into predicting risky driving behaviour and negative reactions in the face of monotonous driving (Zuckerman, 1972). The third, field dependence, refers to an individual's ability to distinguish between task-relevant objects and task-irrelevant objects (Roge, 1996). Based on their findings, Thiffault and Bergeron (2003a) concluded that personality traits are a much stronger predictor of driving performance than are subjective ratings of fatigue. However, it would go beyond the scope of this study to discuss these issues in detail. See Shaw *et al.* (2010) and Matthews *et al.* (2010) for detailed accounts.

The development of fatigue therefore appears to be influenced by a range of both task and individual factors (Shaw *et al.*, 2010; Ackerman *et al.*, 2011). High workload and monotonous tasks that afford the driver little scope for implementing compensatory strategies appear to be most vulnerable to fatigue effects (Matthews *et al.*, 2010). Conversely, tasks that offer high levels of challenge and intrinsic interest can be highly fatigue-resistant (Holding, 1983). What is required to understand how these situations interact with human behaviours is an examination of the core information processing functions of the driver in response to fatigue.

The different sources of fatigue manifest in varying degrees as physical, affective, motivational and cognitive symptoms (Matthews, 2001), and differ in terms of performance effects and the mechanisms through which they impact on information-processing (Hitchcock and Matthews, 2005). Indeed, Zeidner (1998) observed cognitive disturbances to be a better predictor of performance decrement than physical symptoms. Hitchcock and Matthews (2005) explain this to mean that fatigue expressed as physical discomfort may not be equivalent to fatigue expressed as loss of concentration.

2.3 THEORIES RELEVANT TO INFORMATION PROCESSING

2.3.1 Basic Concepts

To understand how humans interact with information, introduction of some basic concepts is required. The concept of a limited processing capacity is inherent and implied in all information processing theories (e.g., Broadbent 1958, Kahneman, 1973, Posner, 1978, Wickens, 1984). Kahneman (1973), for instance, specifies the metaphor of a single undifferentiated capacity from which resources are available for task performance. O'Donnell and Eggemeier (1986) do not differentiate between the metaphors of "capacity" and "resource". Wickens (1992), however, disagrees with this, defining capacity as the maximum or upper limit of processing capability, while resources represent the mental effort supplied to improve processing efficiency. This is in line with Norman and Bobrow (1975) who also refer to resources as processing effort. In this study, the differentiation between capacity as upper limit of capability and resources as amount of processing facilities allocated will be followed. As the estimation of different resource capacities is complex, the term allocation will be used in this thesis to mean what is intended for the term capacity.

Norman and Bobrow (1975) further distinguish between data-limited and resource-limited tasks to explain two factors that limit task performance. In data-limited tasks, performance cannot improve because there is a limitation in the quality of the task, and not a limitation on the part of the operator. If task performance can be improved by applying additional effort or attentional resource, it is said to be resource-limited. In most cases, pure driving would be classed as a resource-limited task. This distinction is an important concept in understanding what influences the upper and lower limits of information processing. This is also important to consider when attempting to correctly determining whether performance changes are due to fatigue or merely the task characteristic.

2.3.2 Information Processing Model

Wickens' (1984) information processing model (Figure 4) builds on single resource theories (Kahneman, 1973; Norman and Bobrow, 1975). Wickens' model describes a qualitative model of human information processing that incorporates stages used to perceive sensations,

transform data and choose an action in response. The different stages of the information processing are sensory processing, perception, cognition and memory, and response selection and execution. Processing at each stage takes time and requires mental resources, with any additional considerations such as uncertainty and overload potentially extending processing time.

The sensory memory (Figure 4) concerns itself with the visual and auditory senses of the eyes, ears and the proprioceptive or kinaesthetic senses of the body and limb position. Wickens (1992) posits that all processes that follow this stage may be influenced, as each sensory system has a unique limitation, which influences the quality and quantity of information that may be initially registered.

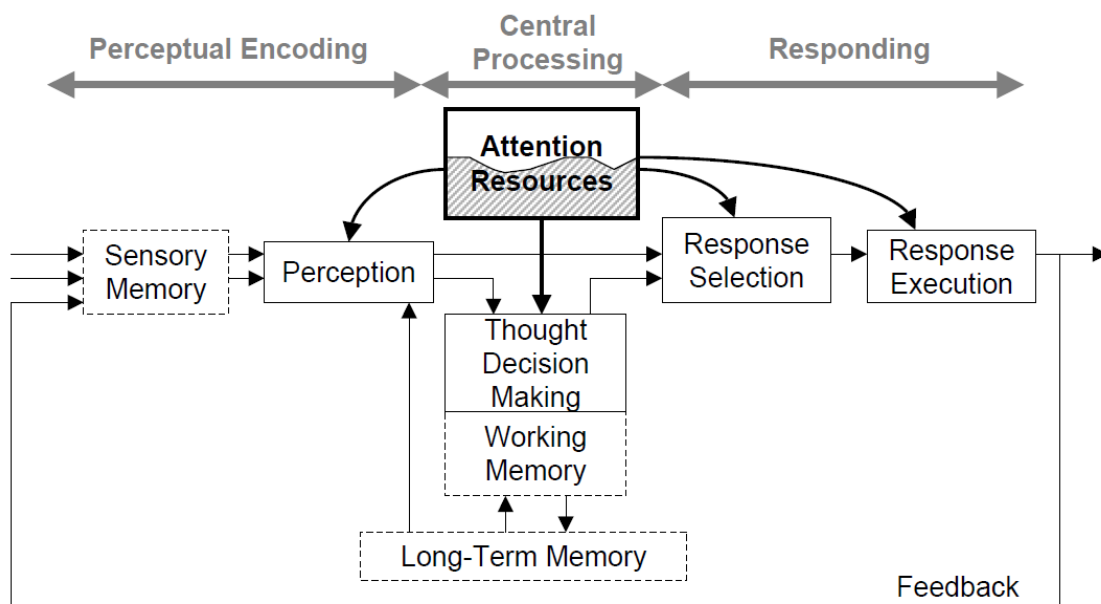


Figure 4: Model for human information processing (adapted from Wickens, 1984, pg. 12).

Information from the sensory memory is then passed to stages of perception, at which point the stimulus is identified or categorised in terms of previously learned or stored neural codes in the brain (Wickens, 1992). This stage is generally processed automatically and requires little or no attention. Perception is driven by both sensory inputs (bottom-up processing) and long-term memory (top-town processing), with top-down processing implying user-directed

attentional processing, while bottom-up processing involves cues in the environment that attract attention.

Following recognition, information is passed to decision- and response-selection and execution processes in which its implications for action are assessed, including the choice of a response. Otherwise known as cognition, this stage is distinguished from perception by the amount of time required to process information as well as the mental effort or attention involved. These central processes are therefore intimately related to memory (Wickens, 1984). Eventually a response is selected, leading to execution of the response by the appropriate muscles, a distinction which Wickens emphasises.

It is important to note that any task performed uses the whole information processing chain. However, different tasks may tax the components of information processing differently. For this reason, when investigating a multi-component skill such as driving, assessment of the entire processing chain is necessary.

As with most closed-loop feedback systems, this system is in dynamic interaction with the external world, and is driven by feedback signals. Wickens (1992) describes the attentional aspects of the system as being represented by the shape labelled attention resources, which are assumed to be finite (Matthews and Desmond, 2002), though there is some evidence to suggest that resource capacity may vary with task-demands and other factors (Malleable Resource Theory: Young and Stanton, 2002, Young and Stanton, 2004).

This processing system operates in both controlled and automatic modes. Tasks that require automatic processing can be performed without awareness and can be easily controlled. However, these are also dependant on task-demand and workload, which is typically dependant on the availability of attentional resources. On the other hand, automatic processes do not require attentional resources. Thus, they can be initiated without conscious thought and can be performed without awareness. These processes usually result in shorter reaction times, with performance improving for a longer time (Schneider and Shiffrin, 1977). While controlled processes can be easily established and altered, they are difficult to modify once learned (Wickens, 1984).

Questions have been raised as to the efficacy of the model, especially in terms of its inability to explain and predict performance in low task-demand situations, such as monotonous driving (Sanders, 1997). Nevertheless, it still stands as a useful simplifying framework for interpreting human performance in simple and complex tasks.

2.4 FATIGUE PROCESSES

Past research has failed to pinpoint the specific information-processing mechanisms responsible for fatigue-induced performance decrement (Hitchcock and Matthews, 2005), with the effects of fatigue shown to be elusive even in controlled studies (Craig and Cooper, 1992). This may be due, in part, to the lack of consensus as to what fatigue actually is. However, as Hitchcock and Matthews (2005) point out, it is likely that fatigue works through multiple mechanisms, including changes in neural function, changes in information-processing components such as attentional resource availability, and regulation of attentional effort and therefore task strategies (Matthews *et al.*, 2000).

Matthews (2001) categorises the process models for fatigue and stress into two broad types: biocognitive models and cognitive-adaptive models. Biocognitive models refer to mechanisms that reflect changes in parameters of neural and cognitive architectures, and include changes in resource availability. In contrast, cognitive-adaptive mechanisms reflect changes in the subject's goals and intentions, which may lead to strategy changes, such as regulating task-directed effort (Helton *et al.*, 2009).

From a strict resource perspective, Sanders (1997) refers to these same mechanisms as resource-volume model and resource strategy model, respectively. These embody many of the same assumptions as the previous distinction; however, the Sanders view is typically applied in studies of dual-task performance.

In the next section, we explore two leading candidate mechanisms seeking to account for the link between fatigue effects and performance decrement: from a biocognitive model perspective, Resource Theory (Kahneman, 1973) and from a cognitive-adaptive perspective, Effort-Regulation Theory (Hancock and Warm, 1989).

2.4.1 Resource Theory

Attentional Resource Theory assumes attentional capacity, or resources, exist in a fixed quantity (Kahneman, 1973; Matthews *et al.*, 2010) and are believed to facilitate information processing, thus allowing individuals to perform a task (Staal, 2004). In this context, workload typically refers to the amount of resources required to meet the task-demands (Wickens and Hollands, 2000). According to this model, Warm *et al.* (2008) posit that the effort required to maintain performance in prolonged driving (time on task; see Section 2.2) leads to a depletion of attentional resources, which in turn increases workload. Performance breakdown occurs when there are insufficient resources to meet task demands.

Resource Theory is limited in terms of its ability to predict performance characteristics in underload situations. Problems with Resource Theory include lack of a precise definition and the possibility that attentional resources may be multiple rather than unitary (Wickens, 2002). Thus, Multiple Resource Theory (MRT) emerged to account for, amongst other things, performance in dual task settings (Wickens and Hollands, 2000; Wickens, 2002). The same concept applies to a single-task paradigm, though, depending on the task characteristic, not to as great an extent. The distinction between single and multiple resource theories is not relevant for the current study. What is however important to acknowledge is that both assume that performance is impaired due to a depletion of attentional resources.

2.4.2 Effort-Regulation Theory

As with Resource Theory, the concept of resources is an integral element in Effort-Regulation Theory. However, where resource theories attribute performance impairment to a depletion of attentional resources, Effort-Regulation Theory considers performance decrements to be due to an inability to exercise executive allocation of attentional resources, i.e. match effort to environmental task-demands (Hancock and Warm, 1989; Hockey, 1993; Matthews and Desmond, 2002). This may occur as a function of time, where the effort required to maintain attentional control is both taxing and stressful (Hockey, 1997), suggesting that compensatory regulation is largely under subconscious control (Hockey, 1993). However, Rissler and Jacobsen (1987) demonstrate compensatory behaviour to be a trade off between maintenance of task performance and the level of mental effort that has to be invested in the

task, thus providing evidence that the regulation of effort is at least partially under conscious control. Thus, a person will either voluntarily or involuntarily reduce engagement in a task (Van der Linden *et al.*, 2003), especially when the task is perceived to be simple and require minimal attention or effort (Matthews and Desmond, 2002). Certainly, effort-regulation seems to better acknowledge Hancock and Scallen's (1999) assertion that any models of human performance must include a behavioural component.

Though it may not have spawned the concept of effort-regulation, the emergence of studies on the effect of workload transitions in automation on driver performance have provided support for the model, with some studies using both Resource Theory and Effort-Regulation Theory as a framework to understand the effects of workload transition in automated driving (Funke, 2007).

One of the main overlaps in the core assumptions of resource and effort-regulation is that task performance is dependant on the availability of attentional resources and that effort can be used to temporarily overcome fatigue. However, the important distinction between the two is the explanations they provide as to why this might be so (Sanders, 1997; Hockey, 2007).

Resource theory would account for this by suggesting that more resources are directed towards the task, whereas effort-regulation would claim that performance is maintained because more effort is being applied to the control processes – i.e. those allocating attentional resources. From these accounts, Resource Theory predicts that the effects of fatigue will be most noticeable when task-demands are highest, but effort-regulation makes the somewhat paradoxical prediction that the effects of fatigue on performance will increase when tasks appear to be undemanding.

Thus, Resource Theory attributes performance decrement to a depletion of resources, while the effort-regulation account puts it to an underestimation of effort required by the task (Hancock and Warm, 1989), which is brought about by an attempt to balance task goals and comfort-seeking goals (Fairclough, 2001).

2.5 MEASUREMENT OF FATIGUE

As previously stated, while fatigue is a familiar state for drivers, it is generally hard to define and measure with any rigor (Gawron *et al.*, 2001). Nevertheless, different measures can be used to follow the evolution of fatigue. When designing a driving task with the aim of inducing fatigue and examining its underlying processes, some of these metrics are intrusive and should not be used. The task of obtaining these measures should not interfere with the driving task, as is the case with many subjective assessments of fatigue states. Also, factors such as sleep homeostasis, circadian cycle, temperature, luminosity, noise and personality have to be under control to reveal the impact of the task-related aspect on the development of fatigue, on its own. The measures adapted to the study of task-related fatigue in driving are presented in the following sections. These measures include behavioural, subjective, and/or psychophysiological responses. It is not within the scope of this study to review all such measures related to study of driver fatigue. Detailed consideration will therefore be reserved for measures that will be used in the current research. All measures have been shown to be impaired during fatigue and thus provide a reasonable choice of measures likely to be impaired during fatigued driving.

2.5.1 Behavioural Measures

Using behavioural measures refers to deducing the presence of a fatigue state based on the performance of either a primary task or secondary task (Eggemeier *et al.*, 1991). The most typical characterisation thereof is a degradation of performance after continuous workload and a slowing of sensorimotor performance (Zhang *et al.*, 2009).

Behavioural measures are an integral aspect of the study of fatigue, however they are limited somewhat in their ability to fully detect and explain the fatigue state. In their taxonomic assessment of fatigue, Hitchcock and Matthews (2005) argue that the multifaceted nature of the phenomenon suggests that one cannot assume that loss of performance can be directly attributed to fatigue, or that a fatigued driver will necessarily reflect any performance decrement. Mascord and Heath (1992) explain this to mean that fatigue can be masked by the mobilisation of either additional cognitive resources in the case of Resource Theory or additional effort/motivation in the case of effort-regulation (Hockey, 1997). Thus, performance

measures may reflect fatigue only once it is in advance state, by which point interventions may be too late. de Waard (1996) argues further that primary task measures are insensitive to variations in individual sensitivities of task-demand. Therefore, given that under the same task stress, individuals vary considerably both in their upper limit of workload capacity and their ability to compensate for varying task demands, it is necessary to acknowledge these measures alongside subjective accounts of performance variations. These would provide a more valid and fuller understanding of an individual's energetical state and this will be discussed in the following section.

Standard Deviation of the Lateral Position

In the context of driving, Parkes (1991) defines the primary goal as being the maintenance of safe control over the vehicle, with one of the major subtasks being lateral position of the car. Various authors (O'Hanlon and Volkerts, 1986; Jorna, 1992; Ramaekers and O'Hanlon, 1994; O'Hanlon *et al.*, 1995; Verwey and Zaidel, 1999; Contardi *et al.*, 2004) have shown the standard deviation of the lateral position to be a sensitive performance measure that is correlated with fatigue. As a task that usually requires keeping a vehicle between the lines of a lane, de Waard (1996) refers to simulator driving task as being largely psychomotor in nature, involving hand-eye coordination. For this reason, he likens it to a typical laboratory tracking task.

2.5.2 Subjective Measures

Subjective measures are widely used in the study of fatigue, possibly because they are easy to construct and use. They can be developed according to the context in which they are to be applied, such as health or vehicle operations (Matthews and Desmond, 1998). Certainly, given the large individual differences among drivers (de Waard and Brookhuis, 1997; Thiffault and Bergeron, 2003a), it is not surprising that some have suggested that subjective measures may be more sensitive to variations in mental workload and thus fatigue than other measurement techniques (Hart and Staveland, 1988). While the NASA task-load index (TLX) has been shown to be sensitive to cognitive load, it was not used for the current study, as the

nature of the testing protocol would not have allowed participants to accurately assess each test.

One of the limitations of subjective measures, as noted by Recarte *et al.* (2008), is that they are not able to gauge any of the subconscious internal processes linked to the development and onset of fatigue. In the same way, individuals may not be able to discriminate between constructs that may not appear entirely distinct from one another, such as the distinction between difficulty and effort. This may seem trivial, but given that many subjective scales seek to probe such distinctions for the purposes of investigating for example the differences between effort-regulation and resource depletion, its importance becomes evident.

Borg CR-10

Borg's CR-10 scale (Category Ratio) (Borg, 1982) is a uni-dimensional rating scale that has been shown to be a reliable measure of the intensity of overall fatigue (Ahsberg *et al.*, 2000). For instance, Zhang *et al.* (2009) found it is a well-developed category scale with ratio properties. The Borg CR-10 scale ranges from 0-10 and contains text ranging from "very very light" to "very very hard" alongside the values to assist the individual with choosing the most correct rating (Borg 1991).

2.5.3 Psychophysiological Measures

The last category of fatigue measures is derived from the individual's psychophysiology, which has been used extensively to examine changes in energetical state in response to various stressors (Jorna, 1992). Psychophysiological measures have been shown to be reflective of various levels of physiological arousal such as drowsiness and sleepiness (Wijesuriya *et al.*, 2007), sensorimotor function and information processing (Johns, 2000).

As physiological responses require no overt response by the operator, they hold a distinct advantage over the collection of subjective and performance measures (De Waard, 1996). Physiological responses carry a further important advantage for a study of this nature in that they can be collected continuously, an important consideration when using it against continuous behavioural measures. However, as with the limitation cited above for behavioural

measures, Hitchcock and Matthews (2005) argue that physiological assessments too are at risk of circularity if they are not independent of the performance indicator.

Various psychophysiological and physiological response systems have been explored in relation to the development and onset of fatigue, including eye movements, electroencephalography (EEG), heart rate variability, cerebral blood flow and the biochemical changes associated with chronic fatigue states (Akin *et al.*, 2008). In particular, EEG is widely used to explore the development of fatigue, with some evidence that it can provide an early warning of the onset of fatigue. However, this link is probably coincidental, as EEG recordings are typically used to follow low vigilance states. Matthews *et al.* (2012) question the sensitivity of neurophysiological measures, if we assume that fatigue should be distinguished from low cortical arousal. The authors note that there remains doubt as to whether measures such as the EEG are optimal for detecting the changes in motivational control that some accounts (e.g. Hockey, 1997) claim to underlie the fatigue process. This is supported by Craig and Cooper (1992), who argue that while neuropsychological measures such as EEG are potentially attractive due to their objective nature, there exists a lack of evidence of reliable physiological correlates of mental fatigue. Cerebral blood flow and biochemical measures are complex and provide no evidence that they might shed light on the distinctions required for the current study. In the following two sub-sections, we consider the cardiovascular and oculomotor systems as two potential measures for fatigue in driving.

Heart Rate and Heart Rate Variability

Heart rate (HR) and heart rate variability (HRV) are non-invasive variables used to assess fatigue states (Patel *et al.*, 2011).

Heart Rate

Heart rate is derived from the inherent rhythmicity of the sino-atrial (S-A) node; however the sympathetic and parasympathetic processes have an effect on the inter-beat-interval (IBI) of the heart (Mascord and Heath, 1992). According to Lacey and Lacey (1974), an increase in heart rate reflects internal attentional processes, while a decrease in heart rate is indicative of external attentional demands placed on an individual. Heart rate has been used as a fatigue

indicator (Hartley and Arnold, 1994; Lal and Craig, 2001), where it increases with task difficulty and under conditions of distraction, and decreases with decreased task difficulty and tasks involving elevated fatigue levels (Jorna, 1992; Mascord and Heath, 1992). Factors affecting heart rate include age, body position and respiration (Jorna, 1992). It has also been found to be sensitive to changes in mental workload, emotional strain and physical activity (Mascord and Heath, 1992). However, despite the various factors cited to influence HR, there have been questions raised as to its reliability as a fatigue measure (Hefner *et al.*, 2009). Heart rate variability on the other hand has gained support as an indicator of fatigue (Egelund, 1982; Davy, 2010; Lombard, 2010).

Heart rate variability

HRV is typically evaluated using time-based measures or frequency domain measures (Jorna, 1992). It reflects cardiovascular autonomic control exerted by both parasympathetic and sympathetic nervous systems (Mourot *et al.*, 2004), and has been used to examine both mental workload (Hancock and Verwey, 1997) and driver fatigue Horne and Reyner, 1995. Some authors provide evidence suggesting that increased HRV is a sign of a fall in the level of cerebral activation, which is associated with a diminished alertness (Harris *et al.*, 1972).

Time-domain measures of HRV are calculated by analysing the standard deviation of R–R (inter-beat) intervals (Patel *et al.*, 2011), the increase of which is an indication of decrease in mental workload (Hancock and Verwey, 1997), decrease in performance and associated increased levels of fatigue (Oron-Gilad and Ronen, 2007; Egelund, 1982). Within the context of driving, a decrease in tracking performance is typically associated with an increase in HRV which indicates an increase in fatigue (Egelund, 1982), especially over prolonged monotonous drives (Horne and Reyner, 1995). For example, Gershon *et al.* (2009) found HRV to increase as a function of time during a 140-minute simulated drive, with the post-task response also higher than the initial value.

However, Patel *et al.* (2011) argue that lower workload may also be linked to lower vigilance, which could also account for a decrement in driving performance. As discussed above, individuals vary considerably in terms of their responses to fatigue. This also applies to physiological measures, thus HRV is always calculated relative to the individual driver (i.e., the degree of change over time) and not relative to an objective criterion. Jorna (1992) notes

that HRV is limited in terms of its ability to discriminate between subtle changes in workload. In addition, Mulder (1986) contends that HRV is only able to differentiate between tasks if they differ considerably in terms of controlled processing. In much the same way, Jorna (1992) argues that time domain analyses are not able to account for the source of variance influencing HRV. Therefore, to gain a fuller understanding of how resource depletion and effort-regulation accounts might manifest in terms of cardiovascular responses, it is necessary to consider spectral analysis of heart rate fluctuations (Task Force, 1996).

Frequency-domain analysis is based on mathematical transformations of the signals from time-domain into separate frequency ranges (Patel *et al.*, 2011). The low frequency (LF) component (0.04–0.15 Hz) is typically associated with activity of both the parasympathetic and sympathetic, while the high frequency (HF) component (0.15–0.4 Hz) is said to reflect parasympathetic activity (Bezerianos *et al.*, 1999). The LF:HF ratio is considered to be a measure of sympathovagal balance (Task Force, 1996), with a decrease related to a more drowsy state (Byeon *et al.*, 2006), while increases indicate greater mental workload or alertness (Sato *et al.*, 1998). Thus, the increases and decreases in the LF:HF ratio are linked with sympathetic and parasympathetic dominance, respectively.

While there is strong evidence for the mediating factors for both HF and LF (when combined with LF:HF ratio), the physiological correlates of ultra low frequency (ULF) and very low frequency (VLF) components are still largely unknown (Batchinsky *et al.*, 2007). Moreover, these frequencies do not hold any importance when HRV is analysed in 5-minute intervals (Task Force, 1996), as is the case in the present study. Patel *et al.* (2011) therefore concludes that analysis of the LF and HF bands along with the derivation of LF:HF ratio, can provide sufficient and accurate information regarding the extent and type of an individual's fatigue state, over and above that interpreted from time-domain measures. This is important: a Resource Theory account of performance decrement would predict that there would be sympathetic dominance in the presence of fatigue to compensate for the lack of attentional resources, while an effort-regulation account would predict a parasympathetic dominance to reflect a reduction in attentional effort. These would confirm and compliment the HRV measures.

Oculomotor Activity

Blink behaviour analysis allows insight into how the individual processes the visual scene while driving. Eye movements are an attractive metric in the study of fatigue, as they can access information that would otherwise not be consciously available to the driver to report on (Chapman *et al.*, 2002). In this way, it somewhat counteracts the limitations of subjective measures. Eye-tracking systems are usually non-invasive and capture near continuous eye data (Marshall, 2000), which allows for assessment of moment-to-moment fluctuations in workload into an eventual fatigue state (Ahlstrom and Freidman-Berg, 2006).

Various oculomotor parameters have been shown to be sensitive indicators of fatigue, most notably time on task, which is linked indirectly to the onset of drowsiness in task environments that are monotonous (Van Orden *et al.*, 2000). These parameters include blink behaviour (Schleicher *et al.*, 2008), gaze movement (Zhu *et al.*, 2004), glance duration (Healey, 2004), and PERcentage of eye CLOSure (PERCLOS) (Wierwille, 1994; Merat and Jamson, 2012).

Van Orden *et al.* (2000) points out that changes in individual task strategies, motivation, and/or effort are not necessarily linked to drowsiness, therefore many oculomotor parameters may fail to detect these changes in the lead up to a critical fatigue state. This is pertinent, as both resource and effort-regulation theories entertain the notion of subconscious activity in their account of performance impairment. Thus, it is necessary to focus on those metrics that have been shown to be sensitive to such considerations. Of all blink parameters assessed during a two-hour simulator drive, Schleicher *et al.* (2008) found blink duration to be the most reliable, correlating with both subjective and objective fatigue measures.

Blink Frequency and Blink Duration

Driver fatigue has been associated with an increase in blink duration (Van Orden *et al.*, 2000; Verwey and Zaidel, 2000; Svensson, 2004; Dingus *et al.*, 2005) and blink frequency (Stern *et al.*, 1994; Summala *et al.*, 1999; Sirevaag and Stern, 2000). In particular, fatigue due to time on task has a particularly strong correlation with both blink frequency (Stern *et al.*, 1994; Galley *et al.*, 1999) and blink duration (Caffier *et al.*, 2003; Galley and Schleicher, 2004; Campagne *et al.*, 2005). Stern *et al.* (1994) comments that increased blink frequency typically indicates light fatigue (the transition from awake to reduced vigilance), whereas the transition

to severe sleepiness is accompanied by an increase in blink duration (Caffier *et al.*, 2003). Similarly, Schleicher *et al.* (2008) associate prolonged blink duration with a down-regulation of several physiological processes.

Hargutt (2003) contends that the inhibition of blinks is attention-driven. Evidence for this assertion can be found in the work of Tsai *et al.* (2007), who reported a higher blink frequency in a dual driving and auditory task when compared to a driving-only condition. As attention is said to vary with levels of fatigue, when the frequency of eye blinks increases, it is indicative of fatigue (Stern *et al.*, 1994).

2.6 Summary

This chapter has surveyed the fatigue theories and has defined fatigue as a general psychophysiological phenomenon, which diminishes the ability of the individual to perform the driving task.

Sources of fatigue have been identified and classified into two categories: sleep-related and task-related factors. These umbrella terms provide all the factors needed to be controlled when designing an experiment to study the control of driving performance and its associated fatigue responses. Amongst the fatigue factors, task related fatigue has been explained further and has been shown to significantly impact fatigue. This review has further outlined the two candidate control mechanisms of driver performance: Resource Theory and Effort-Regulation Theory. Each has different accounts for performance impairment, with Resource Theory attributing performance breakdown to a depletion of attentional resources, while effort-regulation put this down to an inability to match effort to environmental task demand. There is a lack of consensus as to which of these accounts dominates in prolonged driving, and their associated impact on information processing.

To assess which account dominates it is necessary to be able to objectively assess the driver fatigue level. This assessment has to be continuous, reliable, objective and non-intrusive. The standard deviation of the lateral position of the car was selected as the behavioural measure and the Borg CR-10 effort scale was selected as the subjective measure. Heart rate, heart

rate variability, blink frequency and blink duration were selected as the psychophysiological measures.

The following chapter applies the knowledge gained in this chapter to design and implement a driving simulator study that seeks to investigate the contributions of resource depletion and effort-regulation to the decrement of driving performance in a prolonged drive. Together with this, it will present a technique to assess whether this fatigue state impacts on the utilisation of any specific information processing stages.

CHAPTER III

METHODOLOGY

This chapter uses the information summarised in Chapter 2 to design and implement a driving simulator study that investigates the mechanisms purportedly accounting for the development of non-sleep-related driver fatigue during a prolonged driving task. Data on fatigue and performance theories reported in Chapter 2 enabled the design of the experiment and the control for other factors influencing fatigue development. It also provided the justification for the selection of sensors used during this experiment.

In this chapter, the background of the study is highlighted, with a major focus on the objectives and methods used and the expected outcomes. The following section details the design of the experiment, especially the different scenarios developed, research design, materials used and the procedure, before concluding with a summary of the chapter.

3.1 BACKGROUND

Although driver fatigue accounts for a large proportion of the human-error-related motor vehicle accidents, the mechanisms underlying the phenomenon are not well understood. As a consequence, many current fatigue monitors and countermeasures are based only on indices of general fatigue effects, and do not consider the complexity of the fatigue state (Desmond and Matthews, 1997). General fatigue management systems may therefore only be successful in certain, context-specific scenarios. This is a concern when one considers that fatigue is one of a myriad of factors that usually combine to form the sequence of linked precursors resulting in a crash (Hancock and Scallen, 1999). It is therefore pertinent that research focuses on the contextual interactions leading to crashes to gain greater insight into the problem. It is equally important however to understand the mechanisms controlling the origins of performance: the driver, the focal point of the driving task.

3.2 RESEARCH CONCEPT

This study is a simulated driving task experiment. It aims to investigate the impact of a prolonged driving task on resource-specific performance and psychophysiological measures, and in doing so shed light on the mechanisms controlling driving performance.

Given the broad and all-encompassing nature of the current definitions of fatigue, it is not surprising that a “gold standard” for its measurement is yet to be established. Part of the difficulty is evidenced when we consider the fatigue problem in a very specific domain such as mental fatigue, and we discover that our understanding of the cognitive processes underlying its behavioural manifestations falls short of what is needed to fully grasp the phenomenon (Hockey, 1997; Desmond and Hancock, 2001). Despite that the relationship between time on task and fatigue has historically been well researched in a range of laboratory and occupational tasks (Mackie *et al.*, 1994; Pigeau *et al.*, 1995; Dorrian *et al.*, 2007), there is still considerable debate around the nature of the mechanisms governing it. Nowhere is it more important to understand these mechanisms than in the context of driving, which is widely identified as a particularly at-risk vigilance task (Dinges, 1995; Thiffault and Bergeron, 2003b; Papadelis *et al.*, 2007).

Two candidate mechanisms have emerged from previous studies that seek to account for the decrement of driving performance as a response to cumulative time on task. The first proposes a depletion of limited attentional resources, which is said to lead to an inability to maintain appropriate top-down control to maintain adequate task performance (Hockey, 1997; Matthews and Desmond, 2002). The second holds that performance impairment is not due to a depletion of attentional resources, but rather a misallocation thereof (Pattyn *et al.*, 2008; Smallwood *et al.*, 2004).

While there are discrepant views regarding the nature of the relationship between time on task and performance, it is generally accepted that fatigue acts through both mechanisms (Matthews, 2001). However, to what extent performance decrements with time on task can be attributed to either is yet to be established and therefore requires further investigation (Williamson *et al.*, 2011). The aim of this study was to isolate the effects of these components on the decrement of performance, and in doing so test the predictions of Resource Theory and Effort-Regulation Theory.

3.2.1 Experimental Design

The first aim of this research was to evaluate the task-related fatigue effect elicited by a prolonged driving task in terms of the two mechanisms described above.

This study used a low-fidelity driving simulator (Figure 8; considered as more of a continuous tracking task with geometry representative of a driving scenario) to induce fatigue over a 90-minute drive. One way of distinguishing which of the two theories dominates, is to consider the interplay between behavioural and psychophysiological measures. A Resource Theory account assumes performance impairment is the result of progressive resource depletion, which is compensated for by an increase in psychophysiological responses. Effort-regulation assumes performance impairment is due to a misallocation of attentional resources, which would reflect as decreased psychophysiological responses.

In line with this, Resource Theory and Effort-Regulation Theory predict different performance outcomes in response to varying task demands (Table I). Resource theory predicts performance will be best under conditions of low task-demand and worst under conditions of high task-demand, whereas Effort-Regulation Theory predicts performance will be best under conditions of high task-demand and worst under low task-demand. To test the predictions and thereby gain greater insight into which account dominates, the current study divided participants into three experimental groups corresponding to the three different road widths described in Section 3.4.1.2, thus employing a between-subject design. To the author's knowledge there is limited research that aims to identify the relative contributions of resource utilisation and effort-regulation on the control of driving performance during the completion of a prolonged driving task.

Table I: Resource theory and Effort-Regulation Theory predictions regarding performance over time in response to varying degrees of driving task-demand.

	Resource theory	Effort-Regulation Theory
High task-demand	Worst	Best
Medium task-demand		
Low task-demand	Best	Worst

It is expected that following the prolonged drive general information processing performance will be impaired, or that there will be a compensatory function in the form of a performance-effort trade-off. However, as driving is a multi-component skill, it is relevant to ascertain whether the fatigue state induced by prolonged driving impairs resources specific to any one information processing stage, or whether it is a general function. This constitutes the study's second aim. This was achieved by comparing the difference in allocation of various cognitive resources before and after inducing fatigue via a prolonged or "sub-maximal" driving task. This aim contributes to the conclusions for the initial aim and answers questions relating to information processing impairments at the most basic level. Direct measurement of the stages of information processing is complex as they function in concert to affect desired task performance. Indeed, all tasks use the entire processing chain. This study therefore developed tests designed to probe the allocation of resources used in information processing at different stages. These include perceptual, cognitive, motor output, and driving-specific resources, aligned to the multi-component nature of the driving task (Angell *et al.*, 2006).

Key to the success of this approach was to provide a baseline or reference measure of the resource, which would be compared to the results of the resource test conducted after the fatiguing task. However, different forms of fatigue impact on the allocation of each resource differently. Thus to gain a truer understanding of resource allocation, it is necessary to test resource responses at both a higher and lower workload. Accordingly, an *easy* and a *difficult* variation of the same task were introduced for each resource. The difference in performance for the PRE- *easy* and PRE- *difficult* tasks ($\Delta 1$ Figure 5) is compared to that of the difference between the POST- *easy* and POST- *difficult* tasks ($\Delta 2$ Figure 5). If $\Delta 1$ is equal to $\Delta 2$, then resource A was not affected by the fatiguing task. However, if $\Delta 1$ is not equal to $\Delta 2$, then it can be concluded that the fatiguing task had an effect on resource A. The pre/post- changes in between difficulties were compared, thereby avoiding direct comparisons between resource-specific tasks.

The aim of this approach, referred to as differential analysis, was to understand and objectively quantify, on a process-by-process level, the extent to which the resource was loaded by fatigue induced by a prolonged driving task. The assumption holds that if the difference between pre- and post- is different for both difficulty conditions then it is clear that any performance decrement between pre- and post- can be attributed to that single resource.

In this way, differential analysis was necessary to determine stage-specific resource utilisation and isolate the effect of resource depletion and effort-regulation. This indirectly allowed for the estimation of the relative contributions of resource availability and effort-regulation to driving performance over time.

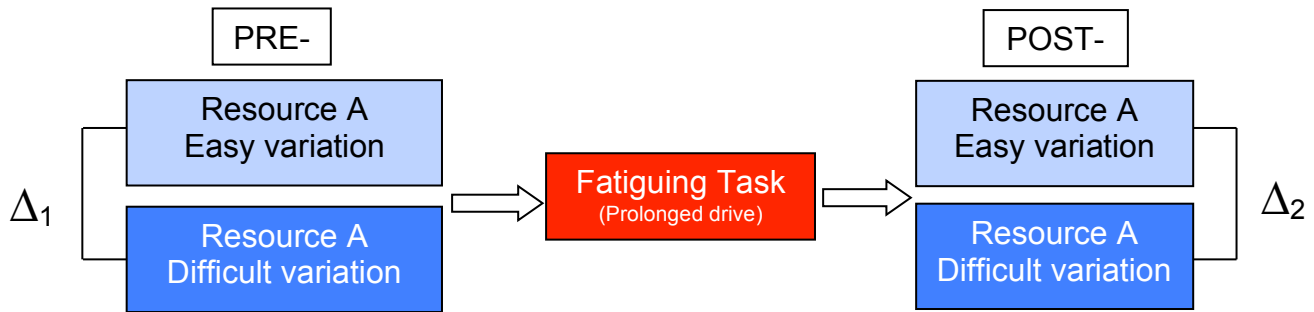


Figure 5: Schematic representation of the basic method for quantifying resource contribution to specific task performance (adapted from Ngcamu and Göbel, 2011).

With reference to Figure 6, the proposed resource component and effort-regulation component can be separated by calculating the difference in performances between the two complexities of each test before and after the main fatiguing task. Firstly, the difference between the pre- and post- responses for each of the three resource tests will provide an indication as to whether performance decrement is resource specific or whether it is a general function. Secondly, the difference between the pre- and post- responses for the maximal-attention driving task will show whether the fatigue is driving-specific resource depletion.

A maximal-attention driving test was implemented before and after both pre- and post-resource test-battery. The intention for this was three-fold: Changes in performance between PRE- 1 and PRE- 2 would highlight any learning effects. Changes between PRE- 2 and POST- 1 would indicate whether there was driving-specific resource depletion, while changes between POST- 1 and POST- 2 would indicate whether there was any recovery effect. If there is no difference in the resource tests, but driving performance is seen to decrease, it can be concluded that effort-regulation dominated. If resources are affected but driving performance reflects no significant decline, resource depletion is assumed to have dominated. However, what is likely is that both driving performance and resource performance will decline, suggesting that the two mechanisms function together to affect adequate task performance.

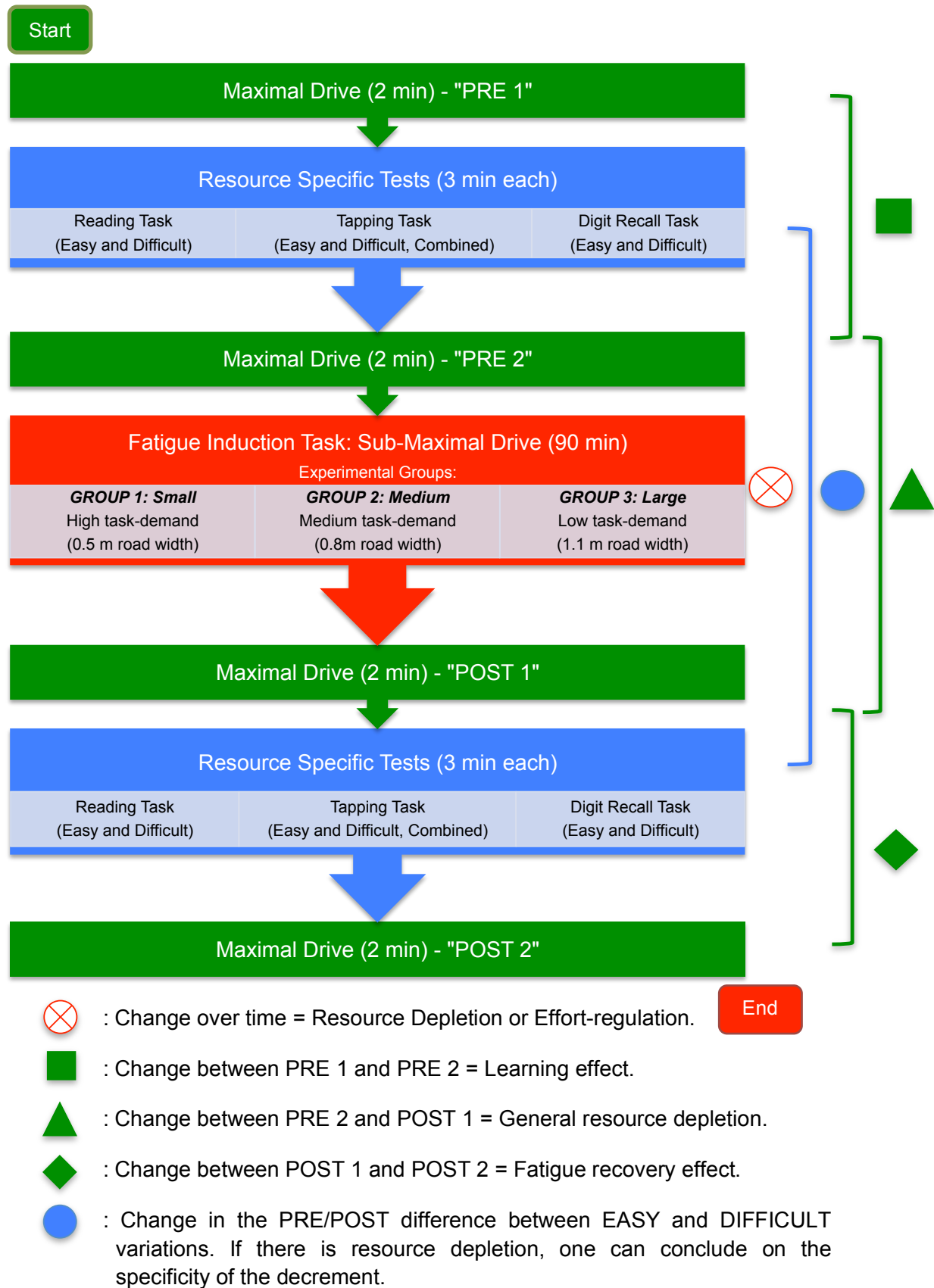


Figure 6: Basic experimental concept and design.

3.2.2 Deception

All information given to participants regarding the testing was accurate but incomplete. The participants were given information regarding the nature of the tasks they would be performing within the testing session and the operational information necessary for successful completion thereof. The participants were deceived in terms of the rationale behind the task order as well as the duration of each task performed in the protocol. Accordingly, all time-keeping devices and references were removed from the testing area.

The rationale behind this deception stemmed from the fact that information about task duration would allow individuals to consciously and subconsciously regulate their performance to either conserve energy (in the case of long duration tasks) or apply more effort (in the case of short duration tasks or knowledge of end point) (Hockey, 1997). Similarly, effort in fact increases as individuals near their goals, or in this case end point (Lewin, 1951; Bonezzi *et al.*, 2011). These relate to behaviours from both an effort-regulation and resource depletion perspective, as both account for the observation that fatigue can be temporarily masked by effort or will (Hole, 2007), which would reflect as decreased heart rate variability (Task Force, 1996).

To understand the underlying mechanisms controlling performance in prolonged driving, it is important to control for any information that would lead to conscious regulation of performance and/or effort. For instance, were the participants to know the duration of the sub-maximal drive it is far more likely that they would actively withdraw effort, rather than trying to maintain goal-consistent behaviour, which would allow for the natural fatigue and subsequent resource depletion or effort-regulation phenomenon to occur.

This principle applies to the short duration tasks as well². Information about task order and rationale would therefore allow participants to actively regulate performance in these aspects. This is especially pertinent for participants who were students within the Department of Human Kinetics and Ergonomics, as they would most probably be familiar with the underlying principles of the study. Therefore, deception in this case was vital to gain the information required to answer the research question. Lastly, the rationale behind this deception was explained to each participant.

² The fact that the participants may have anticipated that it was the same tasks that were being repeated the prolonged drive meant that there was an unavoidable limitation with regards to knowledge of end point.

3.3 HYPOTHESES

3.3.1 Research Hypotheses

This research proposes that prolonged driving will induce fatigue responses in behavioural, psychophysiological and subjective assessments over time. It further proposes that these decrements can be attributed to two candidate mechanisms - resource depletion, or resource preservation via effort-regulation.

If the resource model dominates, it is expected that a decrement in driving performance will be accompanied by an increase in psychophysiological responses. Further, it is hypothesised that performance and psychophysiological measures will differ significantly between the pre/post resource-specific tests. Additionally, changes in pre/post resource test performance will reflect as increased psychophysiological responses.

If the effort-regulation model dominates however, it is expected that a decrement in driving performance will be accompanied by a decrease in psychophysiological responses. Additionally, changes in pre/post resource test performance will reflect as depressed psychophysiological responses.

3.3.2 Statistical Hypotheses

As mentioned previously, objective measures of performance and psychophysiological responses as well as subjective measures were taken. The following hypotheses pertain to general expected responses for and to driving, Resource Theory accounts and Effort-Regulation Theory accounts for performance in the sub-maximal drive as well as in the pre/post tests.

Sub-maximal Drive

1. The null hypothesis states that all performance, psychophysiological and subjective responses will remain unchanged between the beginning and the end of the sub-maximal drive.
2. The null hypothesis states that all performance, psychophysiological and subjective

responses between three experimental groups will remain unchanged in the sub-maximal drive.

3. The null hypothesis states that all performance, psychophysiological and subjective responses between three experimental groups will remain unchanged between the beginning and end of the sub-maximal drive.

Maximal Drive

4. The null hypothesis states that there will be no difference between PRE- 1 and PRE- 2 maximal drive tests performance, psychophysiological and subjective responses.
5. The null hypothesis states that there will be no difference between POST- 1 and POST- 2 maximal drive tests performance, psychophysiological and subjective responses.
6. The null hypothesis states that there will be no difference between PRE- 2 and POST- 1 maximal drive tests performance, psychophysiological and subjective responses.

Resource Tests

7. The null hypothesis states that there will be no difference in performance responses between pre- and post- for all resource specific-tests.
8. The null hypothesis states that there will be no difference in psychophysiological responses between pre- and post- for all resource specific-tests.
9. The null hypothesis states that there will be no difference in oculomotor responses between pre- and post- for all resource specific-tests.
10. The null hypothesis states that there will be no pre- and post- difference in performance responses between the two difficulty variations for the Fitts' tapping task. I.e. there is no differential effect.
11. The null hypothesis states that there will be no pre- and post- difference in performance responses between the two difficulty variations for the digit recall task. I.e. there is no differential effect.
12. The null hypothesis states that there will be no pre- and post- difference in performance responses between the two difficulty variations for the reading task. I.e. there is no differential effect.

3.4 INDEPENDANT VARIABLES

3.4.1 Driving Tasks

3.4.1.1 Maximum attention test

Normal driving requires that drivers merely stay within a lane, and therefore does not require maximal sustained attention to satisfy requirements for safe driving. This behaviour refers to a satisficing versus an optimising strategy (Hancock and Scallen, 1999). Thus, any measure in a normal driving situation will reflect mostly behavioural factors (attention, prioritisation) unless maximum performance is required during critical situations. However, given their unpredictable nature these incidents are difficult to assess *in situ*. Therefore, to assess the ability to mobilise maximal attention, participants were expected to perform a tracking task on a driving simulator. This maximal performance test is a continuous performance measure that implicitly requires participants to act at their upper performance limits by requiring minimum target deviation and minimum reaction time. In this context, tracking performance directly corresponds to resource allocation and information processing capacity (Bubb, 1993). It is important to note that this driving task is not intended as a control condition, and is not analysed as such.

The driving simulator presented a curved road with an arrow at the bottom of the screen. The participant was required to track the middle white line with the tip of the arrow as accurately as possible, while the driving speed remained constant at 9 km.h^{-1} throughout the testing. The maximum performance test required the participant to perform a 2-minute drive on the driving simulator. Previous studies (Birch, 2011; Louw *et al.*, 2013) have shown 2 minutes to be an adequate time frame to sample driving performance measures and attentional state from the driving. Additionally, prolonged duration on this task may induce fatigue effects, which would be counter productive to the aims of the study. All participants performed the maximal performance test with the same parameters and under the same conditions. As illustrated in Figure 6, the test was conducted 4 times during the protocol: directly before and after the pre-resource tests, and directly before and after the post- resource tests.

3.4.1.2 Submaximal driving test (fatigue manipulation)

The design of the submaximal drive is distinct from the maximal drive test in three ways:

Task goal

Unlike the maximal drive test, the submaximal test presented a curved road with a rectangle at the bottom of the screen representing the bonnet of a car. Participants were instructed to drive in the left lane of the road and were encouraged to maintain accurate car tracking within the middle and outer left lines of the road, throughout the duration of the drive. This still presented the challenge of maintaining an adequate level of attention, however not to the extent that participants would willingly withdraw all effort from the task within the 90-minute task. Moreover, sustained performance on this task has been shown to induce mental fatigue (Birch, 2012; Robertson, 2012; Ndaki, 2013; Louw *et al.*, 2013). This is an important element in the overall test, designed to mimic real world driving and thereby evoke possible effort-regulation behaviour.

Task duration

Some simulated driving studies have found performance decrements as early as 20-25 minutes into a drive (Thiffault and Bergeron, 2003b; Peiris *et al.*, 2006), while others have observed significant differences only after 90-minutes (Ting *et al.*, 2008). Prior studies by our research group have shown the Rhodes University Driving Simulator (e.g. Birch, 2012; Robertson, 2012; Ndaki, 2013) to be sensitive to symptoms of fatigue as early as 45-minutes into the drive. The driving task used in these studies to induced fatigue was much more demanding³. To ensure fatigue induction via the submaximal drive, therefore the test required the participant to perform a 90-minute drive on the driving simulator.

Road width

Participants were divided into 3 experimental groups with different road widths, creating a between-group design (Figure 7). More demanding tasks appear to be somewhat more sensitive to fatigue (Craig and Cooper, 1992). Varying the road width, and effectively the margin of allowable error, allowed for a greater insight into whether resource depletion or

³ Equivalent to the maximal driving task used in this study, which requires 100% attention.

effort-regulation dominated. The expounded rationale behind this can be found in Section 3.2.1. This was the only aspect of the protocol that was different between the groups.

The following road widths were used:

Small road: 0.5m (*“Normal” road width decreased by 37.5%*)

Medium road: 0.8m (*“Normal” road width*)

Large road: 1.1m (*“Normal” road width increased by 37.5%*)

It is important to note that while the road widths varied, the task goals did not, thus task monotony remained constant across the 3 experimental groups of sub-maximal test. Across all driving contexts, participants were required only to steer according to the conditions of the road. Neither of the driving tasks involved lane changes, speed changes (including accelerating and breaking), overtaking of other vehicles, gear changes, any in-car functions other than steering (such as indicating), or any road based behaviour modifiers that may increase task workload (such as traffic lights, roundabouts, intersections or stop signs).

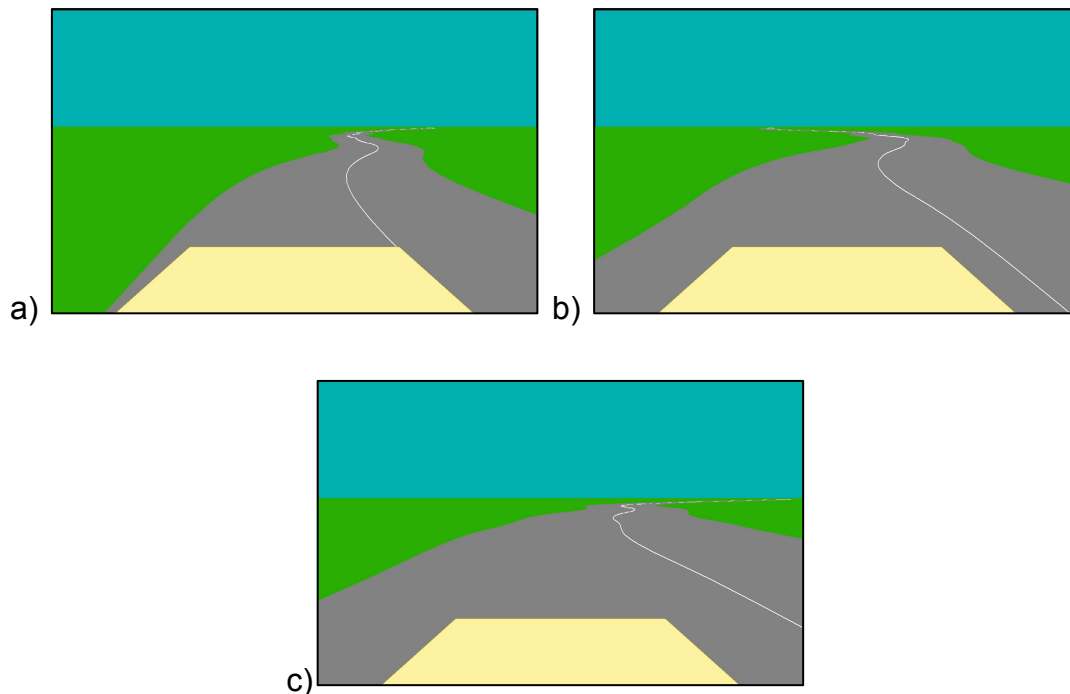


Figure 7: Screenshots of the simulator setup used for the three experimental conditions: *Small* road width (a), *Medium* road width (b), *Large* road width (c).

Variables of interest for the driving tasks:

- *Mean lane deviation* calculates the average deviation from the target line in meters. To describe the tracking quality, the simulator measured the mean deviation values of all the crossed road segments. The amount of deviation was calculated relative to the instant the segment was crossed.
- Physiological measures include recording heart rate and heart rate variability, blink frequency and blink duration.

The initial 10s interval of the deviation data was not considered in data analysis to allow for the drivers to stabilise their driving performance at the commencement of each driving task. The initial output sample was set to 5s, so as to produce one output sample every 5 seconds and avoid strong variations due to chances in street curvature.



Figure 8: Participant performing the sub-maximal drive on the Rhodes University Driving Simulator.

Simulation Software

The driving simulator software used in the current study was developed by Göbel *et al.* (1998). Figure 8 depicts driving scenes from the simulator. The tracking task required participants to use the steering wheel of the car to direct the static yellow arrow on to the moving white line in the middle of a simulated road.

A driving simulator was used since under normal circumstances the driver is not required to perform at maximum performance, thus any measure mainly reflects behavioural factors (attention, performance allocation etc.) unless maximum performance is required during critical situations (Kim *et al.*, 2005). Further, due to practical limitations and ethical concerns road driving is unsuitable for this study. Therefore, driving reliability and safety has been shown to correlate directly to tracking and to reaction performance (Göbel *et al.*, 1998).

The simulator task requires 100% attention since it is a tracking task, which is a continuous performance measure implicitly requiring participants to act at its upper performance limits by requiring minimum target deviation and minimum reaction time. Tracking performance therefore directly corresponds to resource allocation and information processing capacity (Bubb, 1993; Louw *et al.*, 2013). Thus, the performance loss induced by secondary task interaction was computed by performance measures during phases of driving with simultaneous secondary task attention. The participants were therefore required to complete a lane-tracking task. The roadway was completely flat, and monotonous, with constant variable curvatures, but with no traffic, hills or trees. The scenario was designed to be understimulating, to mimic the driving conditions that most motorists encounter when driving on a rural highway. Such driving conditions have been likened to a vigilance task (Dinges, 1995; Papadelis *et al.*, 2007; Thiffault and Bergeron, 2003b).

Physical Simulator Set-Up

The simulator used is shown in Figure 8. It consists of a custom-built chassis with a non-force feedback steering wheel.

The driver sat behind the wheel of the car facing the screen onto which the road scene of the simulator was projected. This was placed approximately 3.3m away onto a 2800mm x

1400mm white screen using a Liesegang digital projector, which had a luminance of 5.6 cd/m². The projector was connected to a central computer, which ran the driving simulator software and processed the road scene visuals. Steering movements were detected by a potentiometer mounted on the steering column. Participants were instructed to control steering movements smoothly as would be done under typical driving conditions. In keeping with the South African transport traffic regulations, participants were expected to drive in the left lane of the road.

The route was set with the parameters listed in Appendix B3. The distance covered was a function of task duration. Further, as the parameters of the simulator system are hypothetical and do not represent literal units, distance covered and speed travelled should not be considered as such. The perception of speed in the simulator was dependent on the factors of the design and perspective of the street. The parameters for the route as well as the perspective parameters were changeable at will, however to ensure consistency the parameters were kept constant and are listed in Appendix B3, for both maximal and sub-maximal conditions. The driving data were determined by using the coordinates of the relative position of the arrow on the streets and the input data of the steering wheel.

The driver perspective was selected such that it simulated the most realistic street situation. The viewing angle for the road ("viewing skew") was set at 8.5° to correspond with the real seat position in a car. The colours of the street, the display area and the sky replicated natural conditions. The exact values of the parameters can be found in Appendix B3.

3.4.2 Resource-Specific Tests

It is important to note that all resource tests employed in this study use the whole information processing chain (perception - cognition - motor output). It is not possible to use only part of it. The tests are designed such that each uses exactly same resources with the exception of one resource, the one that is being tested. The following tasks were used as the resource tests, which were conducted prior to and immediately after the prolonged drive/fatiguing task.

The PRE- resource tests were used to establish a baseline/reference measure. The same resource tests performed initially would be repeated after the fatiguing task (POST). The performance and individual responses from the POST- resource tests conducted after the fatiguing task will be compared to the reference responses from the PRE- resource tests. Any differences between the PRE- and POST- resource test can be attributed to changes induced by the submaximal drive task.

3.4.2.1 Perceptual Resource: Digit Recall Memory Test

Numerous studies have demonstrated that cognitive fatigue is associated with impairments in working memory (Babkoff *et al.*, 1988; Tyagi *et al.*, 2009). This study therefore employed an adapted auditory digit recall memory task (Digit Span Version 0.1) to test for attention and working memory (Wetherill and Fromme, 2011) as well as perceptual-motor processing speed (Brumback *et al.*, 2007). The digit recall task was obtained from the Psychology Experiment Building Language (PEBL) Test Battery Version 0.5 (Mueller, 2007).

The digit recall task provided information regarding participants' perceptual resource allocation before and after the submaximal-driving task. A string of numbers was presented visually and orally at a rate of 1 digit per second and participants were required to repeat the string via keyboard input in serial order after an 8 second delay (Figure 10). To test for specific resource depletion of the working memory, the length of the digit span test was varied. The *easy* variation consisted of a five-string digit span, while the *difficult* variation consisted of a seven-string digit span. Each condition was presented as a separate task, and permuted as such within the resource specific task set (Appendix B4). There were no restrictions in time for recall. Variables of interest for the Digit recall memory test

- Performance measured by the number of identified numbers (in sequence) over time.
- Physiological measures include heart rate and heart rate variability, blink frequency and blink duration.

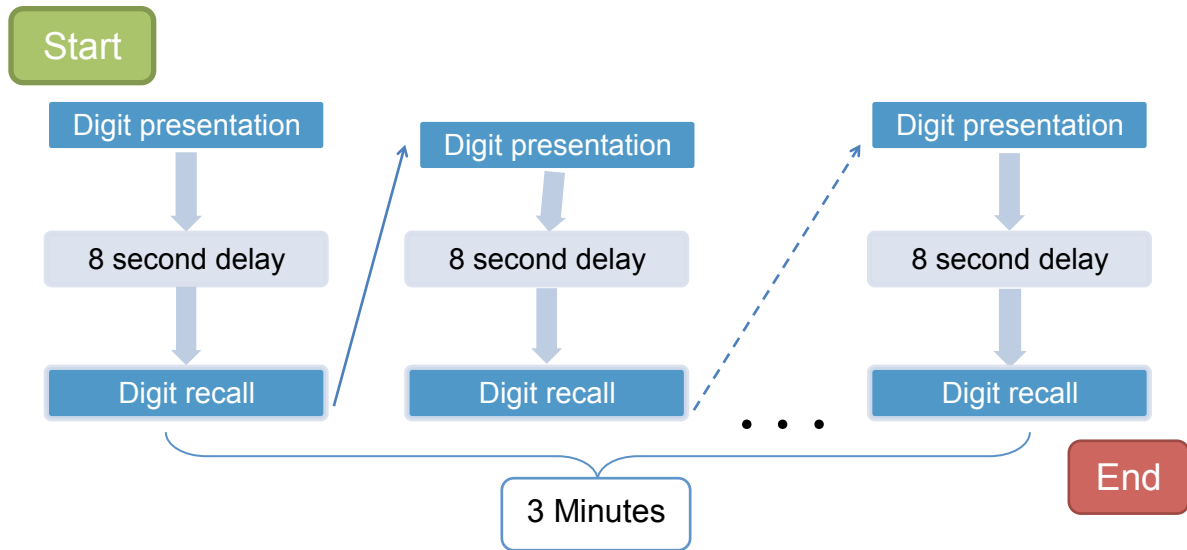


Figure 9: Schematic representation of the digit recall task for quantifying short term working memory contribution.



Figure 10: Participant performing the digit recall task.

3.4.2.2 Motor Resource: Modified Fitts' Tapping Task

A modified computer-based Fitts' tapping task (Fitts, 1982) using a 17" LG touch screen was employed to analyse motor resource utilisation. Participants were required to respond to presented stimuli by touching a green dot with their index finger as fast as possible once the stimulus was presented. The response test involved participants responding to consistently sized green dots on a black background. As with the digit span task, the task encompassed two difficulty variations. However, the two variations were integrated into one task, i.e. within the Fitts' task, each presented stimulus alternated in difficulty between the *easy* and *difficult* variations (Figure 11). The stimulus in the *easy* variation condition was a green dot presented in the centre of the screen, whereas in the *difficult* variation it was presented at a random point on the screen.

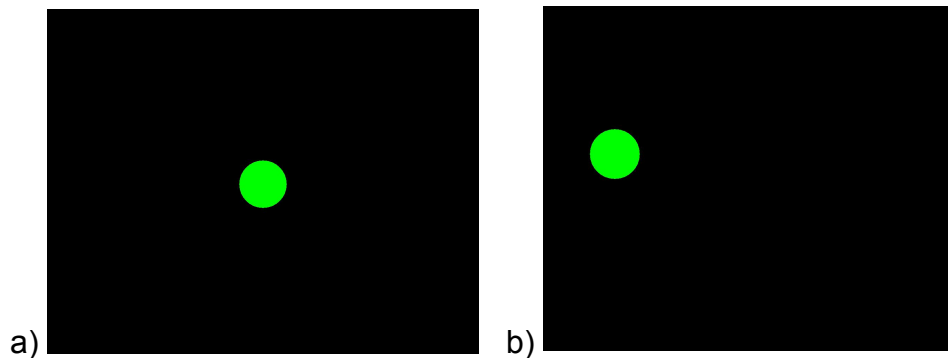


Figure 11: Examples of the *easy* (a) and *difficult* (b) variations of the modified Fitts' tapping task.

Exclusion criteria were set for both the *easy* and *difficult* variations. The working field was set to 220mm by 220mm. The size of the green dot was set at 24mm, with the time between presentations varying from 250 to 500ms. The first trial was excluded, including any trials with a response time less than 0.1s; this constituted a double tap on the screen, and any response time greater than 1s. Additionally, any target deviations greater than 150mm were excluded, with the test being completed after three minutes.

Variables of interest for the Fitts' task

- Performance measured by the extent of target deviation (accuracy of movement) and the time taken to select targets (speed of movement).

- Physiological measures include heart rate and heart rate variability, blink frequency and blink duration.



Figure 12: Participant performing the modified Fitts' tapping task.

3.4.2.3 Cognitive Resource: Visual Scanning with Object Recognition Reading Task

Cognitive processing was assessed using an object recognition reading task based on previous studies of attention and fatigue (e.g. Chaplin, 2010; Ngcamu and Göbel, 2011; Goble, 2013). The reading task required participants to read and identify spelling errors within a hard copy piece of text. The errors were characterised by the amount of missed errors in the text. In order that participants engaged with the text, context-specific spelling errors were included. For example, understanding of context is required to determine whether the words “too” or “thee” are preferable to the words “to” or “the”, respectively. Error frequency was limited to 4 errors per 100 words, which were randomly assigned within each section of 100 words.

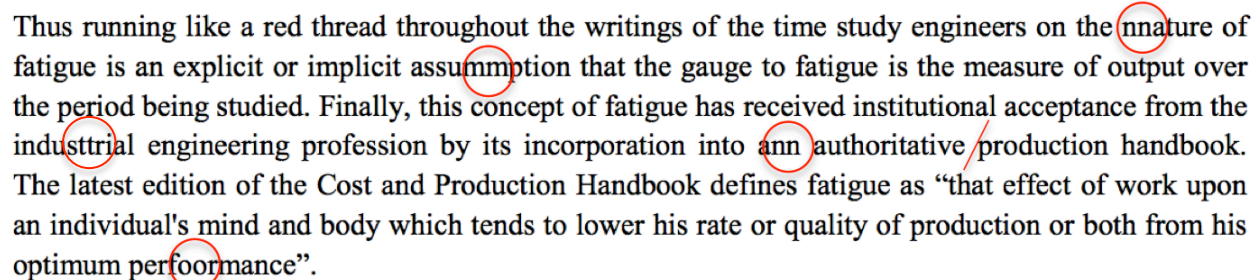
In line with the differential approach outline above, the reading task was comprised of an *easy* and *difficult* variation, high-resolution text and low-resolution text, respectively. Using the ADOBE Acrobat Professional X, the high-resolution was adjusted to 300 dots per inch (DPI) (Figure 13), whereas the low-resolution text was adjusted to 60 DPI (Figure 14). For each

reading task, the participant was required to complete the task as fast as possible for the duration of three minutes. Participants were instructed to circle in pencil any spelling errors they identified and then to continue scanning the text for further errors. At the conclusion of the three-minute test, participants were asked to indicate how far they had read by placing a mark in the text, which allowed for the estimation of reading speed. Reading speed was self-paced. See Figure 13 and Figure 14 for illustrations.

The text was formatted to Times New Roman font, 12pnt font size, justified columns and 1.15 line spacing.

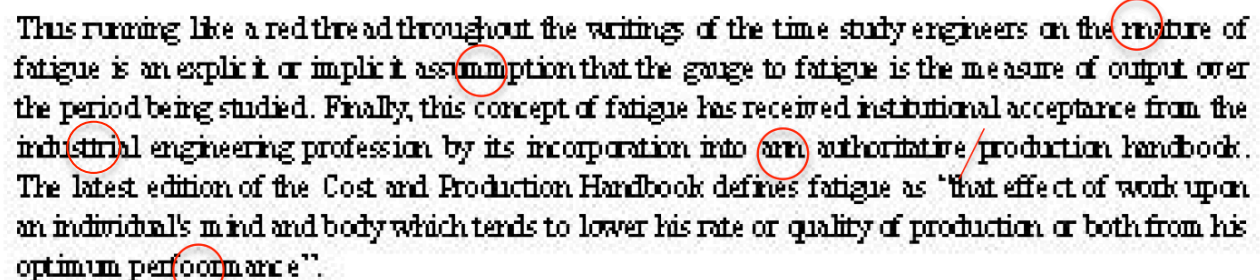
Variables of interest for the reading task

- Performance measured by reading speed (words per minute) and reading accuracy (the percentage of errors identified).
- Physiological measures include heart rate and heart rate variability, blink frequency and blink duration.



Thus running like a red thread throughout the writings of the time study engineers on the nnature of fatigue is an explicit or implicit assummmption that the gauge to fatigue is the measure of output over the period being studied. Finally, this concept of fatigue has received institutional acceptance from the indusstrial engineering profession by its incorporation into ann authoritative production handbook. The latest edition of the Cost and Production Handbook defines fatigue as “that effect of work upon an individual's mind and body which tends to lower his rate or quality of production or both from his optimum performmance”.

Figure 13: Example of 300 DPI texts used in the reading task.



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Figure 14: Example of 60 DPI texts used in the reading task.



Figure 15: Participant performing the reading task.

3.4.3 Subjective Analysis

3.4.3.1 Borg CR-10

CR-10 is a uni-directional rating scale that has been shown to be a reliable measure for the intensity of overall fatigue (Ahsberg *et al.*, 2000). The Borg CR-10 scale (Appendix B2) ranges from 0-10 and contains text ranging from “very very light” to “very very hard” alongside the values to assist the individual with choosing the most correct rating. During habituation, participants were introduced to the scale and taught how to use it. The Borg CR-10 was used to assess the effort required to apply attention to the task at the conclusion of each of the four maximal performance tests and after every 15-minute driving period within the sub-maximal driving task.

It is important to note that the subjective measurement of fatigue and workload was not the main objective of the study and was therefore taken to provide additional insight into the psychophysiological phenomenon and possibly assist with the interpretation of the performance and psychophysiological results.

3.5 DEPENDENT VARIABLES

This study therefore aims to employ a differential approach to provide a quantitative measure of fatigue at a resource level. Specifically, to assess whether performance impairment is related to stage-specific information processing performance impairment. Additionally, the differentiation regarding whether fatigue is actual resource depletion as opposed to a protective proactive effort-regulation to delay fatigue will be investigated.

In an attempt to holistically understand the effects of the protocol, this study will analyse changes in various psychophysiological, subjective and performance parameters over time, as well as how these influence the availability of specific cognitive resource. Heart rate and heart rate variability, blink frequency and blink duration, as well as forehead and tympanic temperatures will be recorded during the test protocol to assess any psychophysiological fluctuations. These measures have all been shown to be sensitive to fatigue (Section 2.5)

3.5.1 Heart Rate and Heart Rate Variability

Heart rate (HR) and heart rate variability (HRV) are non-invasive methods used to assess fatigue states (Patel *et al.*, 2011). Simple heart rate (b.t.min^{-1}) has repeatedly been shown to decrease with increased levels of fatigue (Jorna, 1992; Mascord and Heath, 1992). However, initial heart rate decrement may be reflective of an adjustment to ambient room temperature. HRV is the measure of variation in heartbeats and is calculated by analysing the time series of inter-beat intervals (i.e., the R–R intervals). It reflects cardiovascular autonomic control exerted by both parasympathetic and sympathetic nervous systems (Mourot *et al.*, 2004), and has been used to examine both mental workload (Hancock and Verwey, 1997) and driver fatigue (Egelund, 1982; Horne and Reyner, 1995).

HRV can be evaluated using time-based measures or frequency domain measures (Jorna, 1992). Time-domain measures are calculated using the standard deviation of R–R (inter-beat) intervals (Patel *et al.*, 2011), the increase of which is an indication of decrease in mental workload, decrease in performance and associated increased levels of fatigue (Oron-Gilad and Ronen, 2007). Frequency-domain analysis is based on mathematical transformations of the signals from time-domain into separate frequency ranges (Patel *et al.*, 2011). The low

frequency (LF) power component (0.04–0.15 Hz) is typically associated with activity of both the parasympathetic and sympathetic, whereas the high frequency (HF) power component (0.15–0.4 Hz) is said to reflect parasympathetic activity (Bezerianos *et al.*, 1999).

The present study investigated the following time-domain and frequency-domain components of HRV and fatigue effects:

- SDNN, rMSSD, PNN50, PNN30 were used for time-domain analysis, and were calculated according to intervals set at 120s, as this was the longest interval possible without compromising the data obtained during the 2-minute maximal drive test.
- Low and high frequency spectra were calculated for the frequency-domain analysis. For each band, both total power and centre frequency were calculated. Ultra low frequency (ULF) and very low frequency (VLF) were avoided in the current study, as their physiological correlates are still unknown (Batchinsky *et al.*, 2007). Moreover, these frequencies do not hold any importance when HRV is analysed in 5-minute intervals (Task Force, 1996), as is the case in the present study.

Polar™ T34 heart rate memory belts were used to record the participants' cardiac responses throughout the test session. Located in the electrode of the heart rate belt was a microchip that was responsible for receiving the heart rate data and transmitting it to the DataLog MWX8 receiver.

3.5.2 Oculomotor Activity

Driver fatigue has been associated with an increase in blink duration (Dinges *et al.*, 1997; Van Orden *et al.*, 2000; Verwey and Zaidel, 2000; Svensson, 2004) and blink frequency (Stern *et al.*, 1994; Summala *et al.*, 1999; Sirevaag and Stern, 2000). In particular, increased blink frequency indicates light fatigue (the transition from awake to reduced vigilance) (Stern *et al.*, 1994), whereas the transition to severe sleepiness is accompanied by an increase in blink duration (Caffier *et al.*, 2003). More generally, studies have shown oculomotor functions are negatively affected by increasing task duration (Åkerstedt *et al.*, 2005). It is for these reasons that measures of blink duration and blink frequency were incorporated into the study.

The head-mounted Dikablis eye-tracking system from Ergoneers GmbH (Lange *et al.*, 2006),

on which two cameras recording at 50-hertz are installed was used to assess blink frequency and blink duration (Figure 16). The first camera (eye camera) detects the cornea reflex using an infrared light source and records pupillary movements of the left eye, while the second camera (field camera) is aimed directly in front of the participant and records the participant's field of view. This requires calibration to be performed in two stages. First, the position of the cameras, screen and participant has to be set so that the software can have an accurate axis to represent the simulator room. Next, the participant fixes his/her gaze sequentially on four experimenter-defined reference points in the visual field. At the point of gaze fixation, the experimenter selects the corresponding location on the software's field-view feed and in so doing calibrates the eye-tracking system. This second step is repeated four times. It is vital that the placement of the head unit not be altered, as extensive adjustments will require the system to be recalibrated.

During data collection, the head unit transfers the video information via cable to the recording unit, which stores the information for post-processing with the Dikablis Analysis Software.

The weight of the head unit is supported using the nose support, which is kept secure on the participant's head with an elastic retaining band. The head unit is neither obtrusive nor does it interfere with the driving process, visual or otherwise.



Figure 16: The head unit of the Dikablis eye-tracking system.

3.5.3 Temperature

Skin temperature was used in the current study to assess whether any decrease in heart rate during the submaximal drive would be attributable to adaptation to ambient room temperature. A custom-built temperature sensor was used to measure changes in forehead temperature. This sensor was connected to the DataLog MWX8 receiver, which transferred temperature data to the central computer for analysis.

3.6 CONTROLLED CRITERIA

Extraneous variables and factors have negative impacts on the validity of data. To ensure maximum integrity of the data, certain factors therefore need to be controlled to ensure all participants are exposed to similar conditions. In so doing, subsequent changes in data responses can be better inferred to changes between controlled conditions and test design. The staggered nature of the testing batteries and mixed sample groups within each night shift cycle ensured that any environmental changes would be evenly distributed across the same 12 participants for any of the experimental groups.

The testing laboratory allowed constant controlled exposure of lighting to all participants. Through ceiling florescent lighting, the lighting was constant at 500 lux throughout the testing.

All information given to participants was accurate but incomplete. The participants were given information regarding the nature of each task they would be performing within the testing session and the operational information necessary for successful completion thereof. The deception included the rationale behind the task order as well as the task duration, for each aspect of the protocol. This aspect is explained in detail in Section 3.2.2.

3.7 EXPERIMENTAL PROCEDURE

3.7.1 Participant Recruitment

Participant recruitment took the form of advertisement through posters, e-mail and through student networking. A general breakdown of the research was provided, including exclusion criteria from participation in the study. Potential participants, fulfilling the criteria outlined, were

asked to contact the researchers to set up a date when the participants would attend the first of two habituation sessions. Participants contacted researchers via e-mail, texted messages and calls, all concerns and questions were dealt with before arranging the first meeting, which was to take place in the Human Kinetics and Ergonomics Department.

Once participants were recruited they were required to complete a pre-screening morningness-eveningness questionnaire adapted from Horne and Östberg (1976) (Appendix A2). Through this, the participant provided details regarding age, gender, race, driving experience, morningness-eveningness and current level of education. All information was used in the assignment of the participants to testing groups; this was to ensure a homogenous distribution of participants across conditions. The design worked such that within each of the three experimental groups there was an even split of males and females, a similar distribution of education levels and morningness-eveningness. This was to ensure that variations between groups could be more accurately accounted for due to differences in conditions and not manipulated by an uneven distribution of participants on the basis of gender and level of education. All participants indicated no history of sleeping disorders, had a normal visual field range, were non-smokers, and attained an average of 7–8 hours sleep a night. Participants who did not meet these criteria (also stated in the letter of information; see Appendix A1) were not included in the study.

24 participants, 12 male and 12 female volunteered for this study; the participants' ages ranged from 18–23 years (mean age= 22.50 years, SD=2.87). All participants included in the current study met the abovementioned criteria.

Table II: A summary of characteristics for the male and female participants.

Sex	n	Age (years)	Race	Morning-Evening Level (Score based on Horne and Östberg's Scale)
Male	12	22.92 ($\pm$ 3.78)	10 White 2 Black	21.62 ($\pm$ 4.23)
Female	12	22.08 ($\pm$ 1.62)	8 White 4 Black	19.93 ($\pm$ 3.78)

3.7.2 Habituation

Participants were required to attend a habituation session within the HKE department 24-72 hours prior to testing, lasting approximately 30 minutes. Participants attended in individual sessions. Upon arrival, the investigator outlined the purpose and aims of the research, risks and potential benefits, and introduced the testing equipment. All information was provided in written (letter of information) and oral format. The experimenter then explained and demonstrated the resource specific task set (auditory memory span task, Fitts' tapping task, spelling recognition reading task) that the participant was going to perform during the final testing. All participants practiced one bout of the *easy* and *difficult* variations of each task, which lasted approximately fifteen minutes in total.

The participants were then introduced to the driving simulator task, and were told that they would begin a practice drive that would last for three minutes. They were asked to drive to the best of their ability and to maintain effort required for maximal performance for as long as they could. They were told that this included tracking the road as accurately as possible and avoiding off-road incidents as much as possible. They were then told that driving a simulator can be somewhat different from normal driving, and that they should use the practice drive as an opportunity to familiarise themselves with the steering sensitivity. Participants were informed that they could ask questions about the task throughout the practice drive. This was performed for both the maximal and sub-maximal conditions. The habituation for the sub-maximal driving task corresponded to the experimental group in which the participant was placed. Instructions for the maximal and sub-maximal task reflected the respective task requirements. As mentioned previously, heart rate and eye-tracking equipment was attached, but no data were recorded at the time. The Borg CR-10 scale was explained to the participants in terms of the type of discomfort and effort they were required to report on. Any questions regarding the equipment or the protocol were answered at this time. Additionally, participants were fully informed of the fact that they were under no obligation to remain in the study and that should they at any time feel uncomfortable or unhappy with the requirements of the study, they were fully within their rights to withdraw. After the participant acknowledged this right, they were handed a letter of informed consent (see Appendix A2). Participants read this and, if willing to take part, signed it indicating that they understood the procedure, the risks and benefits, and were willing to take part in the research study.

The participant was instructed to refrain from consuming alcohol for 24 hours, and caffeine for 12 hours prior to the testing session, as well as to have a decent amount of sleep (6 hours or more) the night before, as insufficient sleep has been shown to negatively affect cognitive ability, including attention and memory (Zisape, 2007). Participants were also requested to refrain from participating in any strenuous exercise 12 hours prior to the testing session, as this may also affect their psychophysiological data.

Once the participant felt comfortable with the procedure and equipment, and all questions and/or concerns were addressed, a date and time for the following session was agreed upon.

3.7.3 Experimentation

Participants were tested individually in a quiet room in one session lasting approximately 2.5 hours. The testing laboratory was a light-controlled room, which ensured that participants were exposed to the same environment regardless of testing time. To prevent glare, the testing station was lit from the behind the seated participant. To control for the extent and impact of circadian-related pre-session fatigue on the results, all participants were tested between either 9:00 – 11:30am or 2:00 – 5:00pm. These periods have been found to be similar with regard to circadian rhythm, and avoid the periods of greatest change due to circadian effects (Wijesuriya *et al.*, 2007). Each participant chose a testing time at which they felt they would be most alert.

Once a participant arrived for the second session, the researcher first enquired as to whether all the requirements prior to testing were upheld (Appendix A1). If any of these were not met, the researcher requested that the testing session be rescheduled for a later date, in order that they were to be met for the testing protocol. If the requirements were met, the procedure was verbally explained to the participant again to ensure understanding of what was expected during the test session.

Following this, participants were asked to sit in the adjustable driving chair, which was positioned approximately three meters away from the screen onto which the roadway was projected. Participants were asked to adjust the chair so that they could reach the steering wheel comfortably. They were also given the opportunity to adjust the back of their seat to a

level that was comfortable for them. The participants were then fitted with the Polar™ T34 heart rate belt, the head-mounted eye tracker and the forehead temperature sensor. The electrode/chest strap was secured around the mid-chest of the participant, at the inferior border of the pectoralis major muscle and in line with the apex of the left ventricle. Conductive gel was placed on the electrodes of the heart rate belt to ensure a stronger conduction and reading of the participant's heart rate. After the testing equipment was fitted to the participant, the head-mounted eye tracker was calibrated. This was done by instructing the participant to direct their gaze sequentially at the four corners of the main task display without moving their head, and adjusting the settings until all four corners were calibrated. Using the Dikablis hardware and software, all participants' eye data were recorded throughout the 180-minute testing session.

Once the eye-tracker, heart rate monitor and temperature sensors were activated, the participant was asked to remain seated in the driving simulator and to sit quietly for five minutes with their eyes closed. This allowed for the stabilisation of heart rate and temperature data.

The testing protocol then began (Figure 6). The participant was first required to perform a 2-minute maximal-performance driving test. Second, the resource specific task set was performed, the order of which was balanced across participants. The resource specific task set lasted approximately 20 minutes. Following the resource specific task set, the participant performed a 2-minute maximal-performance driving test. These measures served as a baseline against which fatigue effects were later measured. Directly following each of the 2-minute maximal-performance drives, the researcher asked the participants to rate their level of subjective mental effort based on the Borg CR-10 scale. Following this task the participant performed the continuous 90-minute sub-maximal driving task. At 15-minute intervals throughout the duration of the drive, the researcher briefly asked the participant to rate their level of subjective mental effort based on the Borg CR-10 scale. Directly following the sub-maximal drive, the participant performed an additional 2-minute maximal-performance driving test, followed immediately by another set of resource-specific tasks. The participant then performed a final 2-minute maximal-performance driving test. The change-over intervals between each task were kept to a minimum, never exceeding 60s between the end of one task and the beginning of the next. This was important to reduce any fatigue recovery effect.

3.8 ETHICAL CONSIDERATIONS

Prior to participant recruitment, ethical approval for the study was received from the Human Kinetics and Ergonomics ethical committee. Full disclosure of procedures and participant requirements was provided to the ethics committee before ethical approval was granted (see Appendix A4). This included the experimental procedure, methodological consideration, and participant requirements. The letter of information and informed consent that the participants would receive during the habituation session was also included.

3.8.1 Informed Consent

Prior to the commencement of the study all recruited participants were familiarised with the research requirements, and the risks and potential benefits, which were explained both verbally and in written form (Appendix A). Participants were then given the opportunity to sign an informed consent document. Throughout all the interaction that the researchers had with the participants, a constant reminder was made that all participants were free to withdraw from the study at any stage, with no prejudice against them. Participants agreeing to be part of the research were assured that all of the personal information gathered during the course of the research would be kept confidential and that their anonymity would be maintained.

3.8.2 Anonymity

All data and personal information recorded during the study were stored in either electronic or paper format, with each participant's data being assigned a code specific to the condition to which they were assigned. All data were stored on personal computers of the researchers involved, and removed from any communal research laptops. Only the primary researcher kept the main lists of codes and names.

3.9 DATA REDUCTION AND STATISTICAL ANALYSIS

3.9.1 Heart Rate and Heart Rate Variability

Heart rate and temperature data were collected via Biometrics DataLog MWX8 and transmitted wirelessly and in real time to the Biometrics DataLog software to permit synchronization with each other. Once the heart rate file was downloaded from the heart rate belt it was converted into an sdf. file, using the Biometrics DataLog software. The sdf. file was then processed using a Data Reduction and Analysis Tool, developed by the Human Kinetics and Ergonomics Department at Rhodes University, which analysed and corrected for any artefacts within the heart rate data and which also allowed for the basic analysis of the data. Heart rate variability was processed from inter-beat-intervals in time domain (coefficient of variability) and in frequency domain, processing Low Frequency band and High Frequency band (0.04-0.15 Hz and 0.15-0.4 Hz, respectively), in intervals of 5 minutes across all tests and for the duration of the protocol. Temperature data were also processed in intervals of 5 minutes across all tests and for the duration of the protocol.

3.9.2 Eye Measures

The stored eye data, in the form of a txt. file, was processed using a data reduction tool, developed by the Human Kinetics and Ergonomics department at Rhodes University. This tool reduced and analysed the blink frequency and blink duration for each participant.

3.9.3 Lane Deviation

The driving simulator record file was processed and analysed using the DriveSim_v7.02 software. Once the record file had been processed, the researcher transformed the record file into an ASCII file using the DriveSim_v7.02 software, allowing for further analyses of the data using the Excel spread sheet, which produced the lane deviation of each participant for the duration of the main task.

Statistical analyses were performed using Statistica software package Version 10 (Statistica®; Statsoft Inc.; Tulsa, Oklahoma, USA). One-factorial, two-factorial and three-factorial repeated

measures analyses of variances (ANOVAs) were conducted to assess the general differences between the three conditions, the time on task and the various resource tests.

3.10 SUMMARY

The design of this MSc project has been presented in this chapter. It aimed to create driver fatigue due to the monotony of the driving task and assess the extent to which this fatigue could be explained via resource depletion or effort-regulation. Factors influencing sustained attention were controlled, particularly fatigue, time on task and circadian rhythms. All scenarios are sustained attention tasks, with driving being reduced to a lane-keeping task at a constant speed. Task-demand is varied through the road design (small, medium, or large road width).

Various direct and indirect measures were used to reliably assess driver fatigue throughout the experiment. These are collected and correlated to driver fatigue in the next chapter. These measures have been shown to modify when the driver is fatigued. They include vehicle control performance, cardiovascular responses, visual performance, resource-specific utilisation and participant factors. All performance and psychophysiological data were collected at a rate that enabled real-time assessment of fatigue development.

This chapter also covered the major components of the implementation of the driving simulator study. Equipment available to implement this study included a low-fidelity driving simulator – which provided the simulated environment as well as the required surrogate variables from the car. The heart rate device used was a Polar™ T34 heart rate belt and receiver and the temperature devices used were forehead and tympanic temperature sensors, the measures from which were captured on the Biometrics DataLOG MWX8. The eye-tracking device used was the Dikablis Gaze Analytic System. All psychophysiological data were synchronised, and analysed simultaneously using the Data Reduction and Analysis Tool.

CHAPTER IV

RESULTS

4.1 INTRODUCTION

The primary aim of this investigation was to analyse driving performance in a prolonged simulated driving task from a behavioural, psychophysiological and subjective perspective, and in doing so distinguish between the contributions of two leading candidate mechanisms proposed to control driving performance: resource depletion and effort-regulation. The second aim was to identify whether the impacts of a prolonged drive differentially tax information processing stages.

Participants were required to perform a sub-maximal drive over a 90-minute period, uninterrupted. This prolonged drive is described as sub-maximal as it requires participants to drive within a lane, and does not require maximal attention to perform the task. Participants were distributed evenly amongst three experimental groups: small, medium, large, which directly corresponds to the relative width of the road on which the sub-maximal driving task was to be performed.

Participants were exposed to a pre- and post-task test battery. These included: maximal driving performance, digit recall ability, high and low precision response time and target deviation, and object recognition. For the psychophysiological perspective, heart rate, heart rate variability and skin temperature was recorded. Neurophysiological assessments included oculomotor measures such as blink frequency and blink duration. Finally, subjective assessment of perceived effort was measured by the Borg CR-10 scale, which was completed in conjunction with the maximal and sub-maximal driving tests.

Key considerations for statistical interpretation

Throughout the results and discussion chapters, *time on task*, the *group*, *pre- and post-*, and *difficulty* effects will be referred to.

- The *time on task effect* or *effect of time* refers to the changes that occur over the course of the 90-minute sub-maximal drive, analysed in *5-minute intervals*.
- The *effect of group* or *group effect* refers to the difference in responses between the three experimental groups: *small*, *medium* and *large*, corresponding to the different road widths. *Group effect* is considered in the analysis of the sub-maximal drive test as well as the pre- and post-task resource tests.
- *Pre/post effect* refers to the difference in responses between the resource tests before and after the sub-maximal drive. Pre- and post- resource test lengths were analysed in *1-minute intervals*.
- *Difficulty effect* refers to difference in responses between the changes in difficulty both within the sub-maximal drive over time and for the resource tests. This effect is therefore valid for both the sub-maximal drive and the resource test analysis.

The statistical consideration for the 90-minute sub-maximal driving test is a covariate analysis to assess the impact of road width (workload) within the sub-maximal drive to ascertain whether varying road widths (workload) result in different performance/fatigue profiles. In essence this will potentially indicate if performance/fatigue profiles are more affected by road width (*small*, *medium*, *large*) or simply by the prolonged driving.

In line with the differential approach, the statistical consideration for the pre- and post-resource specific tests is a 3-way ANOVA analysis assessing overall effects for each of the resource specific tests to look for an interactional effect between *pre- and post- effect* and *difficulty effect*.

Due to the extent and complexity of the data, only significant results pertinent to the aims of the study are presented herein. Tables summarising relevant statistical effects are included at the beginning of each section and detailed tables are included within each sub-section. Complete statistical tables are listed in Appendix C.

Unless otherwise stated, all statistical analyses were performed with a 95% confidence interval ($p < 0.05$), denoted by the error bars in all figures. Statistical methods used for the various analyses are outlined in Table III.

Table III: Statistical table key, indicating which statistical methods were used to determine the following effects.

	Effect	Statistical Method of Analysis
SUB-MAXIMAL DRIVE	GROUP	2 way ANOVA
	Time on task	
	Time on task *GROUP	
MAXIMAL DRIVE	GROUP	3 way ANOVA
	Pre - Post	
	PrePost *GROUP	
	PreR1*PreR2	
	PostR1*PostR2	
	PreR2*PostR1	
RESOURCE TESTS	GROUP	3 way ANOVA
	Pre - Post	
	PrePost *GROUP	
	DIFFICULTY	
	DIFFICULTY *GROUP	
	PREPOST*DIFFICULTY	
	PREPOST*DIFFICULTY*GROUP	

Reference measures, and therefore relative values, were not used in the following analyses as the nature of the differential approach considers overall intra-individual differences rather than inter-individual differences. Relativised values would have been preferable and sensible for the inter-individual differences had they been of interest.

Initially, gender and age were analysed as covariates throughout all analyses. However, they elicit only very minor effects on statistical effects across all analyses. Given its low range within the participant group and to avoid it compounding the main results of interest, age is not considered as a covariate for the analyses presented in this chapter. Gender was evenly distributed across experimental groups and showed little effect on statistical responses and is therefore not included as covariate for the following analyses. Unless otherwise stated, none of the effects described below were calculated with age or gender as covariates.

4.2 PROLONGED SUB-MAXIMAL DRIVE

The following section details changes in dependent variables over the 90-minute sub-maximal drive. There were no interruptions during the drive apart from the brief assessment of subjective ratings of perceived exertion; these took place at 15-minute intervals throughout the drive.

Table IV: Summary of significant time on task and group related effects⁴ for dependent variables (**X** denotes a significant difference, where $p < 0.05$; **XX** denotes a significant difference, where $p < 0.01$).

		GROUP	TIME on task	TIME on task *GROUP
PERFORMANCE	Mean Deviation	X	XX	X
PHYSIOLOGICAL	Heart Rate Frequency		XX	
	HRV: SDNN		XX	XX
	HRV: rMSSD		XX	X
	HRV: PNN30		X	
	HRV: PNN50		X	
	HF Power		XX	XX
	HF Centre Frequency		X	
	LF Power		XX	XX
	LF Centre Frequency		X	
	LF power relative to (LF+HF)		XX	
	Temperature			
OCULOMOTOR	Blink Frequency		XX	
	Blink Duration		XX	
SUBJECTIVE	RPE		XX	

4.2.1 Performance Parameters

4.2.1.1 Driving Performance

Two-factorial analysis of variance (ANOVA) was performed on the driving data to establish the average lane deviation achieved, recorded over the 90-minute task duration. Results are displayed in Table V. Note: While lane deviation is measured in meters, this corresponds only

⁴ **GROUP** = difference in the changes over time between the three experimental groups; **TIME on task** = changes in effect elicited by the time on task; **TIME on task *GROUP** = interactional effect of **GROUP** and **TIME on task**.

with the road geometry used on the specific simulator; therefore the measure should be considered as an arbitrary unit.

Table V: Analysis of variance for lane deviation established during the main task, with time on task and group effect as the two factors (* = significant effect, $p < 0.05$; ** = significant effect, $p < 0.01$).

Lane deviation effect	SS	DoF	MS	F	p
GROUP	0.055453	2,21	0.027727	3.3728	<0.05 *
Time on task	0.021641	17,357	0.001273	7.1772	<0.01 **
Time on task *GROUP	0.010837	34,357	0.000319	1.7971	<0.05 *

Driving (tracking) performance declines significantly over time, demonstrated by the significant increase in overall mean lane deviation ($p < 0.01$; Table V and Figure 17). Specifically, significances exist between minutes 40 and 90 (Figure 17; Appendix C2). In addition to the significant *group effect*, there is a significant interaction between *time on task* and *group effect* ($p < 0.05$; Table V). These data indicate that the profile of driving performance decrement differs significantly between the three experimental groups ($p < 0.05$; Figure 18). The *small* and *medium* groups reflect a similar and steady decrease in driving performance over time. In contrast, the *large* group elicits a comparatively greater decline over time, with greater fluctuations in performance, peaking within the 40-45 minute interval (Figure 18). Therefore, *time on task effect* is almost exclusively attributable to the *large* experimental group. This is not surprising given that the larger road width allows for a greater margin of error.

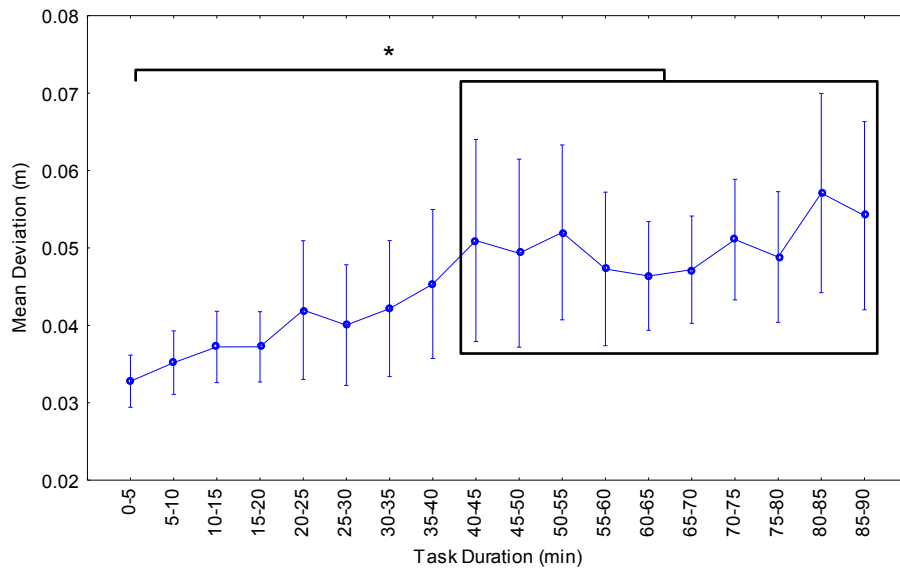


Figure 17: Overall mean lane deviation increases significantly over time for all participants, indicating a significant reduction in driving performance (* represents a significant difference, $p < 0.01$; Error bars denote 95% confidence interval).

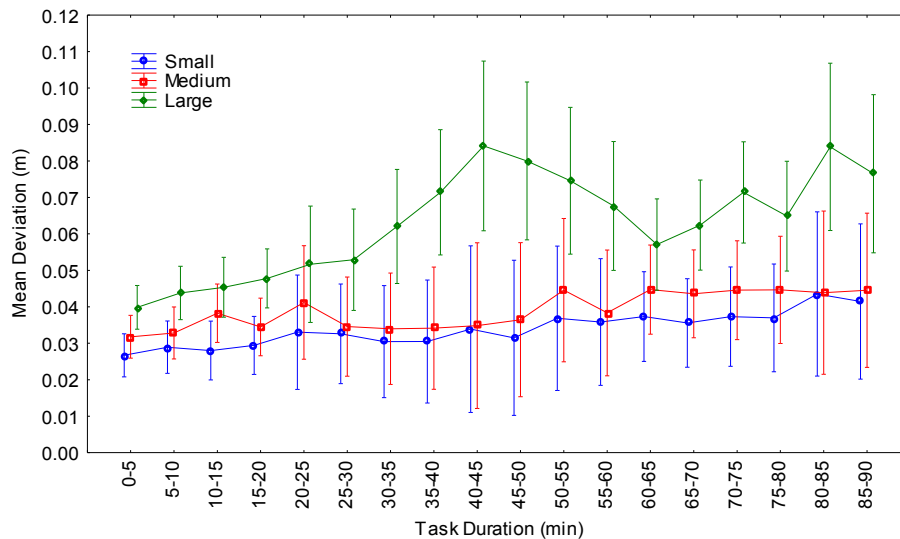


Figure 18: Change in mean deviation over time for all groups (Error bars denote 95% confidence interval).

4.2.2 Cardiovascular Responses

4.2.2.1 Heart Rate Frequency

Table VI: Statistical effects for heart rate frequency established during the main driving task, with time on task and group effect as the two factors (* = significant effect, $p < 0.01$).

Heart Rate Frequency	SS	DoF	MS	F	p
GROUP	953	2,21	477	0.299	0.75
Time on task	1283	17,357	75	8.191	<0.01 *
Time on task *GROUP	141	34,357	4	0.449	0.99

Heart rate frequency decreases significantly ($p < 0.01$) over time, from $74 \text{ bt} \cdot \text{min}^{-1}$ in the first interval to $68 \text{ bt} \cdot \text{min}^{-1}$ at the conclusion of the sub-maximal drive, suggesting that the participants were in a fatigued, sleepy mode at the end of the driving task. Specifically, significances exist between the first interval and minutes 30 and 90 (Figure 19; Appendix C2). There is no significant *group effect* and no interaction effect between *group* and *time on task* (Table VI). This suggests that heart rate changes do not correspond to the different driving profiles shown in Figure 18.

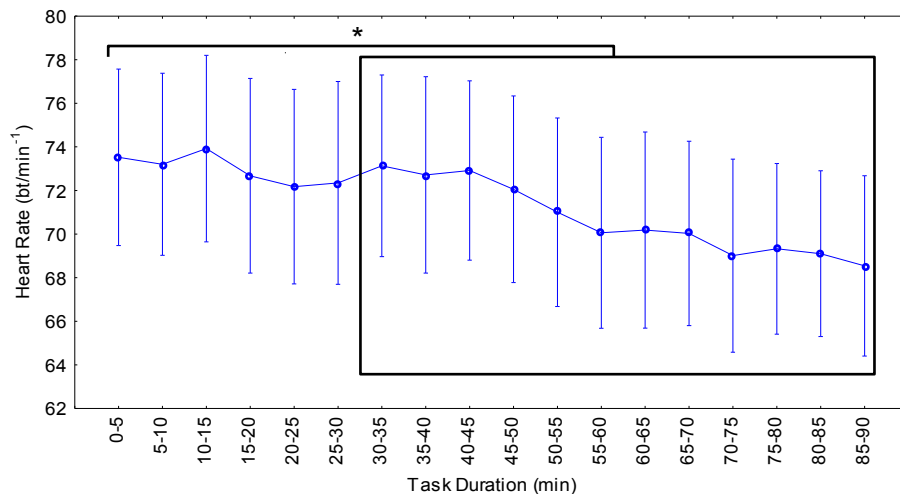


Figure 19: Heart rate frequency ($\text{bt} \cdot \text{min}^{-1}$) decreases significantly over time for all participants (* represents a significant difference, $p < 0.01$; Error bars denote 95% confidence interval).

4.2.2.2 Heart Rate Variability: Time-Domain Analyses

Table VII: Analysis of variance for heart rate variability (rMSSD) established during the main driving task, with time on task and group effect as the two factors (* = significant effect, $p < 0.01$).

rMSSD	SS	DoF	MS	F	p
GROUP	27733	2,21	13867	0.8806	0.43
Time on task	49393	17,357	2905	13.0045	<0.01 *
Time on task *GROUP	17749	34357	522	2.3365	<0.01 *

Heart rate variability (rMSSD) increases significantly ($p < 0.01$) over the 90-minute drive (Table VII and Figure 20). Specifically, differences exist between minutes 5 and 55, with heart rate variability peaking in the 75-80 minute interval (Figure 20; Appendix C2). This indicates a decrease in effort over time. The first significant differences are, however, seen only 15 minutes after the first significant performance decrements.

Time on task and *group effect* interact statistically ($p < 0.01$), indicating that heart rate variability differs significantly between the three experimental groups over time (Table VII and Figure 21). However, this difference is evident only after the 45th minute.

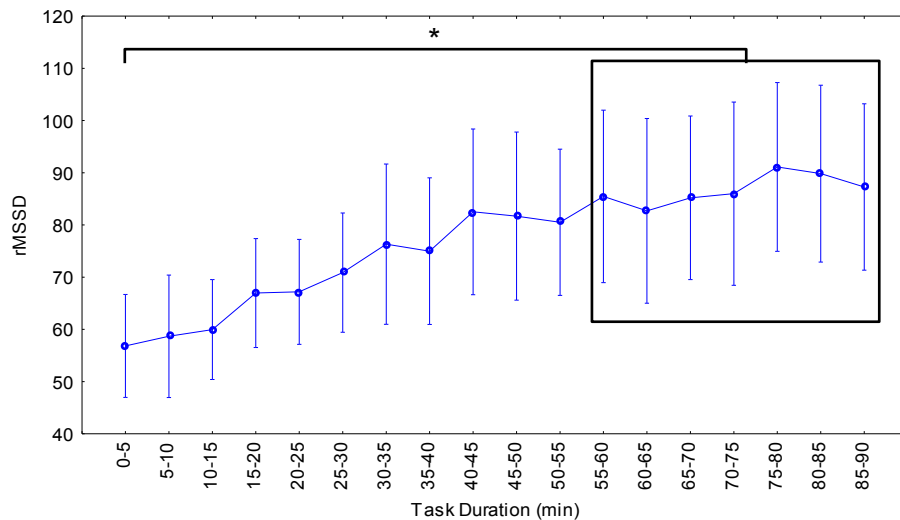


Figure 20: Average heart rate variability (rMSSD) measured for time on task (* represents a significant difference, $p < 0.01$; Error bars denote 95% confidence interval).

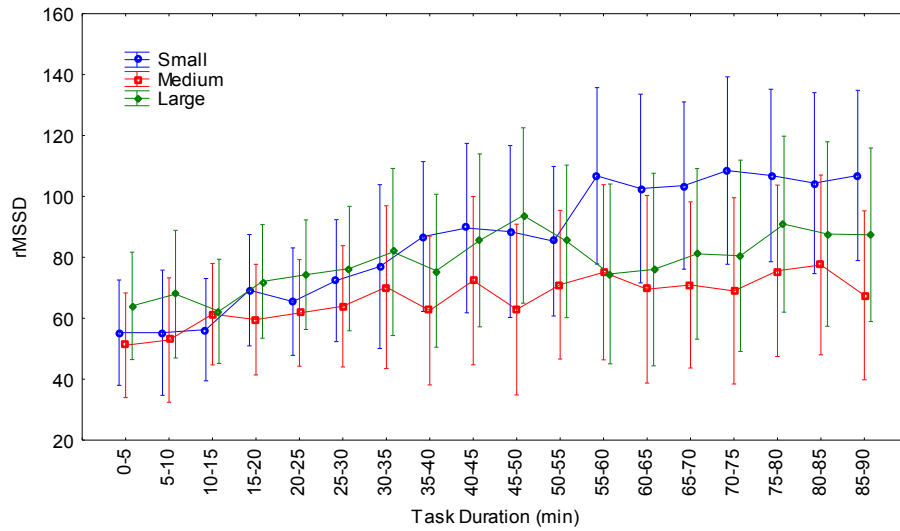


Figure 21: Change in HRV (rMSSD) over time for all experimental groups (Error bars denote 95% confidence interval).

4.2.2.3 Heart Rate Variability: Frequency-Domain Analyses

Within the spectral analysis of heart rate variability, HF and LF power values typically indicate parasympathetic and sympathetic activation of the autonomic nervous system, respectively. It is therefore expected that states of elevated arousal would be accompanied by increases in LF power responses, while low arousal would be accompanied by increases in HF power responses.

Table VIII: Two-factorial ANOVA conducted for HF power spectrum of heart rate variability established over time during the main driving task, with time on task and group effect as the two factors (* = significant effect, $p < 0.01$).

HF power	SS	DoF	MS	F	p
GROUP	34550020	2,21	17275010	1.02176	0.38
Time on task	18832205	17,357	1107777	5.78095	<0.01 *
Time on task *GROUP	14358982	34,357	422323	2.20390	<0.01 *

HF power increases significantly ($p < 0.01$) over time, indicating an elevated parasympathetic response (Table VIII and Figure 22). While there is no significant *group effect* ($p = 0.38$), there is a significant *group* and *time* interaction effect ($p < 0.01$), indicating that the change over time is different between the three groups. These differences however do not correspond to the

magnitude of road widths. Responses for the three groups remain relatively stable until the 45th minute interval, at which point HF power responses begin to fluctuate, with the *small* road width group showing the greatest increase from minutes 50-60 (Figure 23; Appendix C2).

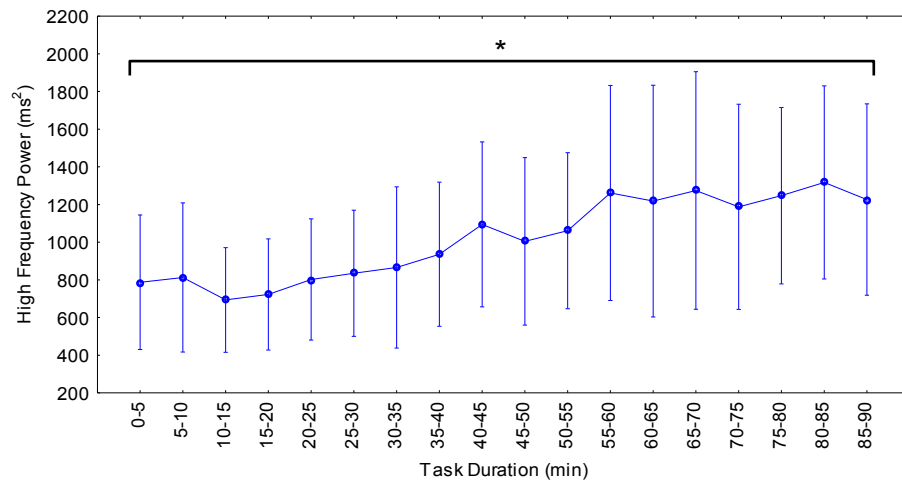


Figure 22: HF power increases significantly over time for all participants (* represents a significant difference, $p < 0.01$; Error bars denote 95% confidence interval).

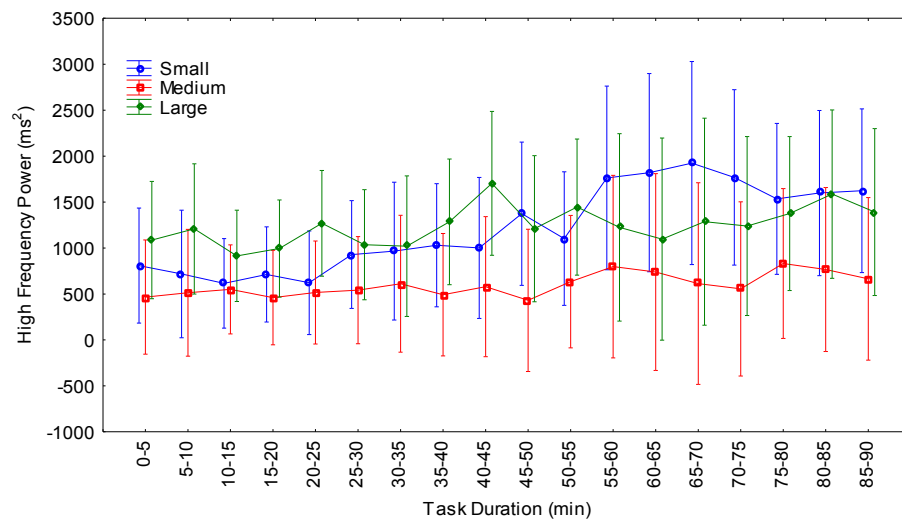


Figure 23: Significant difference in HF power over time between three experimental groups (Error bars denote 95% confidence interval).

Table IX: Statistical effects for heart rate variability (LF power) (* = significant effect, $p < 0.01$).

LF power	SS	DoF	MS	F	p
GROUP	1.480364E+08	2,21	7.401818E+07	1.14932	0.34
Time on task	1.768437E+08	17,357	1.040257E+07	4.21025	<0.01 *
Time on task *GROUP	1.576797E+08	34,357	4.637637E+06	1.87700	<0.01 *

LF power increases significantly over time ($p < 0.01$), increasing progressively until minute 40 (Table IX and Figure 24). Values decrease thereafter and stabilise for the remainder of the drive. *Time on task* and *group* effects interact significantly ($p < 0.01$; Table IX and Figure 25), with the *small* group exhibiting a similar profile to that of the HF power, as seen in Figure 23. All three groups show an elevated LF power in the 40-45 minute interval. While the *medium* and *large* groups show a sudden spike however, responses from the *small* group can be traced to the preceding two intervals where the increase is almost linear. An increase in LF power indicates an elevated sympathetic response and hence increased arousal and alertness. As this apparent arousal does not correspond to any significant improvements in driving performance (Figure 17 and Figure 18) or changes in heart rate variability (Figure 20 and Figure 21), it is hypothesised to be evidence of a sub-conscious effort-regulation. Further, while the *large* and *medium* groups reflect a decreased response following the peak, the *small* group shows an inverse profile after minute 55. No significant *group effect* is observed for LF power (Table IX).

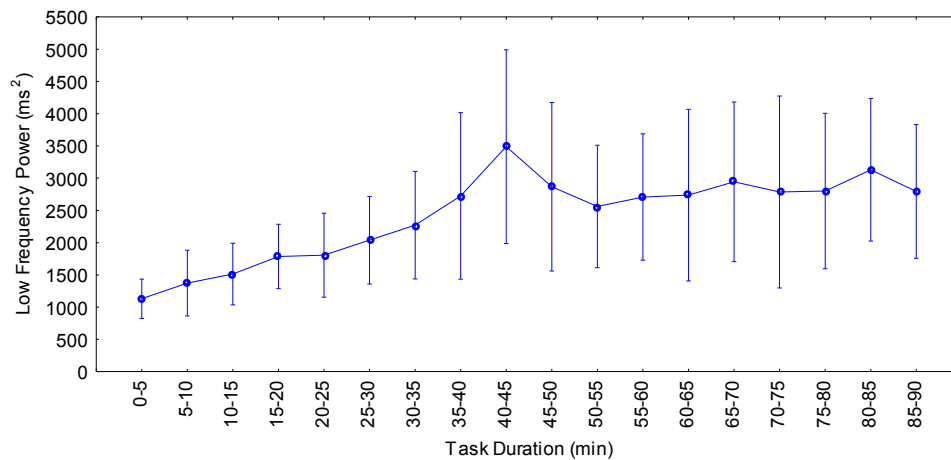


Figure 24: LF power responses over time for all participants (* represents a significant difference, $p < 0.05$; Error bars denote 95% confidence interval).

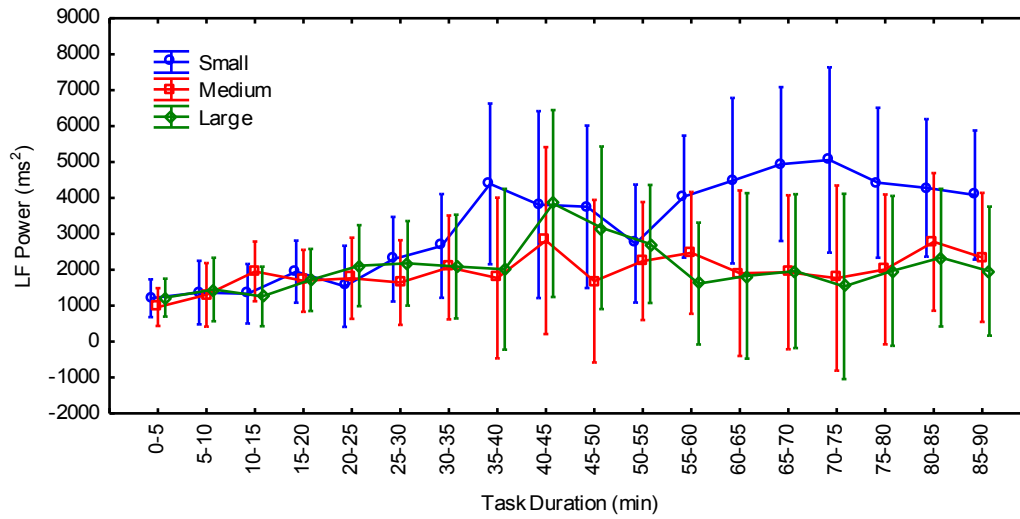


Figure 25: LF power band analysis for the three experimental groups over the sub-maximal drive (Error bars denote 95% confidence interval).

Table X: Statistical effects for LF power relative to (LF+HF) over time (* = significant effect, $p < 0.01$).

LF power relative to (LF+HF)	SS	DoF	MS	F	p
GROUP	7072	2,21	3536	1.6118	0.22
Time on task	4174	17,357	246	4.4709	<0.01 *
Time on task *GROUP	1587	34,357	47	0.8498	0.71

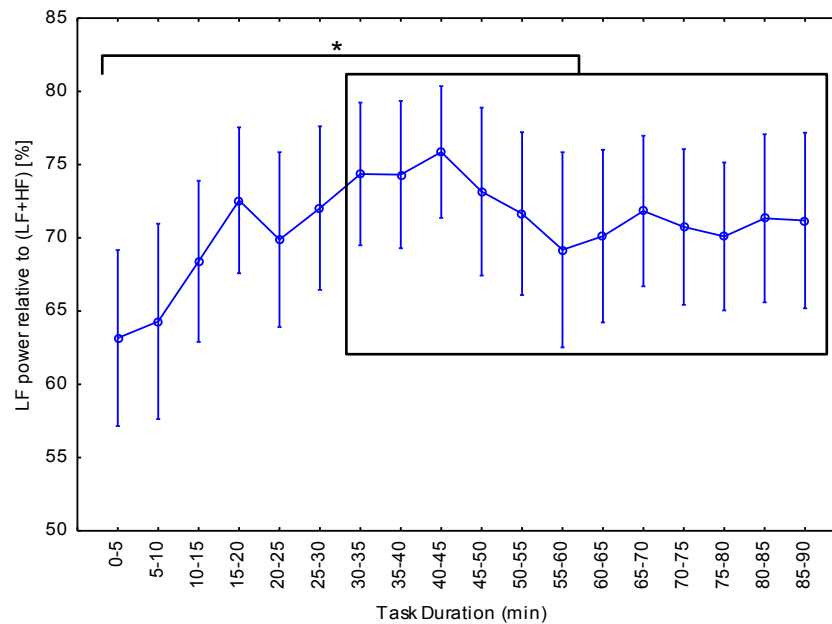


Figure 26: LF power relative to (LF+HF) over time for all participants (Error bars denote 95% confidence interval).

Figure 26 reveals a significant overall increase in the LF:HF ratio over time ($p<0.01$; Table X), substantiating the LF power response in Figure 24: increase in sympathetic activation. However, as is similar to the responses seen in Figure 24, the increase exists only up to the 40-45 minute interval, at which point it decreases and stabilises for the remainder of the drive (Appendix C2). Unlike the *group* effect observed in Figure 25, the LF power component of the LF:HF ratio did not show any *group* effects (Table X).

4.2.3 Oculomotor Parameters

4.2.3.1 Blink Frequency

Table XI: Two-factorial ANOVA for blink frequency (blinks/min⁻¹), measured during the main task with time on task and group effect as the factors (* = significant effect, $p<0.01$).

Blink Frequency	SS	DoF	MS	F	p
GROUP	611.0	2,21	305.5	1.7430	0.20
Time on task	617.7	17,357	36.3	7.0947	<0.01 *
Time on task *GROUP	170.8	34,357	5.0	0.9805	0.50

Blink frequency increases significantly over time ($p<0.01$; Table XI), indicating the presence of fatigue. Average blink frequency in the first 5-minute interval is 14 blinks/min⁻¹ and increases significantly to 17.5 blinks/min⁻¹ over the first 30 minutes, remaining stable thereafter for the remainder of the drive (Figure 27; Appendix C2). These data demonstrate fatigue effects within the first 30 minutes of the drive.

The differences in blink frequency between the experimental groups are nonsignificant ($p=0.20$), as is the interaction between *time on task* and *group* effects ($p=0.50$; Table XI). This suggests that blink frequency is not sensitive to the differences in performance decrements and heart rate variability responses observed between the experimental groups.

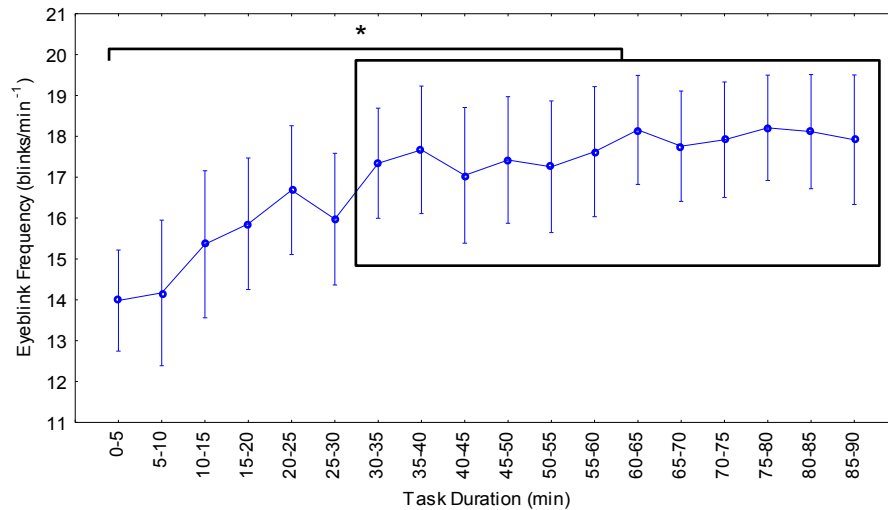


Figure 27: Change in blink frequency (blinks/min⁻¹) over time for all experimental groups (* represents a significant difference, $p < 0.05$; Error bars denote 95% confidence interval).

4.2.3.2 Blink Duration

Table XII: Two-factorial ANOVA for blink duration (milliseconds), measured during the main task with time on task and group effect as the factors (* = significant effect, $p < 0.01$).

Blink Duration	SS	DoF	MS	F	p
GROUP	64941	2,21	32471	1.1116	0.35
Time on task	33149	17,357	1950	2.4280	<0.01 *
Time on task *GROUP	26027	34,357	766	0.9532	0.55

Blink duration increases significantly ($p < 0.01$) over time, from 150ms at the beginning of the drive to 175ms during the last interval. Specifically, significant differences are between minutes 25 and 75, after which blink duration decreases and stabilises for the remaining 15 minutes of the drive (Figure 28; Appendix C2). As with blink frequency, time on task and group effect does not interact statistically ($p = 0.55$) for blink duration (Table XII). The differences in blink duration between the experimental groups are nonsignificant ($p = 0.55$; Table XII).

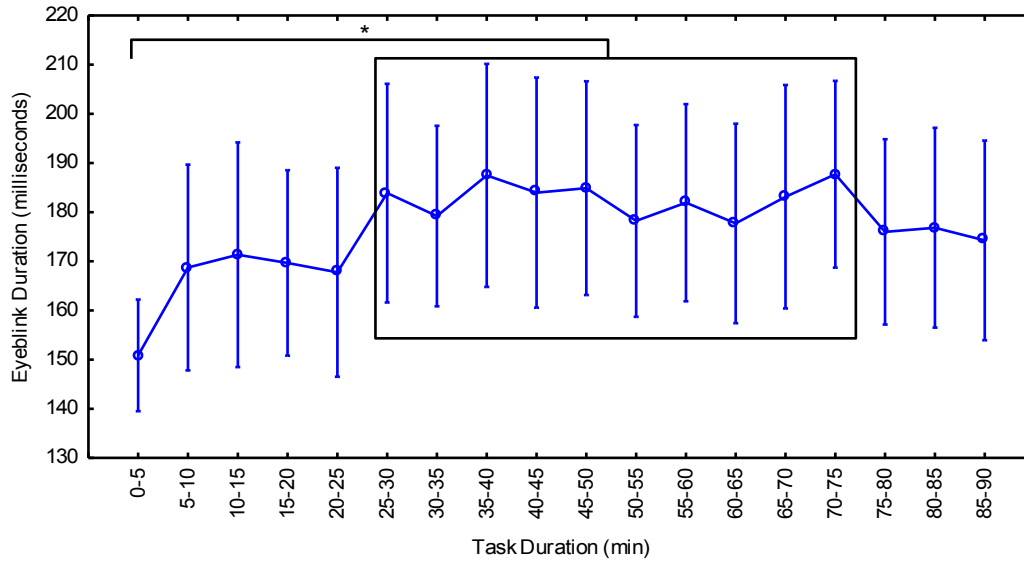


Figure 28: Average blink duration (ms) measured over the course of the sub-maximal drive for all participants (* represents a significant difference, $p < 0.01$; Error bars denote 95% confidence interval).

4.2.4 Subjective Parameters

4.2.4.1 Perception of Effort (RPE)

Table XIII: Average CR-10 rating for all participants over time taken at 15-minute intervals (* = significant effect, $p < 0.01$).

Rate of Perceived Exertion	SS	DoF	MS	F	p
GROUP	16.358	2,21	8.179	0.3891	0.70
Time on task	350.592	5,105	70.118	47.7450	<0.01 *
Time on task *GROUP	15.413	10,105	1.541	1.0495	0.41

Subjective ratings of perceived exertion increase significantly over the sub-maximal drive, with significant differences between all six measures ($p < 0.01$; Table XIII and Figure 29). There is no *group effect* calculated, and no significant *interaction effect* between *time on task* and *group effect* (Table XIII). This suggests that subjective effort is more sensitive to time on task than differences in task workload.

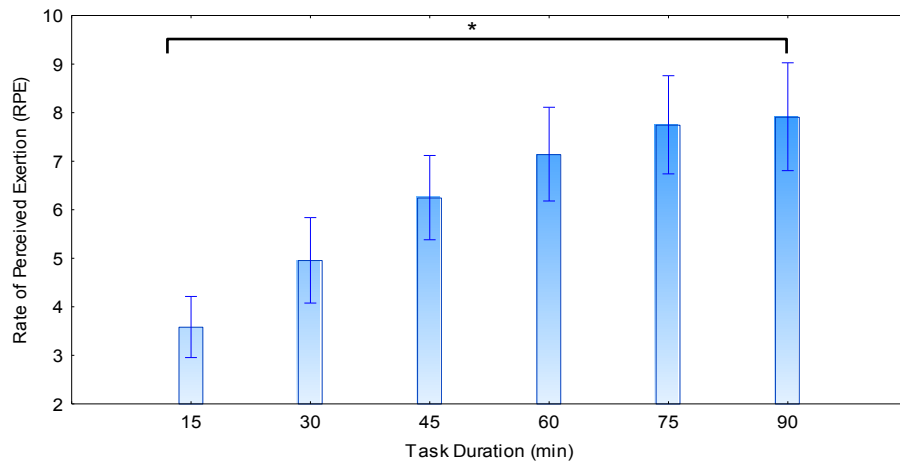


Figure 29: Average rating of perceived exertion (CR-10 rating) for all participants over time at 15-minute intervals (* represents a significant difference, $p < 0.01$; Error bars denote 95% confidence interval).

4.2.5 Temperature

Table XIV: Two-factorial ANOVA conducted for skin temperature, using time on task and group effect as factors.

Temperature	SS	DoF	MS	F	p
GROUP	14.8	2,21	7.4	0.38	0.70
Time on task	1.4	17,357	0.1	0.79	0.70
Time on task *GROUP	1.8	34,357	0.1	0.52	0.99

Temperature shows no statistical effects over the 90-minute sub-maximal drive (Table XIV).

4.3 MAXIMAL DRIVING

To ascertain whether there were any learning effects from the driving, two combinations of the four maximal drive repetitions were considered. The first was PRE- 1 and PRE- 2. As these fell either side of the pre-task resource test battery, this would give an indication as to whether participants' driving ability improved over the course of the test battery. The second was the comparison of PRE- 2 and POST- 1, which would reflect any learning effects gained over the 90-minute drive. The analysis of the difference between POST- 1 and POST- 2 would reflect any recovery from any observed fatigue accumulated over the 90-minute sub-maximal drive.

Table XV: Summary of significant effects⁵ for and between the various dependent variables during the maximal driving tasks (X denotes a significant difference, where $p < 0.05$).

		GROUP	PREPOST	PREPOST* GROUP	PRE 1*PRE2	POST1*POST2	PRE2*POST1
PERFORMANCE	Mean Deviation						
PHYSIOLOGICAL	Heart Rate Frequency		X			X	X
	HRV: SDNN		X				
	HRV: rMSSD		X				X
	HRV: PNN30		X				
	HRV: PNN50		X				
	HF Power		X				
	HF Centre Frequency				X		
	LF Power					X	
	LF Centre Frequency						
	LF power relative to (LF+HF)				X	X	
OCULOMOTOR	Blink Frequency				X		
	Blink Duration						
SUBJECTIVE	RPE		X		X	X	X

4.3.1 Performance Parameters

⁵ **GROUP** = difference in the changes over time between the three experimental groups; **PREPOST** = overall difference between responses before and after the maximal driving task; **PREPOST*GROUP** = interactional effect of **PREPOST** and **GROUP** effect; **PRE1PRE2** = difference in responses between the first and second repetition of maximal drive task PRE- sub-maximal drive; **POST1POST2** = difference in responses between the first and second repetition of maximal drive task POST sub-maximal drive; **PRE2POST1** = difference in responses between the second repetition of maximal drive task PRE- sub-maximal drive and the first repetition of maximal drive task POST sub-maximal drive

4.3.1.1 Driving Performance

Table XVI: Multi-factorial ANOVA conducted for mean lane deviation, using group effect, pre- and post- task and max drive repetition (R1vsR2) as factors.

Max Driving – Driving Performance	SS	DoF	MS	F	p
GROUP	0.000510	2,21	0.000255	0.48095	0.62
PrePost	0.000032	1,21	0.000032	0.24380	0.63
PrePost *GROUP	0.000432	2,21	0.000216	1.65522	0.22
PreR1vsPreR2	0.000003	1,23	0.000003	0.03510	0.85
PostR1vsPostR2	0.000007	1,23	0.000007	0.45323	0.51
Pre2vsPost1	0.000013	1,23	0.000013	0.16625	0.69

Maximal driving performance (mean lane deviation) does not show any significant effects (Table XVI). This suggests that there is no learning effect obtained over the pre-task test battery and no recovery effect over the post-task test battery. The nonsignificant effect between PRE- repetition 2 and POST- repetition 1 suggests that there was no driving performance related learning effect gained over the course of the sub-maximal drive.

4.3.2 Cardiovascular Responses

4.3.2.1 Heart Rate Frequency

Table XVII: Analysis of variance for heart rate frequency during the pre- and post- maximal driving tasks, with group effect, pre- and post- task and max drive repetition (R1vsR2) as the three factors (* = significant effect, $p < 0.05$).

Max Driving – Heart rate frequency	SS	DoF	MS	F	p
GROUP	335.0	2,21	167.5	0.453	0.64
Pre - Post	1387.7	1,21	1387.7	62.516	<0.05*
PrePost *GROUP	31.9	2,21	16.0	0.720	0.50
PreR1vsPreR2	27.3	1,23	27.3	3.050	0.09
PostR1vsPostR2	21.6	1,23	21.6	4.932	<0.05*
Pre2vsPost1	678.8	1,23	678.8	46.482	<0.05*

Heart rate increases significantly between pre- and post-driving task ($p < 0.05$; Table XVII and Figure 30). The same trend is observed after comparing PRE- 2 to POST- 1, with a significant increase in heart rate from c.66 beats/min⁻¹ to c.74 beats/min⁻¹ ($p < 0.05$; Figure 30). There is however a significant ($p < 0.05$) decrease in heart rate over the course of the post-task resource test-battery (POST- 1 vs. POST- 2)(Figure 30).

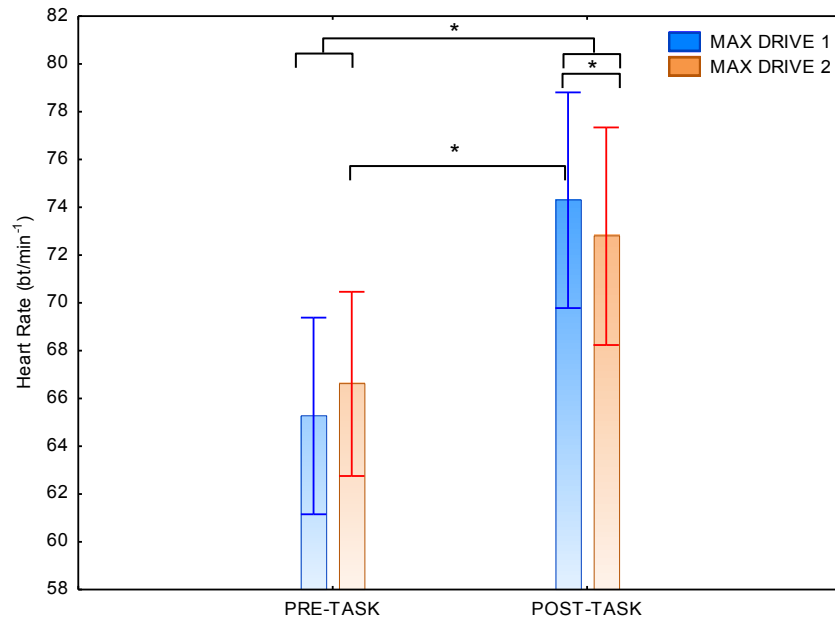


Figure 30: Changes in heart rate frequency (bt.min⁻¹) between the first and second repetition for pre- and post-task maximal driving for both (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.3.2.2 Heart Rate Variability: Time-Domain Analyses

Table XVIII: Analysis of variance for heart rate variability (rMSSD) during the pre- and post-maximal driving tasks, with group effect, pre- and post- task and max drive repetition (R1vsR2) as the three factors (* = significant effect, $p < 0.05$).

Heart rate variability (rMSSD)	SS	DoF	MS	F	p
GROUP	2129.4	2,21	1064.7	0.4451	0.65
Pre - Post	11206.8	1,21	11206.8	16.7802	<0.05*
PrePost *GROUP	3834.4	2,21	1917.2	2.8706	0.08
PreR1vsPreR2	106.6	1,23	106.6	1.1687	0.29
PostR1vsPostR2	221.1	1,23	221.1	0.8191	0.37
Pre2vsPost1	3875.9	1,23	3875.9	10.2727	<0.05*

Heart rate variability declined significantly ($p < 0.05$) from pre- to post-task, indicating an increased cognitive workload during the post-task maximal drives (Table XVIII and Figure 31). The non-significant difference in HRV between POST- 1 and POST- 2 suggests that this is a general state change. Despite the three experimental groups showing significantly different heart rate variability profiles over time (Figure 21), there is no such effect for the maximal

drive task (Table XVIII). Further, there are no significant effects between the first and second repetition in both the pre- and post-task drives (Table XVIII).

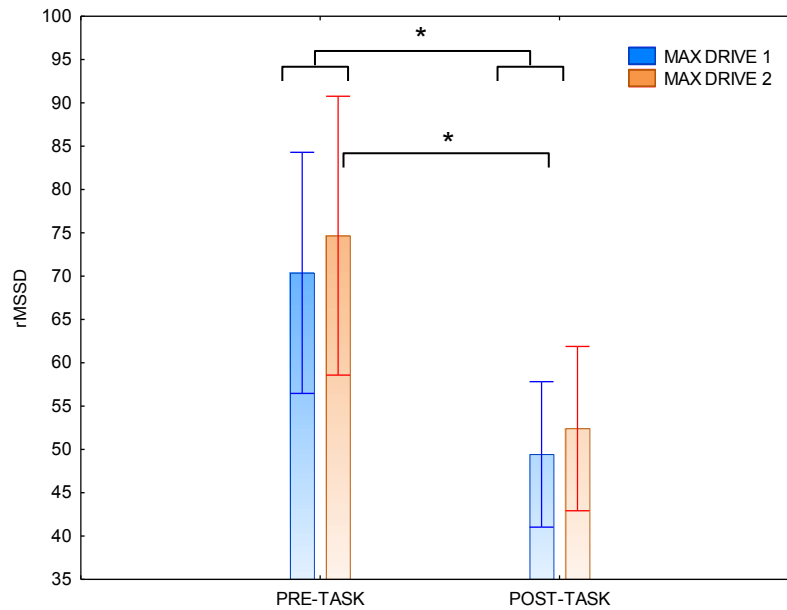


Figure 31: Pre- and post-task difference in heart rate variability (rMSSD) for the first and second repetition of maximal driving tasks (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.3.2.3 Heart Rate Variability: Frequency-Domain Analyses

Table XIX: Analysis of variance for HF power during the pre- and post- maximal driving tasks, with group effect, pre- and post- task and max drive repetition (R1vsR2) as the three factors (* = significant effect, $p < 0.05$).

HF power	SS	DoF	MS	F	p
GROUP	9953511	2,21	4976755	0.75671	0.48
Pre - Post	0.011022	1,21	0.011022	21.644	<0.05*
PrePost *GROUP	0.001251	2,21	0.000626	1.229	0.31
PreR1vsPreR2	26173	1,23	26173	0.28254	0.60
PostR1vsPostR2	4928171	1,23	4928171	3.16395	0.09
Pre2vsPost1	2428503	1,23	2428503	3.70033	0.07

HF power reflects a significant increase from pre- to post-task, indicating greater overall parasympathetic response after the sub-maximal drive ($p < 0.05$; Figure 32). Similarly, there is a numerical difference between PRE- 2 and POST- 1 ($p = 0.09$), the two drives immediately

preceding and following the sub-maximal drive. There is a numerical difference between POST- 1 and POST- 2 ($p=0.07$), indicating a lower parasympathetic response in the second of the two post-task maximal drives. This may account for why there is only a numerical difference between PRE- 2 and POST- 1.

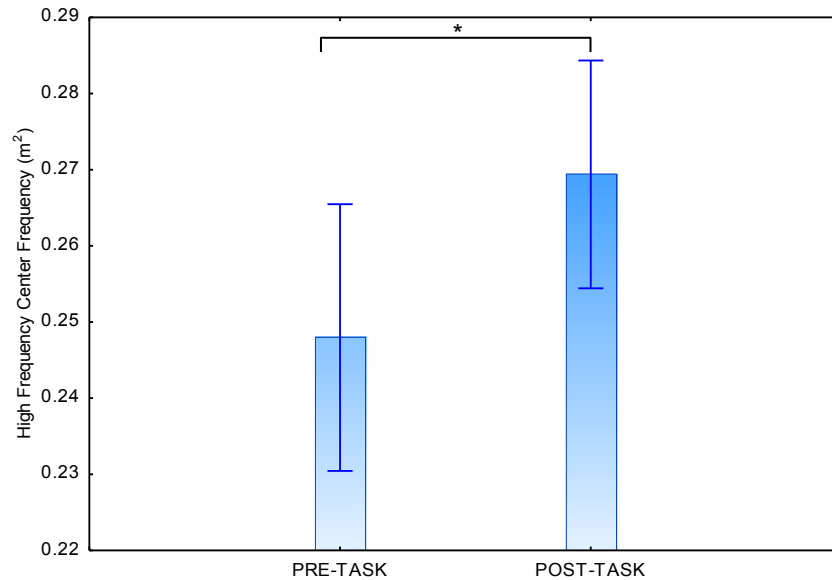


Figure 32: Pre- and post-task difference in heart rate variability (HF power) for the maximal driving tasks (* = significant effect, $p<0.05$; Error bars indicate 95% confidence interval).

Table XX: Analysis of variance for LF power during the pre- and post- maximal driving tasks, with group effect, pre- and post- task and max drive repetition (R1vsR2) as the three factors (* = significant effect, $p<0.05$).

LF power	SS	DoF	MS	F	p
GROUP	12760465	2,21	6380233	0.93669	0.40
Pre - Post	20772829	1,21	20772829	4.07135	0.06
PrePost *GROUP	31087532	2,21	15543766	3.04649	0.07
PreR1vsPreR2	2549565	1,23	2549565	8.80374	<0.05*
PostR1vsPostR2	186609	1,23	186609	0.18624	0.67
Pre2vsPost1	4877194	1,23	4877194	1.47963	0.24

There is a significant increase in LF power between the first and second pre-task maximal drive ($p<0.05$; Table XX and Figure 33), indicating a greater sympathetic drive. While not statistically significant, there is a numerical pre/post effect

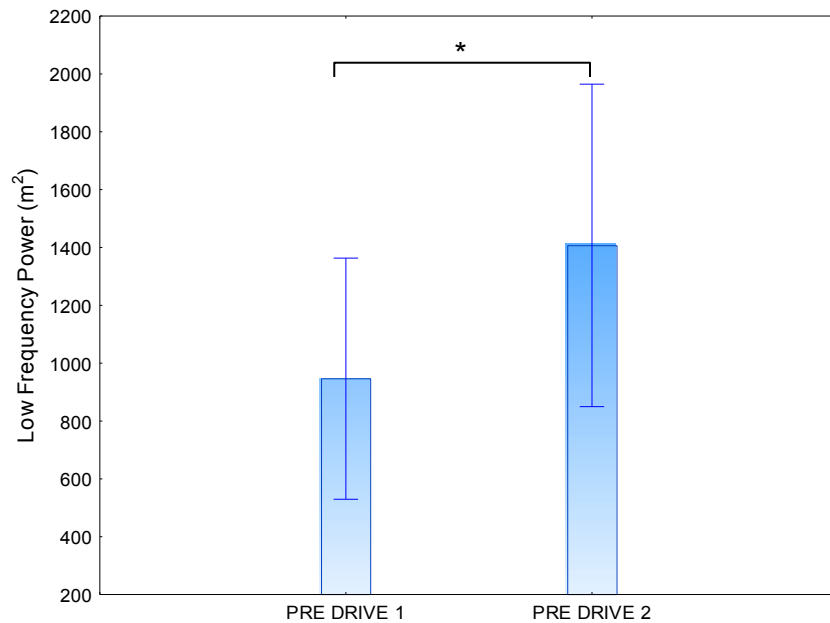


Figure 33: Pre- and post-task difference in heart rate variability (LF power) for the maximal driving tasks (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

Table XXI: Analysis of variance for LF power relative to (LF+HF) during the pre- and post-maximal driving tasks, with group effect, pre- and post- task and max drive repetition (R1vsR2) as the three factors (* = significant effect, $p < 0.05$).

LF power relative to (LF+HF)	SS	DoF	MS	F	p
GROUP	3628.7	2,21	1814.4	2.1383	0.14
Pre - Post	62.4	1,21	62.4	0.4187	0.52
PrePost *GROUP	38.1	2,21	19.0	0.1277	0.88
PreR1vsPreR2	944.0	1,23	944.0	9.7436	<0.05*
PostR1vsPostR2	485.5	1,23	585.5	5.7760	<0.05*
Pre2vsPost1	1.5	1,23	1.5	0.0090	0.93

There is a significant increase in LF power between the first and second pre-task maximal drive ($p < 0.05$; Figure 34). Despite the numerical difference between POST- 1 and POST- 2 seen clearly in Figure 34, there is no significant effect. What is noticeable here is that while the LF power component increases during the pre-task battery, it is seen to decrease in the post-task battery. However the non-effect between PRE- 2 and POST- 1 suggests that the prolonged drive did not impact on the LF:HF ratio in the maximal drive.

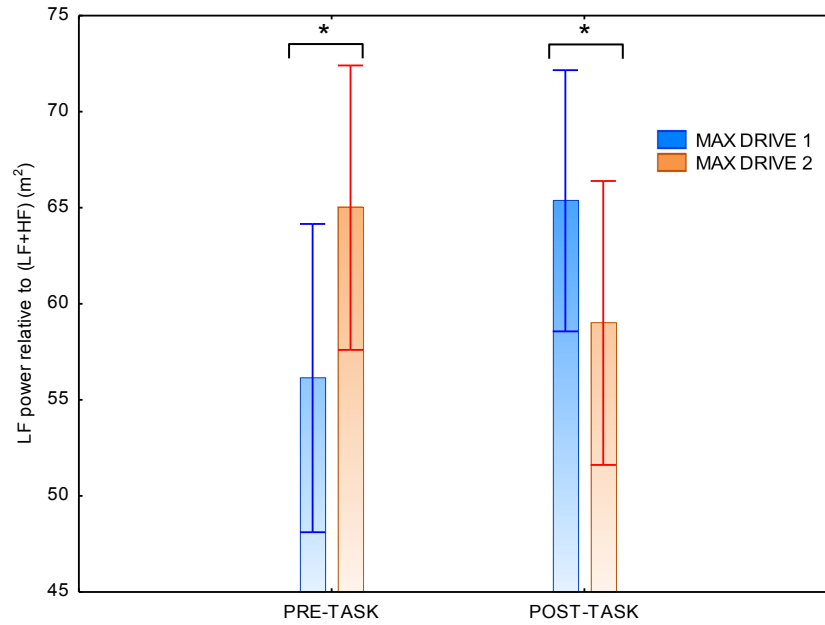


Figure 34: Pre- and post-task difference in heart rate variability (LF power relative to (LF+HF)) for the maximal driving tasks (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.3.3 Oculomotor Parameters

4.3.3.1 Blink Frequency

Table XXII: Analysis of variance for blink frequency during the pre- and post- maximal driving tasks, with group effect, pre- and post- task and max drive repetition (R1vsR2) as the three factors (* = significant effect, $p < 0.05$).

Blink frequency	SS	DoF	MS	F	p
GROUP	2105	2,21	1052	0.670	0.52
Pre - Post	77	1,21	77	0.043	0.84
PrePost *GROUP	3631	2,21	1816	1.015	0.38
PreR1vsPreR2	0.34	1,23	0.34	0.0242	0.88
PostR1vsPostR2	3.63	1,23	3.63	0.2142	0.65
Pre2vsPost1	0.05	1,23	0.05	0.0017	0.97

4.3.3.2 Blink Duration

Table XXIII: Analysis of variance for blink duration during the pre- and post- maximal driving tasks, with group effect, pre- and post- task and max drive repetition (R1vsR2) as the three factors.

Blink duration	SS	DoF	MS	F	p
GROUP	254.89	2,21	127.45	2.6758	0.09
Pre - Post	0.39	1,21	0.39	0.0177	0.90
PrePost *GROUP	54.79	2,21	27.40	1.2337	0.31
PreR1vsPreR2	75	1,23	75	0.0594	0.80
PostR1vsPostR2	16	1,23	16	0.0117	0.91
Pre2vsPost1	0	1,23	0	0.0000	0.99

Oculomotor parameters do not show any significant effects between the pre- and post-task maximal drives (Table XXII and Table XXIII). This indicates an instantaneous reversal of all oculomotor symptoms of fatigue observed in the last interval of the sub-maximal drive. This may be as a result of the increased pre/post HRV (Figure 31) in response to the greater task-demands, which suggests that participants invest more effort to overcome the effects of fatigue and maintain adequate driving performance.

4.3.4 Subjective Parameters

4.3.4.1 Perception of Effort

Table XXIV: Analysis of variance for CR-10 rating for all participants during the pre- and post-maximal driving tasks, with group effect, pre- and post- task and max drive repetition (R1vsR2) as the three factors (* = significant effect, $p < 0.05$).

Rate of perceived exertion	SS	DoF	MS	F	p
GROUP	11.2656	2,21	5.6328	1.0490	0.37
Pre - Post	225.0938	1,21	225.0938	45.5269	<0.05*
PrePost *GROUP	12.7031	2,21	6.3516	1.2847	0.30
PreR1vsPreR2	4.6875	1,23	4.6875	8.58209	<0.05*
PostR1vsPostR2	30.083	1,23	30.083	28.9303	<0.05*
Pre2vsPost1	150.5208	1,23	150.5208	41.3474	<0.05*

A significant increase in subjective effort rating is noted between the pre- and post-task drives ($p < 0.05$ Table XXIV). No group effect is found ($p = 0.37$), though this was not expected, as RPE ratings are subjective and usually based on the first reference measure and each group was only exposed to one sub-maximal variation.

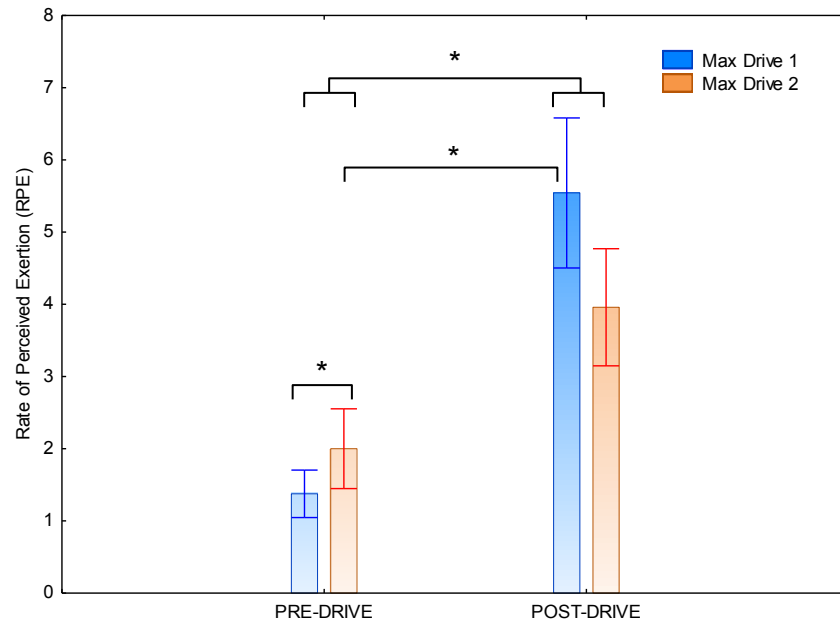


Figure 35: Overall pre- and post-task difference in perceived rate of exertion (Borg CR-10) for the first and second repetition maximal driving tasks (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.4 MOTOR PERFORMANCE (FITTS' TAPPING TASK)

Simple response time was assessed through a modified Fitts' tapping task. As the two variations are integrated into one task, performance results represent the values from both the *easy* and *difficult* variations of the task, while all psychophysiological and oculomotor results represent the combined values. Impaired performance is indicated by an increase response time (ms) and increased target deviation (mm), while improved performance by a reduced response time and reduced target deviation. Typically, response time is associated with speed and target deviation with accuracy. Table XXV provides a summary of analyses performed for the Fitts' task.

Table XXV: Summary of significant effects⁶ for and between the various dependent variables during the motor programming (Fitts') task (where: **X** denotes a significant difference, where $p < 0.05$; / = not measured).

		GROUP	PREPOST	PREPOST*GROUP	DIFFICULTY	DIFFICULTY*GROUP	PREPOST*DIFFICULTY	PREPOST*DIFFICULTY*GROUP
PERFORMANCE	Response Time		X		X		X	
	Target Deviation		X		X			
PHYSIOLOGICAL	Heart Rate Frequency		X	X	/	/	/	/
	HRV: SDNN		X		/	/	/	/
	HRV: rMSSD		X		/	/	/	/
	HRV: PNN30		X	X	/	/	/	/
	HRV: PNN50		X		/	/	/	/
	HF Power		X		/	/	/	/
	HF Centre Frequency				/	/	/	/
	LF Power				/	/	/	/
	LF Centre Frequency				/	/	/	/
	LF power relative to (LF+HF)				/	/	/	/
OCULOMOTOR	Blink Frequency			X	/	/	/	/
	Blink Duration				/	/	/	/

⁶ **GROUP** = difference in the changes over time between the three experimental groups; **PREPOST** = difference between responses before and after the main driving task; **DIFFICULTY** = differences between the *easy* and *difficult* versions of the motor reflex (Fitts') task.

4.4.1 Performance Parameters

4.4.1.1 Response Time

Table XXVI: Analysis of variance for response time recorded during the pre- and post- Fitts' tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Fitts' Response Time	SS	DoF	MS	F	p
GROUP	0.03543	2,21	0.01772	0.4911	0.62
Pre - Post	0.03121	1,21	0.03121	5.0223	<0.05*
PrePost *GROUP	0.00281	2,21	0.00140	0.2257	0.80
DIFFICULTY	0.11683	1,21	0.11683	12.8299	<0.05*
DIFFICULTY *GROUP	0.00417	2,21	0.00209	0.2292	0.80
PREPOST*DIFFICULTY	0.01704	1,21	0.01704	4.7976	<0.05*
PREPOST*DIFFICULTY*GROUP	0.01039	2,21	0.00519	1.4620	0.25

Response time is significantly affected by the sub-maximal driving task, demonstrated in the significant ($p < 0.05$) interaction between pre/post and difficulty effects (Figure 36). While pre/post response time increases for the *easy* variation, it remains unchanged for the *difficult* variation. Therefore, the significant ($p < 0.05$) pre/post effect is attributable almost exclusively to the *easy* variation (Figure 36). There is no overall group effect ($p = 0.62$) and no interactional effect between pre/post and group effect ($p = 0.80$; Table XXVI). This indicates that while response time is affected by the sub-maximal drive, the change is not different between the three groups. No additional interactional effects are observed (Table XXVI).

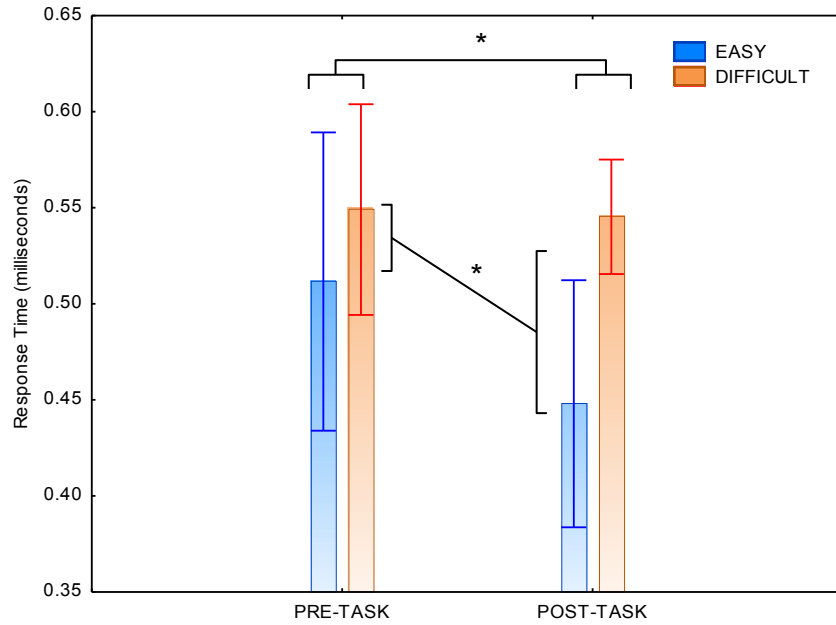


Figure 36: Overall pre- and post-task difference in response time for the *easy* and *difficult* variations of the Fitts' tapping tasks (* = significant effect, $p<0.05$; Error bars indicate 95% confidence interval).

4.4.1.2 Target Deviation

Table XXVII: Analysis of variance for target deviation during the pre- and post- Fitts' tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p<0.05$).

Fitts' Target deviation	SS	DoF	MS	F	p
GROUP	1.927	2,21	0.964	0.0951	0.91
Pre - Post	13.870	1,21	13.870	5.0398	<0.05*
PrePost *GROUP	0.563	2,21	0.282	0.1023	0.90
DIFFICULTY	16.310	1,21	16.310	19.9499	<0.05*
DIFFICULTY *GROUP	3.117	2,21	1.559	1.9064	0.17
PREPOST*DIFFICULTY	0.088	1,21	0.088	0.0936	0.76
PREPOST*DIFFICULTY*GROUP	0.048	2,21	0.024	0.0256	0.97

As with response time, there is a significant ($p<0.05$) pre/post effect for target deviation (Table XXVII), increasing between pre- and post-task (Figure 37). This trend is also present for the difficulty effect, with the *difficult* variation reflecting significantly greater overall target deviation than the *easy* variation ($p<0.05$; Figure 38). However, the non-significant ($p=0.76$) interaction

between pre/post effect and difficulty effect suggests that the overall difference in pre/post target deviation is not isolated to either of the variations (Figure 37).

Considered together, target deviation and response time results suggest that there is a speed/accuracy trade-off for the *easy* variation but not for the *difficult* variation. That is, while an increased target deviation in the *easy* variation corresponds to an increased response time, an increased target deviation in the *difficult* condition is not accompanied by an increased response time.

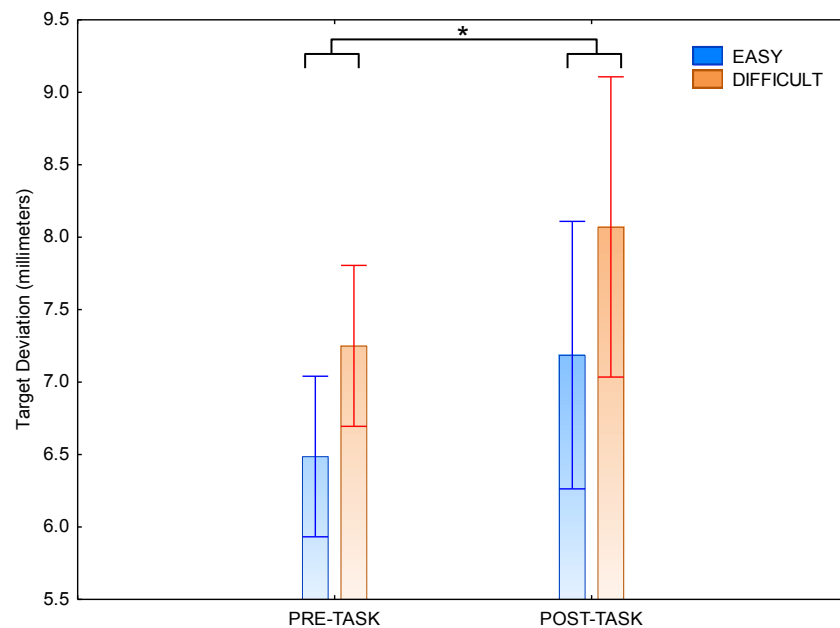


Figure 37: Significant overall pre- and post-task difference in target deviation for the *easy* and *difficult* variations of the Fitts' task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

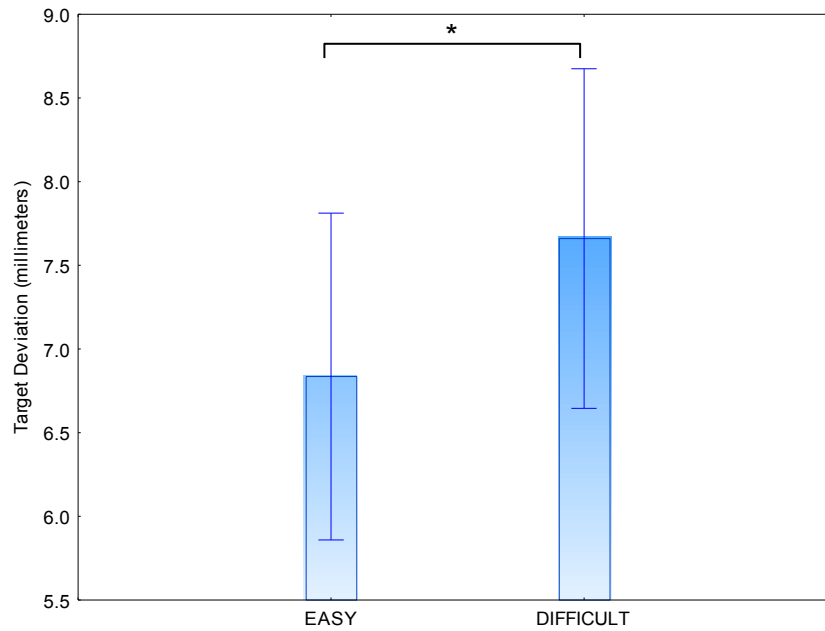


Figure 38: Overall difference in target deviation recorded between the *easy* and *difficult* variations of the Fitts' tapping task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.4.2 Cardiovascular Responses

4.4.2.1 Heart Rate Frequency

Table XXVIII: Analysis of variance for heart rate frequency during the pre- and post- Fitts' tasks, with pre/post effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Heart rate frequency	SS	DoF	MS	F	p
GROUP	196.1	2,21	98.0	0.629	0.54
Pre - Post	737.5	1,21	737.5	90.050	<0.05*
PrePost *GROUP	94.2	2,21	47.1	5.751	<0.05*

Heart rate declines significantly ($p < 0.05$) between pre- and post- Fitts' task (Figure 39). There is no significant group effect ($p = 0.54$), however pre/post effect and group effect interact statistically ($p < 0.05$; Figure 39 and Table XXVIII), indicating a significant pre/post difference between the groups. Post- hoc analysis reveals significant pre/post differences within the small and medium group (Appendix C), however not for the large group.

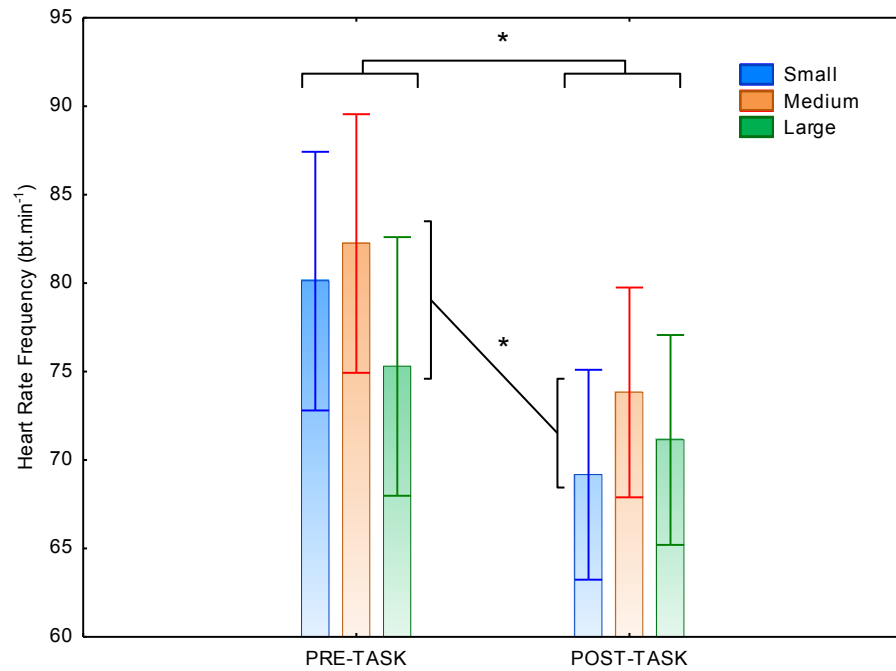


Figure 39: Pre- and post- task differences in heart rate frequency (bt.min⁻¹) for the three experimental groups recorded during the Fitts' task (* = significant effect, p<0.05; Error bars indicate 95% confidence interval).

4.4.2.2 Heart Rate Variability: Time-Domain Analyses

Table XXIX: Analysis of variance for heart rate variability (rMSSD) during the pre- and post-Fitts' tasks, with pre/post effect and group effect as the two factors (* = significant effect, p<0.05).

rMSSD	SS	DoF	MS	F	p
GROUP	834.8	2,21	417.4	0.3633	0.70
Pre - Post	3865.3	1,21	3865.3	7.7843	<0.05*
PrePost *GROUP	1087.6	2,21	543.8	1.0951	0.35

Heart rate variability (rMSSD) increases significantly between pre- and post-sub-maximal drive Fitts' task (Table XXIX and Figure 40), indicating a decreased cognitive effort. However, there is no group effect (p=0.70), nor is there any interaction effect between the two p=0.35). This suggests that while heart rate variability decreases overall, the road widths of the sub-maximal drive do not influence post-task workload.

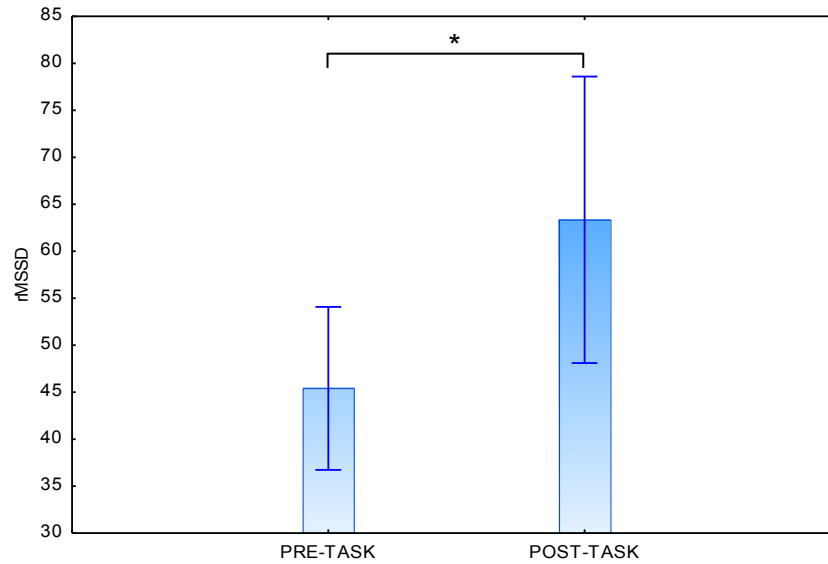


Figure 40: Changes in pre- and post-task heart rate variability (rMSSD) recorded during the Fitts' task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.4.2.3 Heart Rate Variability: Frequency-Domain Analyses

Table XXX: Analysis of variance for HF power of heart rate variability during the pre- and post- Fitts' tasks, with pre/post effect and group effect as the two factors (* = significant effect, $p < 0.05$).

HF Power	SS	DoF	MS	F	p
GROUP	398787	2,21	199393	0.23963	0.80
Pre - Post	1605638	1,21	1605638	6.41518	<0.05
PrePost *GROUP	908187	2,21	454094	1.81429	0.19

HF power increases significantly ($p < 0.05$) between pre- and post-task Fitts' tasks (Table XXX and Figure 41). There is no *group effect* ($p = 0.80$), nor does *group* and *pre/post effect* interact statistically ($p = 0.19$), which suggests there is no significant pre/post difference between the groups.

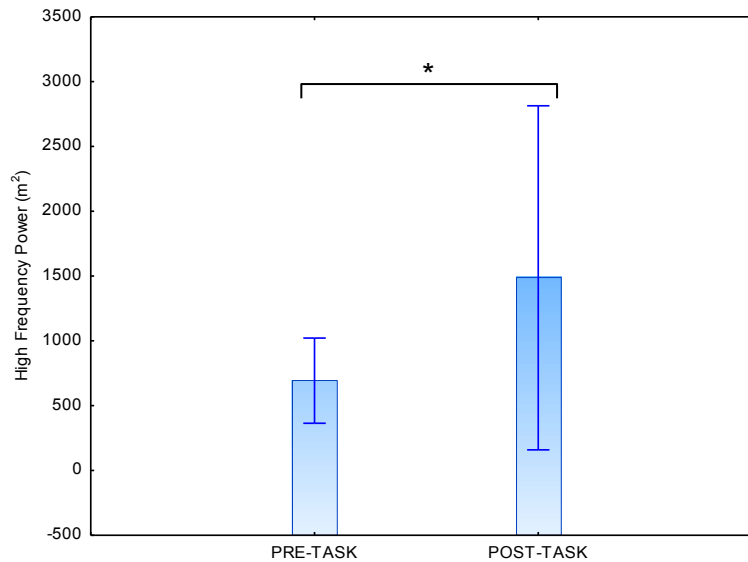


Figure 41: Difference in HF power responses between pre- and post-task for the Fitts' tapping task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

Table XXXI: Analysis of variance for LF power of heart rate variability during the pre- and post- Fitts' tasks, with pre/post effect and group effect as the two factors (* = significant effect, $p < 0.05$).

LF Power	SS	DoF	MS	F	p
GROUP	1288164	1,21	64482	0.13961	0.87
Pre - Post	11395261	1,21	11395261	3.18990	0.09
PrePost *GROUP	5382759	1,21	2691379	0.75340	0.48

Table XXXII: Analysis of variance for LF power relative to (LF+HF) during the pre- and post- Fitts' tasks, with pre/post effect and group effect as the two factors (* = significant effect, $p < 0.05$).

LF power relative to (LF+HF)	SS	DoF	MS	F	p
GROUP	225.2	2,21	112.6	0.3024	0.74
Pre - Post	254.1	1,21	254.1	2.2691	0.15
PrePost *GROUP	104.5	2,21	52.3	0.4668	0.63

Neither the LF power (Table XXXI) responses nor the LF power relative to (LF+HF) (Table XXXII) show any *group* or *pre/post* effects. This suggests that there are no changes to sympathetic activation of the autonomic nervous system during the Fitts' task, either as a result of fatigue during the prolonged drive, or as how that fatigue was induced.

4.4.3 Oculomotor Parameters

4.4.3.1 Blink Frequency

Table XXXIII: Analysis of variance for blink frequency during the pre- and post- Fitts' tasks, with pre/post effect and group effect as the two factors (* = significant effect, $p < 0.05$).

Blink frequency	SS	DoF	MS	F	p
GROUP	20.481	2,21	10.240	0.4936	0.62
Pre - Post	14.564	1,21	14.564	0.4829	0.49
PrePost *GROUP	239.145	2,21	119.573	3.9644	<0.05*

Blink frequency does not show a significant effect between pre- and post- sub-maximal drive ($p = 0.49$), nor is there any overall *group effect* ($p = 0.62$; Table XXXIII). However, *group effect* and *pre/post effect* interact statistically ($p < 0.05$; Figure 42, Table XXXIII) indicating significantly different pre/post responses for each group. While blink frequency increases in the *small* group, there is a decrease in both the *medium* and *large* groups, though to a greater extent in the *large* group (Figure 42).

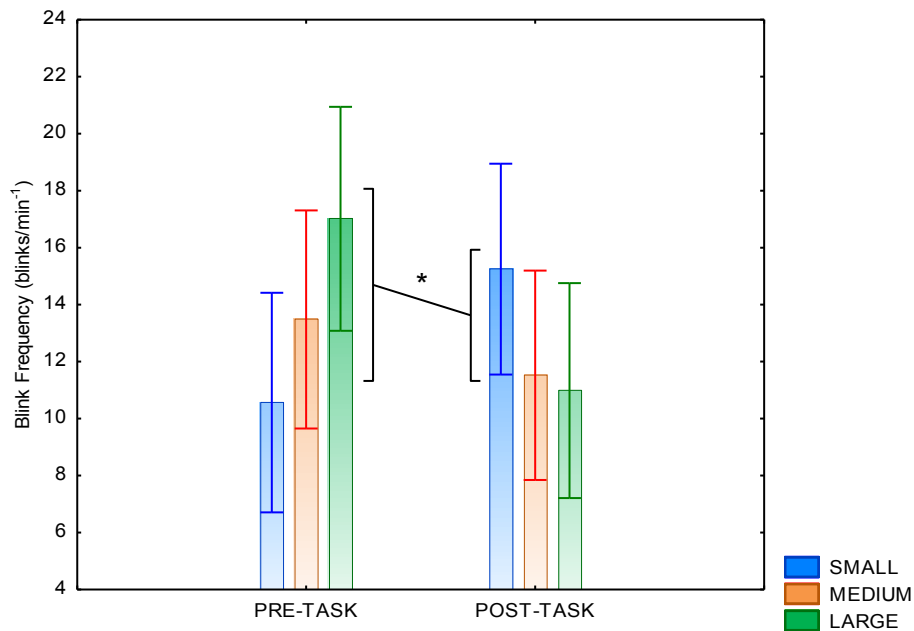


Figure 42: Pre- and post- task differences in blink frequency for the three experimental groups (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.4.3.2 Blink Duration

Table XXXIV: Analysis of variance for blink duration during the pre- and post- Fitts' tasks, with pre/post effect and group effect as the two factors.

Blink duration	SS	DoF	MS	F	p
GROUP	5502	2,21	2751	0.5180	0.60
Pre - Post	21	1,21	21	0.0208	0.89
PrePost *GROUP	1077	2,21	538	0.5447	0.59

Blink duration shows no significant effects for the Fitts' tapping task (Table XXXIV).

4.5 WORKING MEMORY (DIGIT RECALL TEST)

Short term or working memory was assessed through the application of a simple digit recall memory test: participants were presented with a string of digits (5 for *easy* variation, 7 for *difficult* variation), after which they had to recall as many digits in the correct order as possible after an 8 second delay. *Response delay* refers to the amount of time the participant takes to initiate the digit recall via keyboard entry. *Response duration* refers to the amount of time the participant takes to enter the digit string. *Percentage correct* refers to recall ability or accuracy. That is, the percentage of digits correctly recalled in the correct sequence.

Table XXXV: Summary of significant effects⁷ for and between the various dependent variables during the digit recall task (X denotes a significant difference, where $p < 0.05$).

		GROUP	PREPOST	PREPOST*GROUP	DIFFICULTY	DIFFICULTY*GROUP	PREPOST*DIFFICULTY	PREPOST*DIFFICULTY*GROUP
PERFORMANCE	Response Duration				X			
	Response Delay							
	Percentage Correct		X		X		X	
PHYSIOLOGICAL	Heart Rate Frequency		X		X		X	
	HRV: SDNN		X					
	HRV: rMSSD		X		X			
	HRV: PNN30		X					
	HRV: PNN50							
	HF Power		X					
	HF Centre Frequency				X			
	LF Power		X		X			
	LF Centre Frequency							
	LF power relative to (LF+HF)							
OCULOMOTOR	Blink Frequency							
	Blink Duration						X	

⁷ **GROUP** = difference in the overall changes between three experimental groups; **PREPOST** = difference between responses before and after the main driving task; **DIFFICULTY** = differences between the *easy* and *difficult* versions of the digit recall task.

4.5.1 Performance Parameters

4.5.1.1 Percentage Correct

Table XXXVI: Statistical effects for percentage of numbers correctly recalled during the pre- and post- memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Memory Span Percentage Correct	SS	DoF	MS	F	p
GROUP	69.9	2,21	34.9	0.086	0.92
Pre - Post	243.6	1,21	243.6	5.365	<0.05*
PrePost *GROUP	105.6	2,21	52.8	1.163	0.33
DIFFICULTY	6077.1	1,21	6077.1	26.730	<0.05*
DIFFICULTY *GROUP	198.6	2,21	99.3	0.437	0.65
PREPOST*DIFFICULTY	162.0	1,21	162.0	4.534	<0.05*
PREPOST*DIFFICULTY*GROUP	25.6	2,21	12.8	0.358	0.70

Digit recall ability improves significantly ($p < 0.05$) following the sub-maximal drive, evinced by the significant interaction between pre/post effect and difficulty effect ($p < 0.05$; Table XXXVI and Figure 43). As the *easy* variation showed no pre/post changes, the improvement is attributed almost exclusively to the *difficult* variation, which showed a significant ($p < 0.05$) improvement in post-task recall ability. The non-significant ($p = 0.65$) interaction between pre/post effect and group effect suggest that the changes are not different between the experimental groups. Further, the significant ($p < 0.05$) difficulty effect indicates that the *easy* variation showed a significantly higher percentage of correctly recalled number strings than the *difficult* variation.

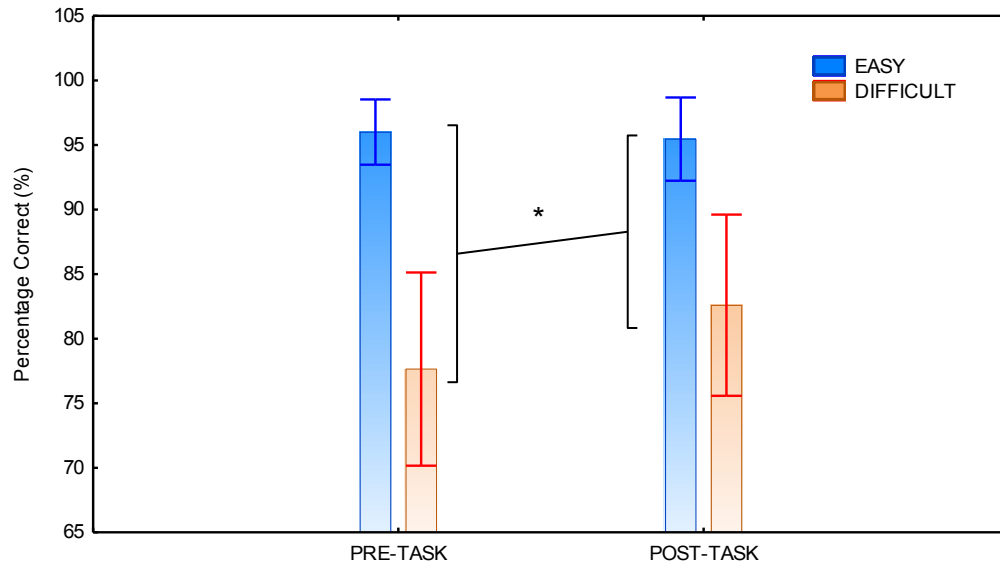


Figure 43: Overall pre- and post-task difference in percentage of number strings correctly recalled for the *easy* and *difficult* variations of the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.5.1.2 Response Duration

Table XXXVII: Analysis of variance for response duration established during the pre- and post- memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Memory Span Response Duration	SS	DoF	MS	F	p
GROUP	3.594078	2	1.797039	1.9776	0.16
Pre - Post	4.419492	1	4.419492	5.2560	<0.05*
PrePost *GROUP	5.038612	2	2.519306	2.9961	0.07
DIFFICULTY	2.506992	1	2.506992	54.9387	<0.05*
DIFFICULTY *GROUP	4.985226	2	2.492613	0.5462	0.59
PREPOST*DIFFICULTY	9.109347	1	9.109347	1.6858	0.20
PREPOST*DIFFICULTY*GROUP	3.451961	2	1.725981	3.1941	0.06

There is a significant pre/post difference in response duration ($p < 0.05$; Figure 44). Task difficulty significantly impacts on response duration ($p < 0.05$), with the *difficult* variation eliciting significantly longer response durations than the *easy* variation (Figure 45). However, this was expected as difficulty was manipulated by varying the number of digits presented, which directly impacts on response duration. The non-significant pre/post difficulty interaction

($p=0.58$) indicates that the prolonged drive does not impact on the participants' ability to recall within a certain time frame. No further significant effects were observed (Table XXXVII).

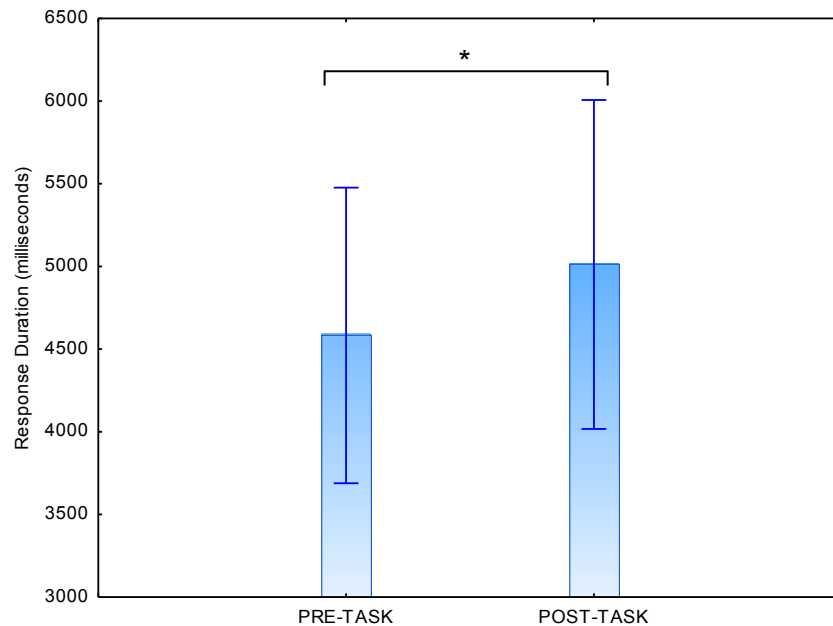


Figure 44: Changes in pre- and post-task response duration recorded during memory span task (* = significant effect, $p<0.05$; Error bars indicate 95% confidence interval).

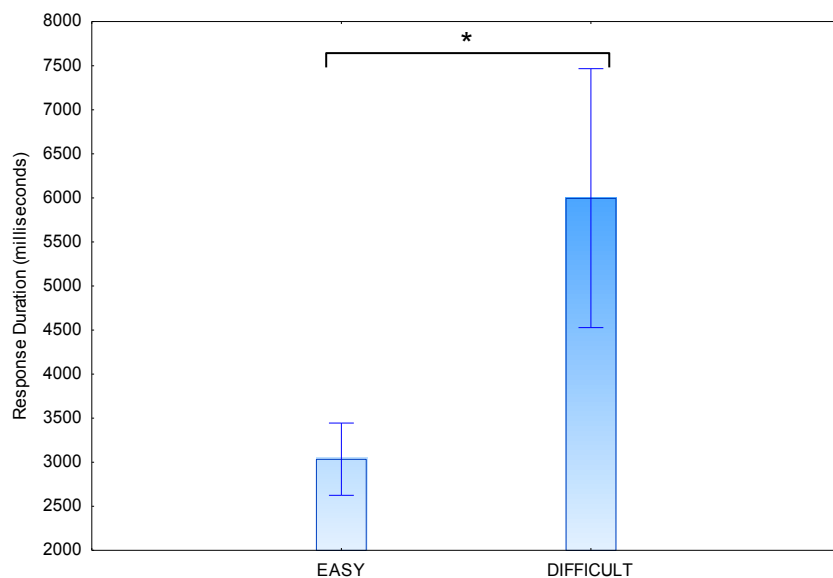


Figure 45: Difference in response duration for the *easy* and *difficult* variations of the memory span task (* = significant effect, $p<0.05$; Error bars indicate 95% confidence interval).

4.5.1.3 Response Delay

Table XXXVIII: Analysis of variance for response delay established during the pre- and post-memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Memory Span Response Delay	SS	DoF	MS	F	p
GROUP	939732	2,21	469866	0.5841	0.57
Pre - Post	50512	1,21	50512	0.1100	0.74
PrePost *GROUP	968281	2,21	484140	1.0541	0.37
DIFFICULTY	1115815	1,21	1115815	2.3183	0.14
DIFFICULTY *GROUP	780248	2,21	390124	0.8106	0.46
PREPOST*DIFFICULTY	126686	1,21	126686	0.3480	0.56
PREPOST*DIFFICULTY*GROUP	1046305	2,21	523153	1.4369	0.26

Response delay does not reflect any significant statistical effects (Table XXXVIII), indicating that the time taken to initiate a response from working memory is not affected by the sub-maximal drive.

4.5.2 Cardiovascular Responses

4.5.2.1 Heart Rate Frequency

Table XXXIX: Analysis of variance for heart rate during the pre- and post- memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Memory Span Heart Rate	SS	DoF	MS	F	p
GROUP	680.7	2,21	340.4	1.378	0.27
Pre - Post	1457.5	1,21	1457.5	58.928	<0.05*
PrePost *GROUP	13.0	2,21	6.5	0.263	0.77
DIFFICULTY	140.1	1,21	140.1	6.061	<0.05*
DIFFICULTY *GROUP	9.9	2,21	4.9	0.214	0.81
PREPOST*DIFFICULTY	47.6	1,21	47.6	6.153	<0.05*
PREPOST*DIFFICULTY*GROUP	0.9	2,21	0.5	0.061	0.94

Heart rate frequency in the digit recall task declined significantly ($p < 0.05$) from pre- to post-task (Table XXXIX and Figure 47). There is a significant *difficulty effect* ($p < 0.05$), illustrated by the significant increase in heart rate during the *difficult* variation than the *easy* variation (Figure 46). However, the interactional effect ($p < 0.05$) between *pre/post* and *group effects* indicates that the difference in heart rate between the two difficulty variations is statistically smaller during the post-task tests than during the pre-task tests (Figure 47). No further effects are calculated for heart rate during digit recall (Table XXXIX).

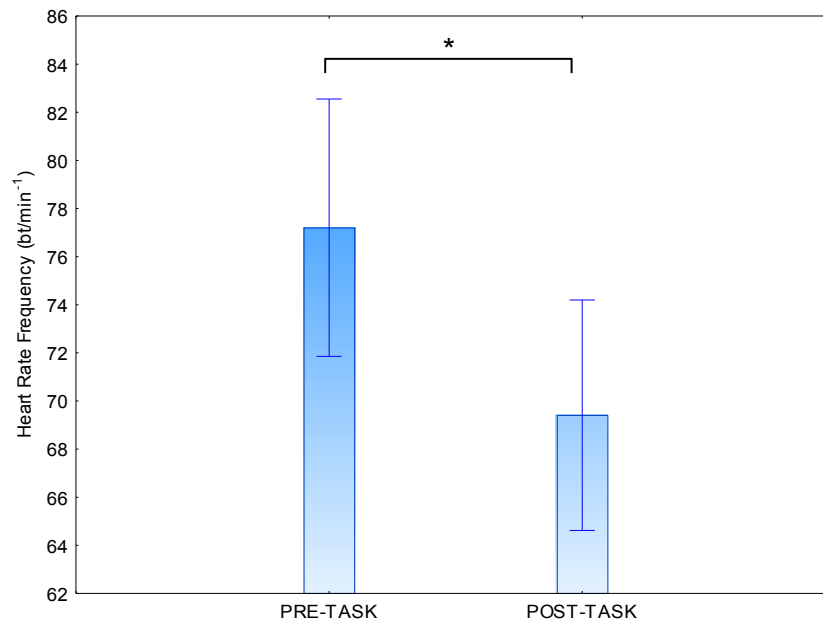


Figure 46: Overall pre- and post-task difference in heart rate frequency response observed during the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

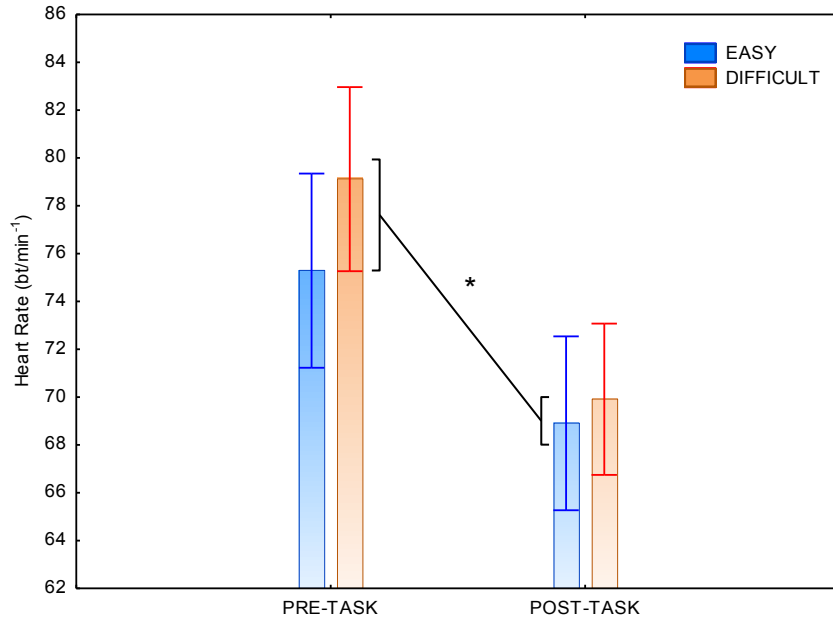


Figure 47: Overall pre- and post-task difference in heart rate frequency between pre- and post-task for the *easy* and *difficult* variations of the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.5.2.2 Heart Rate Variability: Time-Domain Analyses

Table XL: Analysis of variance for heart rate variability (rMSSD) during the pre- and post-memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Memory Span rMSSD	SS	DoF	MS	F	p
GROUP	2343.6	2,21	1171.8	0.3795	0.69
Pre - Post	12094.8	1,21	12094.8	25.2287	<0.05*
PrePost *GROUP	910.8	2,21	455.4	0.9499	0.40
DIFFICULTY	1341.8	1,21	1341.8	9.0062	<0.05*
DIFFICULTY *GROUP	596.2	2,21	298.1	2.0010	0.16
PREPOST*DIFFICULTY	23.5	1,21	23.5	0.2619	0.61
PREPOST*DIFFICULTY*GROUP	86.5	2,21	43.3	0.4818	0.62

Heart rate variability decreases significantly ($p < 0.05$) between *pre- and post-task* digit span tasks (Table XL and Figure 48), indicating a higher cognitive workload following the sub-maximal drive. Difficulty has a significant ($p < 0.05$; Table XL) effect on heart rate variability, with the *easy* variation eliciting significantly higher rMSSD than the *difficult* variation (Figure 49). No further significant effects were observed (Table XL).

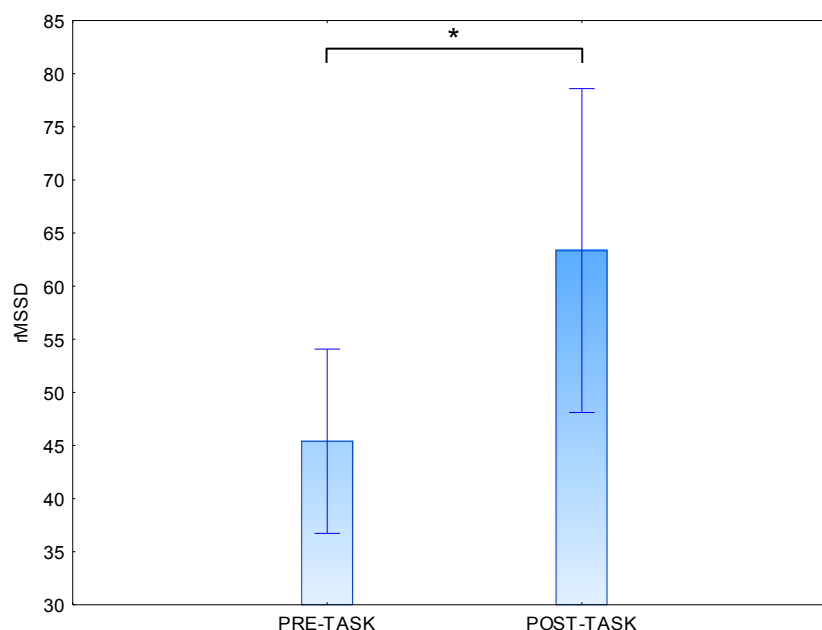


Figure 48: Pre- and post- task changes in heart rate variability (rMSSD) pre- and post-task difference in heart rate frequency response observed during the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

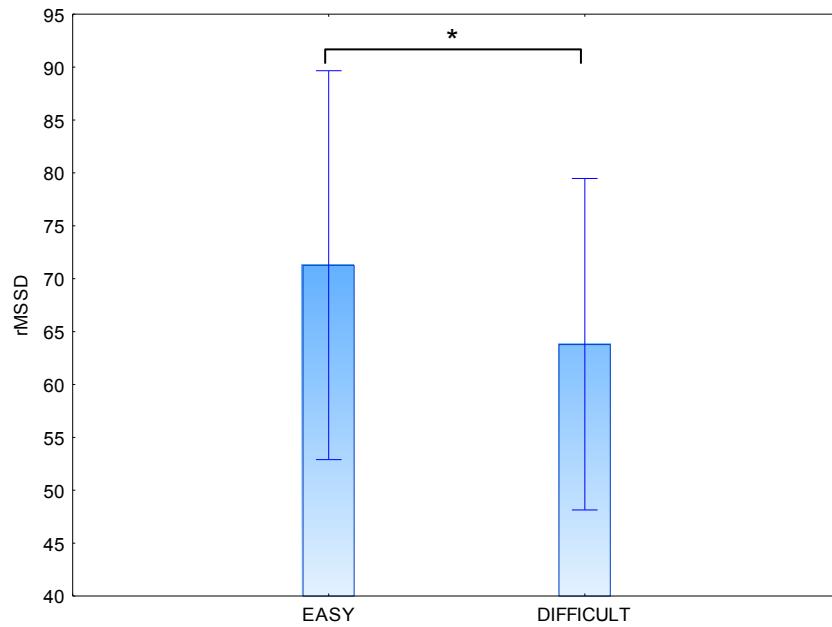


Figure 49: Overall changes in rMSSD between the *easy* and *difficult* variations of the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.5.2.3 Heart Rate Variability: Frequency-Domain Analyses

Table XLI: Analysis of variance for HF power of heart rate variability analysis during the pre- and post- memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

HF Power	SS	DoF	MS	F	p
GROUP	10185529	2,21	5092764	0.52608	0.60
Pre - Post	19810503	1,21	19810503	5.74435	<0.05*
PrePost *GROUP	7717474	2,21	3858737	1.11890	0.35
DIFFICULTY	1086299	1,21	1086299	3.68164	0.07
DIFFICULTY *GROUP	836462	2,21	418231	1.41745	0.26
PREPOST*DIFFICULTY	51199	1,21	51199	0.30506	0.59
PREPOST*DIFFICULTY*GROUP	13992	2,21	6996	0.04169	0.96

Both LF power and HF power increased significantly from pre- to post- sub-maximal drive ($p < 0.05^*$ and $p < 0.05^*$, respectively; Table XLI and Table XLII, Figure 50 and Figure 51). While HF power response was not shown have a *group effect*, Table XLII and Figure 52 show that LF power showed a significant ($p < 0.05$) *group effect*. No other significant effects were observed.

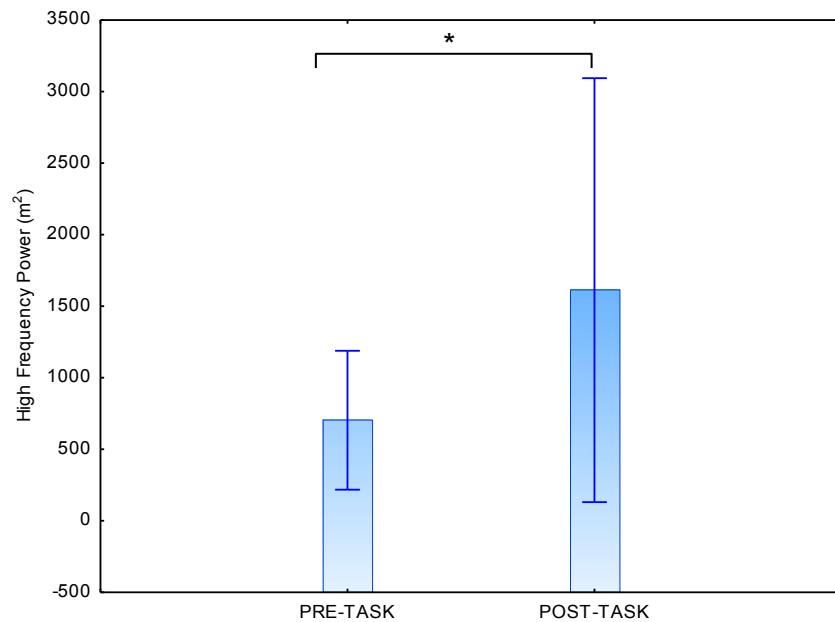


Figure 50: Pre- and post-task difference in heart rate frequency response observed for HF power during the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

Table XLII: Analysis of variance for LF Power of heart rate variability analysis during the pre- and post- memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Memory Span LF Power	SS	DoF	MS	F	p
GROUP	15357555	2,21	7678777	0.36802	0.70
Pre - Post	64599598	1,21	64599598	8.69198	<0.05*
PrePost *GROUP	13012186	2,21	6506093	0.87541	0.43
DIFFICULTY	13539984	1,21	13539984	5.92214	<0.05*
DIFFICULTY *GROUP	3717457	2,21	1858728	0.81297	0.46
PREPOST*DIFFICULTY	4373707	1,21	4373707	3.43095	0.08
PREPOST*DIFFICULTY*GROUP	249589	2,21	124794	0.09789	0.91

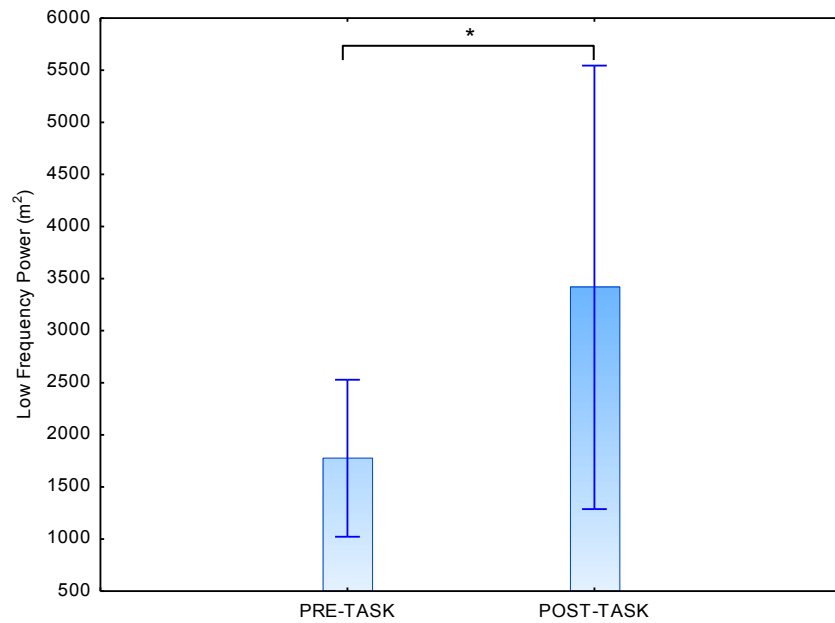


Figure 51: Pre- and post-task difference in heart rate frequency response observed for LF power during the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

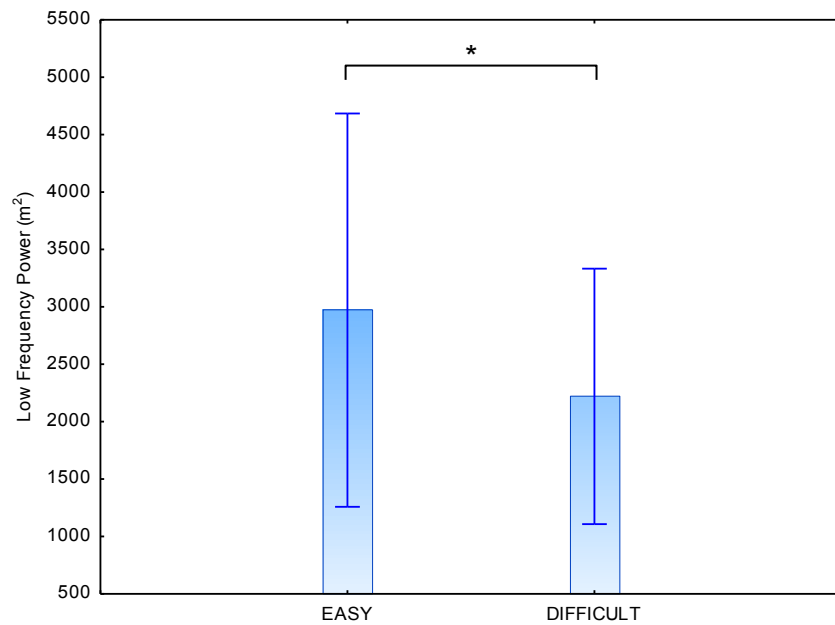


Figure 52: Difference in LF power responses between the *easy* and *difficult* variations of the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

Table XLIII: Analysis of variance for LF Power relative to (LF + HF) during the pre- and post-memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors.

Memory Span LF Power relative to (LF + HF)	SS	DoF	MS	F	p
GROUP	285.2	2,21	142.6	0.2598	0.77
Pre - Post	119.5	1,21	119.5	0.9778	0.33
PrePost *GROUP	154.5	2,21	77.2	0.6318	0.54
DIFFICULTY	119.7	1,21	119.7	2.2237	0.15
DIFFICULTY *GROUP	87.8	2,21	43.9	0.8157	0.45
PREPOST*DIFFICULTY	62.6	1,21	62.6	1.3788	0.25
PREPOST*DIFFICULTY*GROUP	118.4	2,21	59.2	1.3029	0.29

The LF:HF ratio did not reflect any statistical effects for the memory task, indicating that there was no significant state changes of the sympathetic system (Table XLIII).

4.5.3 Oculomotor Parameters

4.5.3.1 Blink Frequency

Table XLIV: Analysis of variance for blink frequency during the pre- and post- memory span tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Memory Span Blink Frequency	SS	DoF	MS	F	p
GROUP	7.26	2,21	3.63	0.196	0.82
Pre - Post	14.33	1,21	14.33	1.978	0.17
PrePost *GROUP	0.21	2,21	0.11	0.015	0.99
DIFFICULTY	0.00	1,21	0.00	0.001	0.98
DIFFICULTY *GROUP	14.38	2,21	7.19	1.875	0.18
PREPOST*DIFFICULTY	2.50	1,21	2.50	0.678	0.42
PREPOST*DIFFICULTY*GROUP	3.63	2,21	1.82	0.493	0.62

No significant effects were observed for blink frequency in the digit recall task (Table XLIV).

4.5.3.2 Blink Duration

Blink duration is significantly ($p < 0.05$) affected by the submaximal drive, demonstrated by the statistical interaction between *pre/post* and *difficulty effect* ($p < 0.05$). This interaction is attributed to the *difficult* variation, which shows a significantly longer post-task blink duration, while the *easy* variation remains unchanged (Figure 53). No significant *group*, *pre/post* or

difficulty effects are calculated for blink frequency in the digit recall task. Further, no additional interactional effects were observed (Table XLV).

Table XLV: Analysis of variance for blink duration during the pre- and post- digit recall tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Digit Recall Blink Duration	SS	DoF	MS	F	p
GROUP	14393	2,21	7196	0.8764	0.43
Pre - Post	2860	1,21	2860	1.0952	0.31
PrePost *GROUP	8681	2,21	4341	1.6621	0.21
DIFFICULTY	2340	1,21	2340	1.8073	0.20
DIFFICULTY *GROUP	3413	2,21	1707	1.3179	0.29
PREPOST*DIFFICULTY	3243	1,21	3243	4.9764	<0.05*
PREPOST*DIFFICULTY*GROUP	2966	2,21	1483	2.2756	0.13

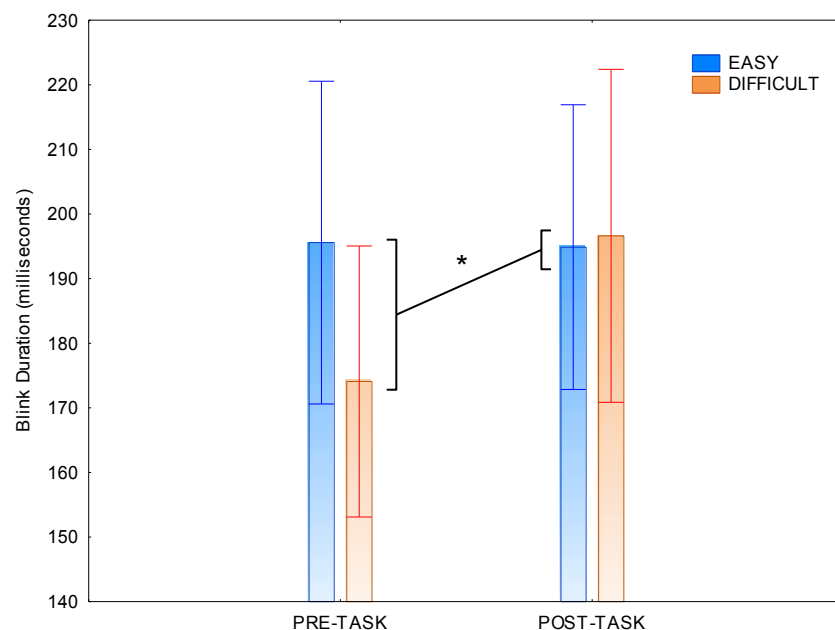


Figure 53: Overall pre- and post-task difference in blink duration observed during the *easy* and *difficult* variations of the memory span task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.6 COGNITION (READING)

Reading performance was assessed via reading speed (number of words read per minute) and reading accuracy (the number of spelling errors identified during the reading tests).

Table XLVI: Summary of significant effects⁸ for and between the various dependent variables during the reading task (**X** denotes a significant difference, where $p < 0.05$).

		GROUP	PREPOST	PREPOST*GROUP	DIFFICULTY	DIFFICULTY*GROUP	PREPOST*DIFFICULTY	PREPOST*DIFFICULTY*GROUP
PERFORMANCE	Reading Speed		X		X			
	Errors identified				X			
PHYSIOLOGICAL	Heart Rate Frequency		X					
	HRV: SDNN		X					
	HRV: rMSSD		X					
	HRV: PNN30		X					
	HRV: PNN50		X					
	HF Power		X					
	HF Centre Frequency				X			
	LF Power		X		X			
	LF Centre Frequency		X					
	LF power relative to (LF+HF)				X			
OCULOMOTOR	Blink Frequency							
	Blink Duration							

⁸ **GROUP** = difference in the overall changes between the three experimental groups; **PREPOST** = difference between responses before and after the main driving task; **DIFFICULTY** = differences between the *easy* and *difficult* versions of the cognitive reading task.

4.6.1 Performance Parameters

4.6.1.1 Reading Speed

Table XLVII: Analysis of variance for reading speed during the pre- and post- reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Reading Speed	SS	DoF	MS	F	p
GROUP	541870	2,21	270935	1.1651	0.33
Pre - Post	51523	1,21	51523	4.3101	<0.05*
Pre - Post *GROUP	44091	2,21	22046	1.8442	0.18
DIFFICULTY	562734	1,21	562734	59.5417	<0.05*
DIFFICULTY *GROUP	37265	2,21	18632	1.9715	0.16
PREPOST*DIFFICULTY	234	1,21	234	0.0261	0.87
PREPOST*DIFFICULTY*GROUP	26800	2,21	13400	1.4908	0.25

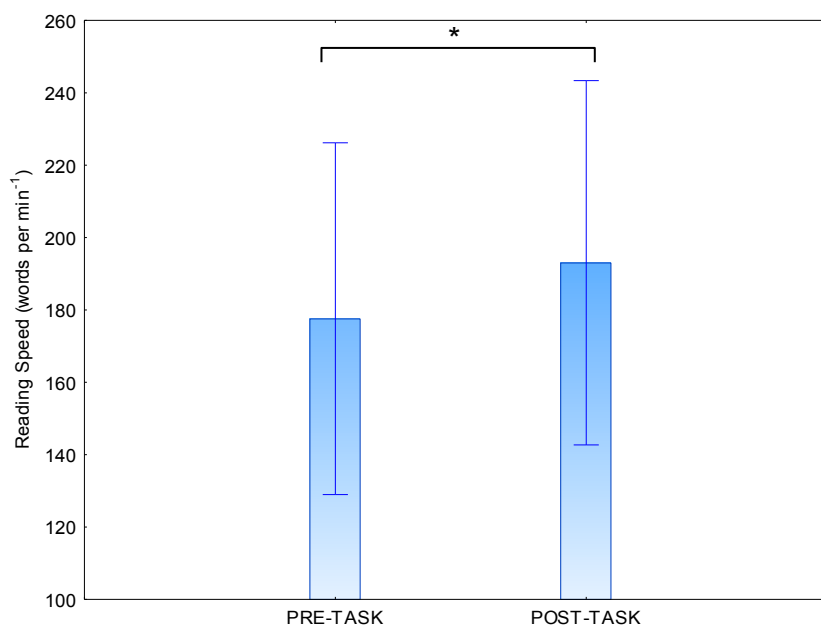


Figure 54: Pre- and post-task difference in reading speed in words per minute observed during the reading task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

Reading speed is significantly affected by *difficulty* variation ($p < 0.05$; Table XLVII), with the easy variation reflecting significantly higher reading speed between pre- and post-task

reading tests than the *difficult* variation (Figure 54). However, this difference is expected, as task-difficulty was manipulated by changing the resolution of the text. This variation directly influences legibility and therefore reading speed. While there is no group effect, reading speed does increase significantly in the post-task (Figure 55). No further significance was established for reading speed (Table XLVII).

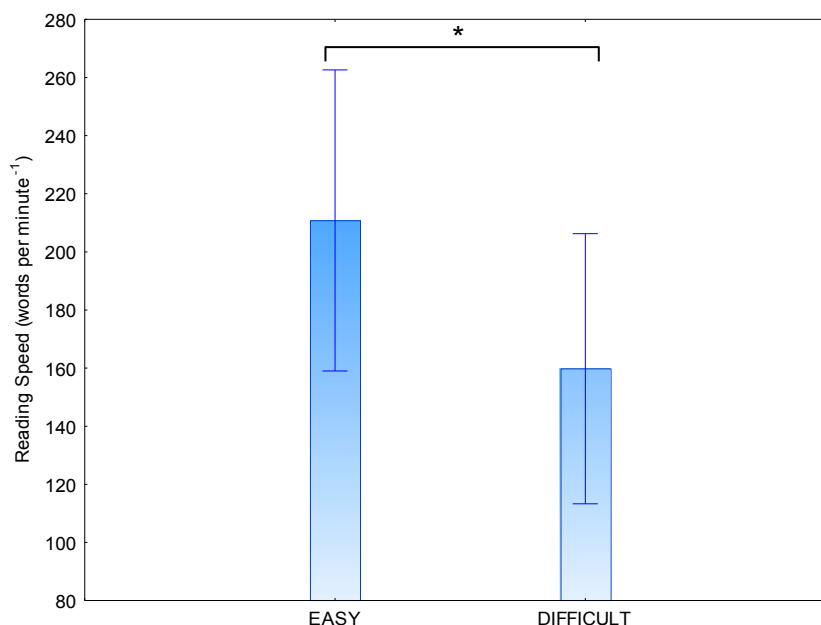


Figure 55: Changes in reading speed between the *easy* and *difficult* variations of the reading task (Error bars indicate 95% confidence interval).

4.6.1.2 Errors Identified

Table XLVIII: Analysis of variance for percentage of errors identified during the pre- and post-reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Reading Task – Errors identified	SS	DoF	MS	F	p
GROUP	0.34353	2,21	0.17177	1.9517	0.17
Pre - Post	0.01515	1,21	0.01515	1.0049	0.33
PrePost *GROUP	0.01538	2,21	0.00769	0.5100	0.61
DIFFICULTY	0.28437	1,21	0.28437	15.1348	<0.05*
DIFFICULTY *GROUP	0.00644	2,21	0.00322	0.1715	0.84
PREPOST*DIFFICULTY	0.02565	1,21	0.02565	2.1460	0.16
PREPOST*DIFFICULTY*GROUP	0.03166	2,21	0.01583	1.3244	0.29

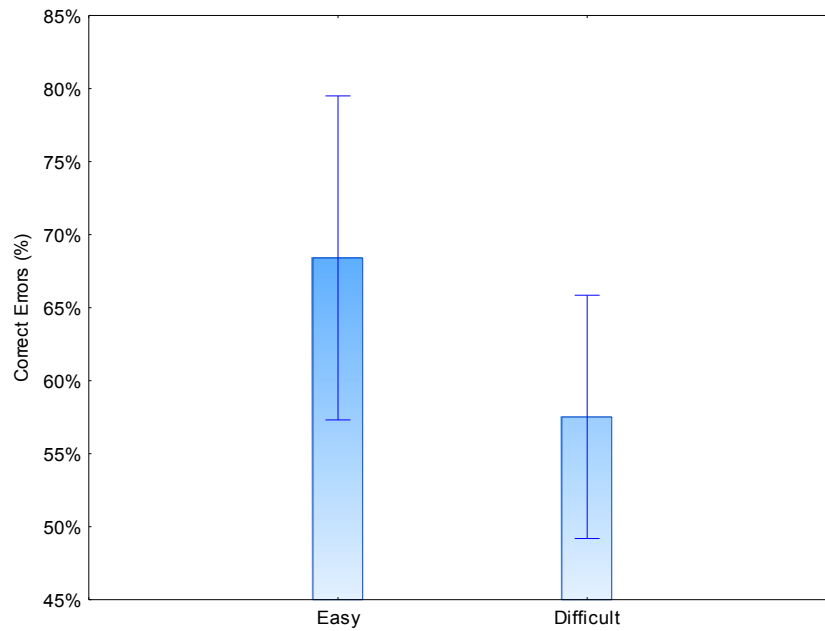


Figure 56: Overall *easy* and *difficult* variation difference in percentage of errors identified correctly during the reading task (Error bars indicate 95% confidence interval).

Neither *group* nor *pre/post* yielded significant statistical effects in the number of words correctly identified during the reading task (Table XLVIII). That is, reading accuracy did not change after the prolonged drive, and reading accuracy was not different between the groups. However, a significant *difficulty effect* was found, confirming that participants recognised significantly fewer errors overall for the *difficult* variation than the *easy* variation (Figure 56 and Table XLVIII). No significant interactional effects were calculated (Table XLVIII).

4.6.2 Cardiovascular Responses

4.6.2.1 Heart Rate Frequency

Heart rate responses during the post-task reading tests are significantly lower ($p < 0.05$) than those recorded in the pre-task tests, demonstrated by the significant *pre-post effect* (Figure 57 and Table XLIX). While differences in heart rate between the *easy* and *difficult* variations do not elicit statistical significance ($p = 0.06$; Table XLIX), Figure 57 illustrates how the *difficult* variation elicits a substantially lower heart rate response. No additional significant effects are observed (Table XLIX).

Table XLIX: Analysis of variance for heart rate frequency ($\text{bt} \cdot \text{min}^{-1}$) during the pre- and post-reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Reading Task – Heart Rate Frequency	SS	DoF	MS	F	p
GROUP	171.3	2,21	85.7	0.292	0.75
Pre - Post	1513.0	1,21	1513.0	79.484	<0.05*
PrePost *GROUP	29.9	2,21	14.9	0.785	0.47
DIFFICULTY	22.5	1,21	22.5	3.972	0.06
DIFFICULTY *GROUP	0.2	2,21	0.1	0.015	0.99
PREPOST*DIFFICULTY	9.4	1,21	9.4	1.618	0.22
PREPOST*DIFFICULTY*GROUP	0.8	2,21	0.4	0.070	0.93

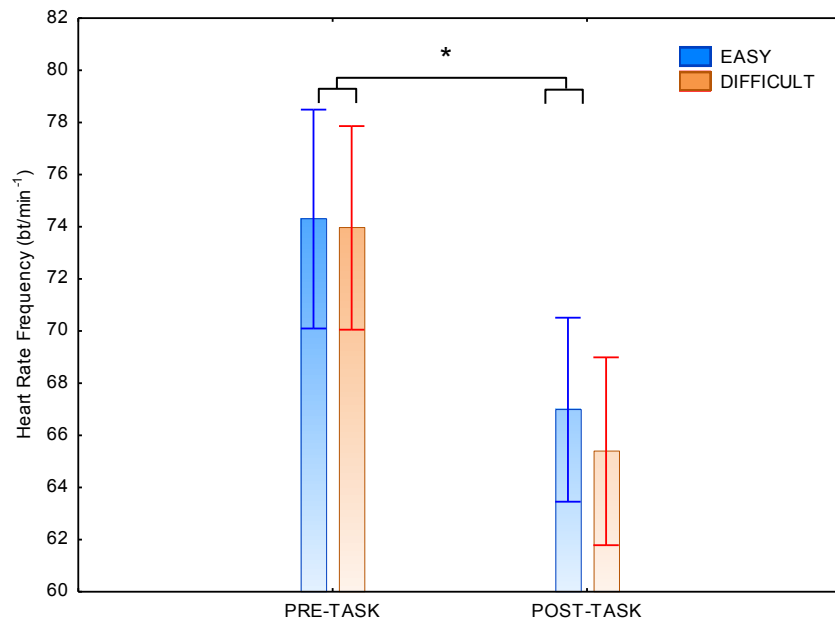


Figure 57: Overall pre- and post-task difference in heart rate frequency observed during the *easy* and *difficult* variations of the reading task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

4.6.2.2 Heart Rate Variability: Time-Domain Analyses

Table L: Analysis of variance for heart rate variability (rMSSD) during the pre- and post-reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

rMSSD	SS	DoF	MS	F	p
GROUP	2719.2	2,21	1359.6	0.5861	0.57
Pre - Post	7776.8	1,21	7776.8	13.1862	<0.05*
PrePost *GROUP	27.6	2,21	13.8	0.0234	0.98
DIFFICULTY	641.0	1,21	641.0	4.2060	0.05
DIFFICULTY *GROUP	395.4	2,21	197.7	1.2971	0.29
PREPOST*DIFFICULTY	1.3	1,21	1.3	0.0149	0.90
PREPOST*DIFFICULTY*GROUP	63.5	2,21	31.7	0.3646	0.70

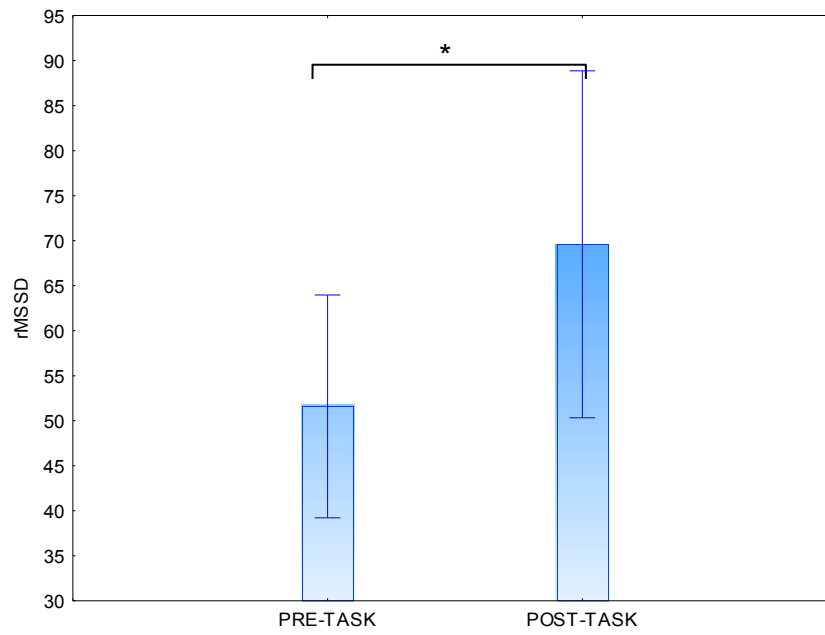


Figure 58: Overall pre- and post-task change in heart rate variability (rMSSD) observed during the reading task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

Heart rate variability (rMSSD) during the reading tasks increases significantly between pre- and post-task tests (Figure 58), indicating a significantly lower cognitive workload following the sub-maximal drive. While rMSSD does not elicit any statistical differences between the difficulty variations ($p = 0.05$; Table L), Figure 59 shows that heart rate variability is substantially lower in the *difficult* variation. No other significant effects are calculated for rMSSD (Table L).

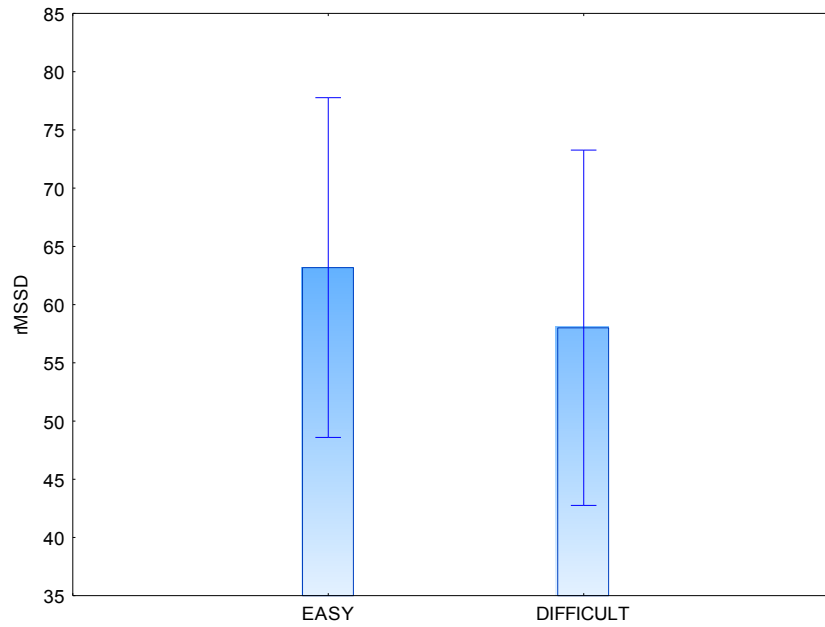


Figure 59: Changes in heart rate variability (rMSSD) between the *easy* and *difficult* variations observed during the reading task (Error bars indicate 95% confidence interval).

4.6.2.3 Heart Rate Variability: Frequency-Domain Analyses

Table LI: Analysis of variance for heart rate variability (HF power) during the pre- and post-reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

HF power	SS	DoF	MS	F	p
GROUP	10185529	2,21	5092764	0.52608	0.60
Pre - Post	19810503	1,21	19810503	5.74435	<0.05*
PrePost *GROUP	7717474	2,21	3858737	1.11890	0.35
DIFFICULTY	1086299	1,21	1086299	3.68164	0.07
DIFFICULTY *GROUP	836462	2,21	418231	1.41745	0.26
PREPOST*DIFFICULTY	51199	1,21	51199	0.30506	0.59
PREPOST*DIFFICULTY*GROUP	13992	2,21	6996	0.04169	0.96

HF power and LF power are both significantly higher in the post- task reading tests thn pre-task responses ($p < 0.05$ and $p < 0.05$, respectively; Table LI and Table LII, Figure 60 and Figure 61). This indicates interplay between a strengthening of both the parasympathetic and sympathetic branches, respectively. LF power reflects a significant ($p < 0.05$) *group effect*; the *easy* variation elicits significantly higher responses than the *difficult* variation (Table LII). While HF power does not elicit a statistical *group effect* ($p = 0.07$), there is a numerically higher response for the *difficult* variation (Table LI). No additional significant effects are calculated for frequency domain analyses (Table LI and Table LII).

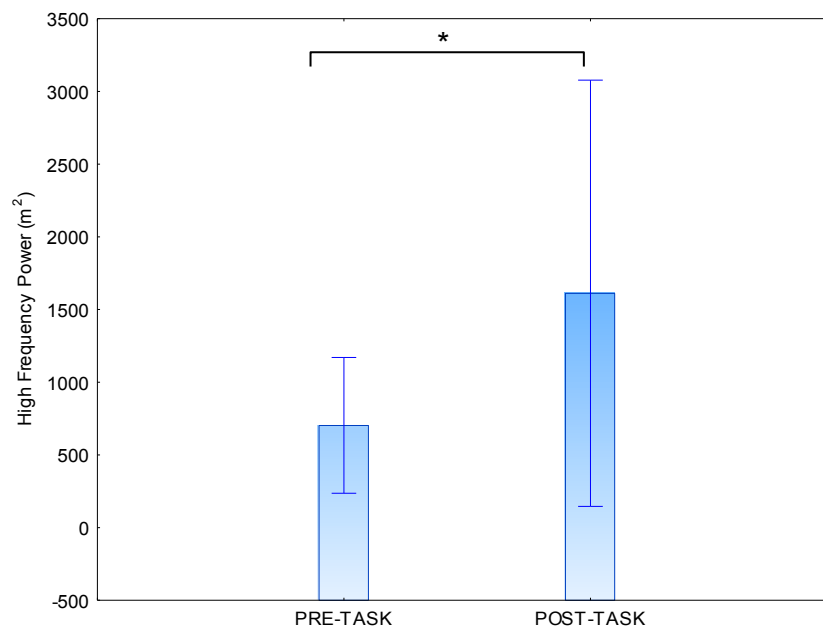


Figure 60: Pre- and post-task difference in heart rate variability (HF power) for the reading tasks (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

Table LII: Analysis of variance for heart rate variability (LF power) during the pre- and post-reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Reading Task - LF power	SS	DoF	MS	F	p
GROUP	8447653	2,21	4223827	0.80676	0.46
Pre - Post	10899066	1,21	10899066	5.99601	<0.05*
PrePost *GROUP	68481	2,21	34240	0.01884	0.98
DIFFICULTY	2536118	1,21	2536118	5.24691	<0.05*
DIFFICULTY *GROUP	258463	2,21	129231	0.26736	0.77
PREPOST*DIFFICULTY	466549	1,21	466549	1.83884	0.19
PREPOST*DIFFICULTY*GROUP	533019	2,21	266510	1.05041	0.37

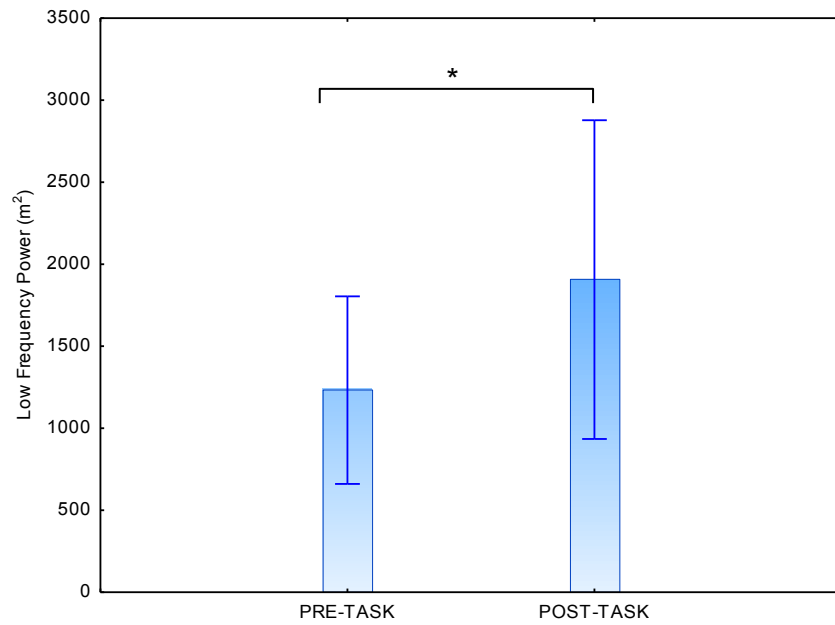


Figure 61: Pre- and post-task difference in heart rate variability (LF Power) for the maximal driving tasks (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

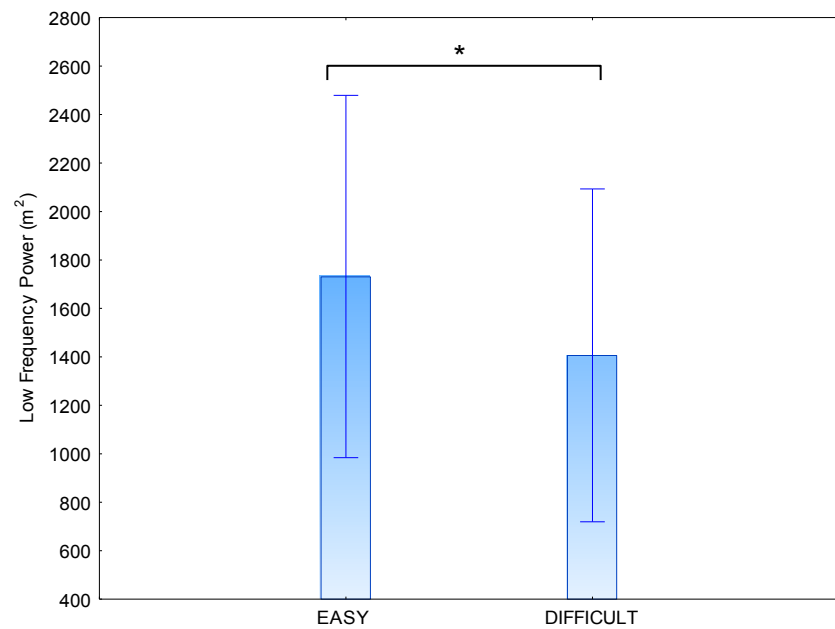


Figure 62: Difference in LF power response duration for the *easy* and *difficult* variations of the reading task (* = significant effect, $p < 0.05$; Error bars indicate 95% confidence interval).

Table LIII: Analysis of variance for LF power relative to (LF+HF) during the pre- and post-reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

LF power relative to (LF+HF)	SS	DoF	MS	F	p
GROUP	1153.2	2,21	576.6	0.6445	0.53
Pre - Post	530.6	1,21	530.6	3.3993	0.08
PrePost *GROUP	100.8	2,21	50.4	0.3230	0.73
DIFFICULTY	712.2	1,21	712.2	7.5811	<0.05*
DIFFICULTY *GROUP	5.1	2,21	2.5	0.0270	0.97
PREPOST*DIFFICULTY	12.0	1,21	12.0	0.1873	0.67
PREPOST*DIFFICULTY*GROUP	189.9	2,21	94.9	1.4799	0.25

LF power responses reflect a significant increase between pre- and post-task ($p < 0.05$; Table LII and Figure 61), and although the LF power relative to (LF+HF) shows no such effect, there is a numerical difference (Table LII). This suggests that sympathetic dominance increased following the prolonged drive. Both LF power analyses reflect significantly lower sympathetic activity in the *difficult* variation of the reading task ($p < 0.05$; Table LII and Table LIII). No further effects were calculated for LF power analyses.

4.6.3 Oculomotor Parameters

No significant statistical effects are calculated for either blink frequency or blink duration during the pre- and post-task reading tasks (Table LIV and Table LV, respectively).

4.6.3.1 Blink Frequency

Table LIV: Analysis of variance for blink frequency recorded during the pre- and post-reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Reading Task – Blink Frequency	SS	DoF	MS	F	p
GROUP	402.50	2,21	201.25	0.8327	0.45
Pre- - Post	149.93	1,21	149.93	0.8035	0.38
PrePost *GROUP	528.15	2,21	264.07	1.4153	0.27
DIFFICULTY	95.38	1,21	95.38	0.5165	0.48
DIFFICULTY *GROUP	588.67	2,21	294.33	1.5937	0.23
PREPOST*DIFFICULTY	282.67	1,21	282.67	1.6032	0.22
PREPOST*DIFFICULTY*GROUP	429.76	2,21	214.88	1.2187	0.32

4.6.3.2 Blink Duration

Table LV: Analysis of variance for blink duration during the pre- and post- reading tasks, with pre/post effect, difficulty effect and group effect as the three factors (* = significant effect, $p < 0.05$).

Reading Task – Blink Duration	SS	DoF	MS	F	p
GROUP	17077	2,21	8539	0.8262	0.45
Pre - Post	78	1,21	78	0.0153	0.90
PrePost *GROUP	1936	2,21	968	0.1893	0.83
DIFFICULTY	39	1,21	39	0.0232	0.88
DIFFICULTY *GROUP	184	2,21	92	0.0542	0.98
PREPOST*DIFFICULTY	1	1,21	1	0.0004	0.99
PREPOST*DIFFICULTY*GROUP	2707	2,21	1354	0.6074	0.55

4.7 SUMMARY OF RESULTS

4.7.1 Sub-Maximal Driving

As indicated in Table IV, with the exception of temperature, all variables measured during the sub-maximal drive reflected a significant *time on task* effect. Performance decreased over time, as did heart rate. Heart rate variability (rMSSD), HF power, LF power, and LF power relative to (LF+HF), blink frequency and blink duration all increased over time. These effects confirm that fatigue induction was successful.

There was a significant *group* effect for mean deviation, indicating that driving performance between the three experimental groups was different overall. However, this effect was not found for any psychophysiological variables, indicating that the extent of fatigue developed was dependant on the three groups. This is confirmed by the significant *time on task* and *group* interaction effect for mean deviation, heart rate variability and LF power. The *large* group reflected the greatest increase in deviation over time, while the small and medium groups showed comparatively minor deviations over the same period. Psychophysiological results suggest that the *large* group applied more effort than did those of the *medium* and *small* groups.

Oculomotor parameters were not sensitive to the differences in behavioural or cardiovascular responses between the groups.

4.7.2 Maximal Driving

There were no significant changes for mean deviation between the maximal performance tests, indicating that there was no learning effect during the pre-task test battery, or recovery effect during the post-task test battery (Table XV). However, the nature of the calculated cardiovascular effects is typical of a state of down-regulation, which is indicative of a fatigue compensatory effect. Similarly, there were significantly different subjective ratings across all PRE- and POST- comparisons, indicating that while participants may have perceived the task as demanding, their performance and physiology suggested it was not. In contrast, oculomotor parameters reflected no such effects.

4.7.3 Motor Performance (Fitts' Tapping Task)

There was a significant *difficulty* effect for both Fitts' performance parameters, confirming that the two variations were indeed differentially taxing (Table XXV). There was a pre/post effect for both response time and target deviation. Response time reflected a significant *pre/post* and *difficulty* effect, while target deviation did not. For the *easy* variation, pre/post response time improved and target deviation increased. However, for difficult variation pre/post response time did not change but target deviation increased.

Pre/post heart rate decreased, while heart rate variability (rMSSD) and HF power both increased, indicating a down-regulated state. There were no changes to oculomotor parameters.

4.7.4 Working Memory (Digit Recall Test)

There was a significant *difficulty* effect for both response duration and percentage correct, the latter confirming that the two variations were indeed differentially taxing (Table XXXV). There was a pre/post effect for both response duration and target deviation. However, only percent correct reflected a significant *pre/post* and *difficulty* effect. In the *difficult* variation, improved recall ability was matched by longer response duration. However, for the *easy* variation recall ability did not change between pre- and post-, but response duration increased. Overall,

changes in cardiovascular responses indicated participants were in a comparatively down-regulated state following the prolonged drive.

4.7.5 Cognition (Reading)

There was a significant difficulty effect for both reading speed and number of errors identified, confirming that the difficulty variations were differentially taxing (Table XLVI).

For both difficulties, post-task reading speed increased but there was no change in the number of errors identified. These effects were marked by significant pre/post changes in all cardiovascular responses. Post-task heart rate was lower, while heart rate variability (rMSSD) and HF power both increased, indicating a down-regulated state. There were no changes to oculomotor parameters.

CHAPTER V

DISCUSSION

The present study was designed to investigate the validity of resource and effort-regulation models as control mechanisms underlying driving performance in a prolonged simulated drive, and in addition, to identify whether the impacts of a prolonged drive differentially tax resources used in the different information processing stages. Initially it was predicted that over time driving performance would tend to degrade, psychophysiological measures would reflect typical fatigue characteristics, and subjective assessments would increase. It was also predicted that the prolonged drive would degrade information-processing capacity. Differing predictions regarding the effects of different task-demands of the prolonged drive on indices of driving performance and psychophysiological variables were made based on resource and effort-regulation models.

Resource theory predicted that fatigue responses would be lowest under the experimental group with the smaller drive task-demand (i.e., the large road width group) and highest under the higher drive task-demand (i.e., small road width group). Further, Resource Theory predicted that the prolonged drive would negatively impact on the allocation and performance of the various cognitive resources. If the allocation and performance was not affected, Resource Theory predicted that there would be an increase in psychophysiological responses to compensate for the depletion of resources.

By contrast, Effort-Regulation Theory predicted that fatigue responses would be lowest under the experimental group with the higher drive task-demand (i.e., the small road width group) and highest under the smaller task-demand (i.e., large road width group). Further, Effort-Regulation Theory predicted that the prolonged drive would not negatively impact on the allocation of the various cognitive resources, however the performance would be impaired, which would reflect as a decrease in psychophysiological responses due to a withdrawal of effort.

Overall, the results of the current study tended to support predictions from an effort-regulation account of driving performance, as drivers displayed better performance and lower cognitive effort over time in the higher task-demand drive (small road width group), as compared to the lower task-demand group (large road width), which reflected greater variation in lateral position and higher cognitive effort. However, as will be discussed further on, lane width confounds the standard deviation of the lateral position measure.

Hypotheses concerning performance and psychophysiological responses for the post-task test-battery were reasonably supported by an effort-regulation account. Post-task performance generally declined, and psychophysiological responses indicated participants were in a down-regulated state. However, oculomotor responses seemed not to be sensitive to these changes.

There were differential effects for performance parameters in the Fitts' task and the digit recall task. However, as will be discussed below, these effects may be dependant on the trade-off strategy between performance and effort.

Next, the effect of time on task and varying road widths on driving performance, psychophysiological responses and subjective assessments will be discussed in greater detail. The impact of the prolonged drive on information processing will also be discussed, before ending with responses to original proposed hypotheses.

5.1 PROLONGED SUB-MAXIMAL DRIVE

5.1.1 Driving Performance

In terms of driving performance, the standard deviation of the lateral position of the car increased significantly over time (Figure 17). This translates to a decreased tracking performance. These results are similar to the findings of van der Hulst *et al.*, (2001), Thiffault and Bergeron (2003b) and Horne and Reyner (2005). However, these authors found observable performance decrements as early as 15-20 minutes into the drive, while in this study performance differences were seen only after 40-45 minutes. Considering the variability

in simulator parameters, these differences are negligible. This result indicates that fatigue induction was successful, which was vital to answer the research question.

While not significantly different, overall there was a numerical difference ($p=0.05$; Table V) in lane deviation between the groups. These increased in order of magnitude corresponding to the increase in the road width of each experimental condition. This result was expected, as road width was proportional to the margin of allowable error – that is, the two lines in between which participants were expected to keep the car. Participants were encouraged to strive towards the ideal goal, which was to maintain an equal distance between two lines (i.e. in the middle of the lane), with the minimal goal being to avoid an off-road incident.

As expected, there was a significant group difference in lane deviation over time, with the widest road (*large* group) showing the greatest performance decrement over time, whereas the *small* and *medium* road width groups reflecting comparatively modest performance decrements (Figure 18). This suggests that with the development of fatigue, participants accepted diminished performance to accommodate personal comfort. This means that participants took advantage of the extent of the margin of allowable error, accepting the minimal goal over the ideal goal. In this sense, it is expected that the group with the widest road would display a proportionately greater increase in lane deviation over time than the group with the smallest road. Therefore, it is not appropriate to compare fatigue levels between the experimental groups purely based on the extent of lane deviation. The specific purpose of varying road widths was to test the predications of resource and Effort-Regulation Theory on how performance and effort are related when fatigue was induced through different task-demands.

The aspect of performance that can be taken into account is the fluctuations of driving performance. There were also greater cyclical performance changes, or fluctuations, with increasing road widths. The *small* group showed almost no fluctuations over the 90-minute drive, while the *medium* group showed minor fluctuations and the *large* group showed marked fluctuations over 15 minute intervals. This was most notable in the *large* road width group, where there was a sharp rise and fall in lane deviation between minutes 30 and 60. While it can be argued that the extent of fluctuations too are relative to the road widths, it is also true that they are more sensitive to behavioural responses than are pure lane deviations.

These fluctuations demonstrate that participants were capable of coping with processing when task-demands were high (small road) but not when demands were low (large road). Within the Hancock and Warm (1989) and Hockey (1997) framework, this paradox is more consistent with an explanation of fatigue in terms of effort-regulation, than to an explanation in terms of resource depletion. The effort-regulation account suggests that either the participants failed to detect their performance decrement, or they were unwilling or unable to apply compensatory effort once they detected their performance decrement. The fact that the *small* group reflected only minor decrements and fluctuations⁹ in performance suggests that the first explanation is more sensible. Compared with the *small* road, the *large* road possibly provided fewer cues about performance loss, whereas the smaller margin of allowable error in the *small* group may have provided sufficient external feedback for participants to evaluate their performance. This interpretation is supported by the Norman (1988) view that the quality of feedback is critical to the speed of information transmission. Matthews and Desmond (2002) observed this exact paradox when they examined demands of curved vs. straight road driving. They concluded that task-induced fatigue reduces drivers' awareness of performance impairment. This suggests that performance decrements associated with task-induced fatigue may be greater than their psychophysiological manifestations. If the resource depletion account were valid, performance would have been greater in "underload" conditions (*large* road) than when task-demands are greater (*small* road). Further, from a resource account, performance would not improve with increased effort, as was clearly observed in the *small* group.

The obvious question is whether this phenomenon is reflected in the participants' psychophysiology.

5.1.2 Cardiovascular Responses

In this study, heart rate decreased significantly during the prolonged simulated drive by nearly 6 beats/min⁻¹ ($p < 0.01$; Figure 19). Coupled with the significant rise in subjective ratings of effort (Figure 29), it suggests that the participants were in a fatigued, sleepy mode at the end of the driving task (Mascord and Heath, 1992). Riemersma and colleagues (Riemersma *et al.*,

⁹ There may be minor fluctuations that are not observable in the 5-minute interval sampling used.

1977) also found decreases in heart rate in eight hours of night driving. However, they raise arguments against relating heart rate and fatigue, claiming that a steady decline heart rate is usually in response to participants adapting to the experimental situation, and should therefore not be taken as a sign of fatigue. However, the chief aspect of their argument was that if a decline in heart rate were due to a build-up in fatigue, it would be expected later rather than earlier. In the current study, post-hoc analysis reveals significant differences only after the first 30 minutes of a 2-hour drive (Appendix C2); therefore it is unlikely that overall decline is due to an adaptation effect. In addition, adaptation to ambient temperature would correspond to decrease in skin temperature, however no such effects were found (Table XIV). This suggests that fatigue was the primary cause of the decrease in heart rate. A better indication of HR responses could be found in the difference between the PRE- 2 maximal drive and the first 5-minute interval of sub-maximal driving. However, the active nature of the resource test battery is likely to mask any real decline due to adaptation to ambient temperature.

Despite the significant differences in performance between the groups, heart rate did not reflect any group effects (Table VI). This is probably due to heart rate not being as sensitive to cognitive workload as is heart rate variability (Pfendler, 1982; Jorna, 1992). Further, differences in performance do not necessarily share a causal link with differences in heart rate. If it is the case that fatigue and stress are to account for the decline in heart rate, it will be mediated through the autonomic nervous system (Vivoli *et al.*, 1993).

Heart rate variability is a sensitive psychophysiological indicator of mental effort (Lal and Craig, 2001) and driver fatigue (Egelund, 1982), in that the analysis of changes therein can provide insights into the functional state of the body's autonomic systems (Pagani *et al.*, 1997). Some authors interpret the increased HRV as a sign of a fall in the level of cerebral activation, which is associated with a diminished alertness (Harris *et al.*, 1972). In the current study, an ANOVA on the different spectral components of heart rate variability revealed significant differences over time in all cases.

All time-domain parameters reflected a significant increase over time (Table IV), which is reflective of decreased effort and increased levels of fatigue (Oran-Gilad and Ronen, 2007). This increase is probably due to the monotonous nature of the driving task, which previous

studies have linked to decreased arousal (Thiffaultt and Bergeron, 2003). As per the performance data, this result supports the effort-regulation account, which proposes that with time on task participants display an increasing inability or difficulty to match effort to task-demands (Hancock and Warm, 1989). Resource depletion, on the other hand, holds that the increasing task-demands with time on task would drain cognitive resources, which would require further mobilisation of compensatory effort to maintain adequate performance (Warm *et al.*, 2008).

Further support for effort-regulation is found in the significant group effect over time for SDNN and rMSSD, where the group with the *small* road width showed the greatest increase in rMSSD over time, while groups with the *medium* and *large* road widths reflect modest increases, and therefore reflect higher levels of effort than the *small* road group. As argued before, the *small* road may provided more performance cues, therefore participants may have perceived workload to be lower, which would result in a selective withdrawal of effort. Fairclough (2001) argues that this withdrawal may also signify a switch from external task goals to internal goals, which is likely to be induced by a desire to cope with discomfort. In contrast, the large and medium roads would have provided fewer performance cues given their relatively greater margins of allowable error, which increases task uncertainty and raises task workload. In this scenario, effort-regulation expects participants to reflect greater effort to maintain performance and mitigate fatigue effects.

Time-domain analyses are not sufficiently sensitive to explain sympathetic and parasympathetic nervous system contributions to the development and state of fatigue in drivers. Frequency domain analysis reflects sympathovagal balance of the autonomic nervous system. High frequency (HF) responses reflect fluctuations of efferent parasympathetic activity (Fairclough *et al.*, 2005).

HF power increased significantly with time on task (Figure 22), indicating there was an overall strengthening of the parasympathetic branch during driver fatigue, indicative of a rise in sleepiness and decline in arousal. There was also a significant group effect over time (Figure 23). The *small* group showed a marked increase in HF power over time. In contrast, the *large* and *medium* groups reflected relatively minor increases in HF power responses, the large

group however showed greater fluctuations. These results are supported by the non-specific findings in the post-hoc analysis (Appendix C2).

The brief decreases in HF power that are evident for all groups throughout the drive are suggestive of some form of self-regulatory behaviour intended to increase attentiveness and arousal. With no time cues given for task duration, this behaviour may be a protective function designed to ensure optimal performance. This is especially noteworthy given that time on task is said to be associated with an increased task-demand (Dinges, 1995).

Low frequency (LF) power is seen to increase significantly over time (Figure 24). However, these fluctuations are regarded with some controversy, with some studies suggesting LF is a marker for sympathetic modulations, while others view it as reflecting both sympathetic and parasympathetic control (Jaffe *et al.*, 1993, Task Force, 1996). In their analysis of continuous ECG recordings during a 52-hour Constant Routine Protocol, Citi *et al.* (2010) found an increase in LF:HF to reveal an increasing sympathetic drive correlating with worsening of objective performance measures. Consequently, the LF:HF ratio was used to reflect sympathetic modulations (Task Force, 1996).

There is a significant increase in the LF:HF ratio (Figure 26), which suggests that autonomic balance is shifted towards sympathetic dominance, which is positively correlated with driving performance (Figure 17), and potentially entails a higher level of arousal. The hypothesis holds that the arousal response is either a subconscious mechanism functioning to optimize performance or a conscious effect by the participants to increase concentration and alertness in an attempt to resist the increasing levels of fatigue. However, the correlation holds true only until the 45th minute, at which point the LF:HF index declines for 15 minutes and reflects no changes for the remaining 30 minutes of the drive. The fact that HF power at this point retains its upward trend and shows no sign of a decrease for the remainder of the drive suggests that the decline in LF:HF index must be accounted for by a decline in sympathetic activity, and subsequent shift towards parasympathetic predominance. This reflects a distinct adaptive function of the autonomic nervous system to the task-demands.

Given the disagreement that exists around the origin and interpretation of the LF component, it is difficult to confidently argue support for either resource or effort-regulation theories based purely on frequency responses. This, especially since there is sparse literature linking these

theories to HRV responses, not least to the LF component, in the context of prolonged simulated driving. However, based on the current and accepted understanding thereof, the results tentatively suggest effort-regulation dominance.

5.1.3 Oculomotor Responses

Increased blink frequency is indicative of light fatigue and a transition from awake to reduced vigilance and increase drowsiness, whereas increased blink duration is typically seen in the transition to severe sleepiness (Lal and Craig, 2001). As expected, there was a significant increase in both blink frequency and blink duration over the duration of the sub-maximal driving task (Figure 27 and Figure 28). Blink frequency and blink duration increased from 14 blinks/min⁻¹ and 150ms in the first interval to 17.5 blinks/min⁻¹ and 175ms in the last interval, respectively. This finding is in line with previous studies that have found increases in blink frequency (Stern *et al.*, 1994; Galley *et al.*, 1999) and blink duration (Caffier *et al.*, 2003; Galley and Schleicher, 2004; Campagne *et al.*, 2005) with time on task. The inhibition of blinks is said to be attention-driven (Hargutt, 2003). Therefore, the withdrawal of effort over time, as inferred from the increased HRV (rMSSD; Figure 21), explains the increased blink frequency. Similarly, prolonged blink duration is generally associated with down-regulation of several physiological processes (Schleicher *et al.*, 2008), a process reflected in the increasing parasympathetic activity (HF power; Figure 22).

It is pertinent to note that significances were established within the first 25-35 minutes of the drive, after which there were no noticeable increases. As performance and cardiovascular responses generally demonstrate a progressive increase in fatigue, it is puzzling as to why there exists a plateau in blink behaviour. This is possibly due to one of two things. Either the parameters set to identify blink behaviour limited the identification thereof, or a deeper fatigue state did not in fact exist and the plateau is reflective of the minimal attentional state accepted by the participant to meet their minimum task goals.

If the first explanation is valid, one would expect to see smaller standard deviation as fatigue levels pushed up to the threshold of the parameter identification, however this was not the case for either blink measure (Figure 27 and Figure 28). The second explanation seems more sensible, as deeper fatigue states are typically associated with decreases in blink frequency

and duration, and not increases (Borghini *et al.*, 2012). Blink duration does decrease in the last 15 minutes of the drive, but as these values are higher than those from the initial non-fatigued state, it is suggestive of some form of arousal. However, this interpretation, too, is questionable as there is a decreased sympathetic activity at this point, as interpreted from the LF:HF ratio (Figure 26). This contradiction is difficult to reconcile, as it also does not coincide with any observable performance increases. The reader will recall that no cues regarding task end-point were given. This leads to the suggestion that the state changes experienced by the participants over the drive may be more attention-based than fatigue-based.

Despite lane deviation showing a significant group effect over time, no such effect was found for blink frequency or blink duration (Table XI and Table XII). This suggests that either the differences in task-demands between the three groups were not great enough to elicit changes in blink behaviour, or perhaps the actual levels of fatigue between the three groups were not different. If it is the case that the observed state-changes are attention derived, it may explain the lack of differences in blink behaviour between three groups. If attention demands are not substantially different between the groups, it may explain why their blink profiles do not differ. This is, however, only a tentative supposition.

Blink frequency and blink duration can both be modulated by task-directed attention (Hargutt, 2003), and since both resource and effort-regulation theories assume that fatigue can be temporarily overcome by effort or will (Hole, 2008), it is difficult to ascribe changes in blink behaviour to either mechanism.

To obtain a fuller understanding of how the resource and effort-regulation account may have functioned in the above considerations, it is necessary also to examine the changes to attentional state and information processing capacities.

5.2 MAXIMAL DRIVE

The maximal driving test was implemented before and after both PRE- and POST- resource test batteries, to answer a number of questions regarding state changes throughout the testing. The responses from PRE- 1 and PRE- 2 were compared to assess whether during the course of the resource test battery the participants developed any further adaptation or

proficiency in the driving task. POST- 1 and POST- 2 responses were compared to assess whether recovery effects or state changes occurred during the post-test resource battery. Finally, PRE- 2 and POST- 1 were compared to assess whether the prolonged driving task had any effect on general resource depletion, i.e. whether there was any attention deficit.

The reader will recall that the maximal driving task was distinct from the sub-maximal driving task in three ways: The task required all participants to track the middle of the road with the point of an arrow head. The road width was kept constant for all participants - equivalent to the *medium* road width group (0.8m). The test duration was limited to 2-minutes as the intention was merely to assess attentional state and prevent the induction of any further fatigue effects.

Results from Table XVI indicate that no significant performance effects were observed between any of the maximal driving tasks. In response to the above comparisons, this suggests that no learning effect was gained in the pre-test battery, no recovery effect was observed during the post-test battery, while the non-significant difference between PRE- 2 and POST- 1 indicates that the fatigue effects observed over the prolonged drive did not impact on the maximal drive performance.

However, given the earlier supposition that effort-regulation may have dominated performance changes in the sub-maximal drive, it is necessary to scrutinize the psychophysiological responses for any indication that the same mechanism may have masked any fatigue effects.

Heart rate increased significantly between PRE- 1 and POST- 2 (Figure 30), signifying a distinct arousal effect (Grandjean, 1979). This is particularly notable when one recalls that heart rate decreased significantly over the course of the prolonged drive (Figure 19). The difference also indicates that the mere change of task induced arousal effects that were so great that heart rate increased instantly from sub-maximal drive end value of 68 bt.min^{-1} to 74 bt.min^{-1} during the first maximal drive, coincidentally the same as initial sub-max drive value. This finding is in line with previous studies that report immediate increases in heart rate with the introduction of a memory test (Birch, 2012). There was also a significant decline in heart rate over the post-test battery, indicated by the POST- 1 vs. POST- 2 effect (Figure 30). This probably reflects an adaptation effect after the spike in arousal observed during POST- 1.

Heart rate variability (rMSSD) decreased significantly both overall and from PRE- 2 and POST- 1, reflecting an increased cognitive effort. Given that performance did not change for this comparison the increased effort signifies a compensatory mechanism to offset any possible lingering fatigue effects (Sanders, 1997; Hockey, 1997). The assertion is further strengthened by the fact that HRV does not change between POST- 1 and POST- 2, which would have decreased had the POST- 1 increase been merely an arousal artefact.

Both LF power and HF power increased significantly between pre- and post-task, indicating a balance of the sympathetic and parasympathetic branches of the autonomic nervous system (Figure 32 and Figure 33). In this case, the LF:HF ratio would typically indicate which of these two branches was dominating. However, LF:HF ratio derived for the maximal drives is difficult to explain (Figure 34). The LF:HF ratio increases from PRE- 1 to PRE- 2, but decreases from POST- 1 to POST- 2, indicating that sympathetic activation increases during the pre-test battery and decreases during the post-test battery.

There were also no differences in the above comparisons for blink frequency and blink duration. As with the performance effects, it is likely that the increased effort, evidenced by the lower heart rate variability responses, has masked the effects of fatigue, suggesting that the fatigue induced was not so severe that an increased effort could not overcome it. The finding is further supported by the fact that blink behaviour demonstrated significant differences over the prolonged drive. This conclusion is pertinent as the maximal driving task is an assessment of maximal attention capacity.

There were no significant group effects for either blink frequency or blink duration across all comparisons. However, as no parameters were sensitive to group effects in the sub-maximal drive it would be unlikely that they would show such effects in the maximal drive. This, especially since all groups performed the same maximal drive task and consequently reflected the same levels of effort. Interestingly, ratings of perceived effort were different between these comparisons.

The decrease in subjective ratings during the post-test battery can be accounted for by one of two things. Either the nature of the constant change of tasks in post-test battery was such that participants did not feel as much strain as was built up over the prolonged drive, thus displaying some relief effect, or participants anticipated an end point that may have masked

any actual levels of subjective effort. It is also possible that these effects may function in concert. The different trends for the PRE- and POST- differences underscore the fragility both in the use and assessment of subjective ratings.

These findings strengthen support for the notion that effort-regulation dominates the control of performance and response in prolonged simulated driving. Had the resource account dominated, and general resources were in fact depleted, merely directing additional resources to the task could not have offset a state of severe depletion. An alternative explanation is that the sub-maximal conditions were indeed themselves too sub-maximal, as it were. That is, they were not sufficiently strenuous to induce observable resource depletion, thus rendering the methodology biased towards an effort-regulation interpretation in the first place. However, this is difficult to accept after one recalls that all performance, cardiovascular and oculomotor parameters measured and analysed elicited significant changes over time during the prolonged drive.

While there was clearly a fatigue effect it was masked by an increased effort or allocation of resources to maintain task performance. An alternative interpretation is that the prolonged drive did not inhibit participants' ability to retain attentional control; it did, however, require a significant increase in effort to do so.

To understand whether the masking was indeed an allocation of additional resources, or whether it was merely that more effort was put into the control processes, it is necessary to scrutinise changes in the utilisation of resource for each of the information processing stages.

As no recovery effect was seen between POST- 1 and POST- 2, if resource depletion had occurred it would be evident from the responses of the post- resource test battery.

5.3 RESOURCE TESTS

In all three of the resource tests, it is the interaction between the *pre/post* effect and the *difficulty* effect that is most important to consider, as a statistical effect of this interaction will indicate whether a given resource has been affected. This can be illustrated either through performance measures, or psychophysiological measures. If this interaction were evident in performance measures only, it would suggest that the prolonged drive altered the allocation of

the resources isolated by that test. However, if the interaction were present only in the psychophysiological measures, it would suggest that effort-regulation was functioning to support any resource allocation change. Therefore, in that case there may be resource depletion specific to that stage, but not to the point that it would impact on performance.

A general *pre/post* effect signifies general resource depletion in response to the prolonged task, while a *difficulty* effect serves to validate that the tasks were in fact assessing the upper and lower limits of that particular resource, however these limits are not absolute.

5.3.1 MOTOR PROGRAMMING (FITTS' TAPPING TASK)

The modified Fitts' tapping task was implemented to assess whether resources used for the motor neural system were impaired. To achieve this, two difficulty variations were applied in an integrated task, with stimulus difficulty rotating with each presentation: easy, where the target stimulus was consistently presented in the centre of the screen; difficult, where the target stimulus was presented at random across the screen.

Response time improved significantly between the pre- and post-task Fitts' tapping test (Figure 36) while target deviation increased (Figure 37). However, as can be seen in Figure 36, response time improved only for the *easy* variation and did not change for the *difficult* variation, and there was no statistical difference in the magnitude of difference in target deviation between the two difficulty variations. While it is well established that target deviation increases in a fatigued state, response time results are not in accordance with the literature, which presents overwhelming evidence that response time increases in the presence of fatigue (Dinges *et al.*, 1997; Lal and Craig, 2001).

It is worthy noting that many of these studies investigated response time in states of extreme sleep deprivation (Phillip *et al.*, 2004; Van den Berg and Neely, 2006; Cote *et al.*, 2009) and, as argued by Williamson *et al.* (2011), different fatigue states can manifest as different performance effects, to say nothing of the myriad of factors that could influence this. Nevertheless, the contradiction rests on the assumption that the participants were in fact in a fatigued state. If they were not, one might expect that response time might improve. Results from the prolonged drive suggest that effort-regulation better accounts for the performance

decrement than does resource depletion. To apply the same scrutiny to the Fitts' results it is necessary to unpack the psychophysiological data.

Increased arousal or state of attention is linked to shorter response time (Broadbent, 1971; Welford, 1980). Accordingly, one would expect a shorter response time for both difficulty variations. But, as Figure 36 reveals, only the *easy* variation reflects an improvement. Further to this, heart rate frequency, which is indicative of arousal, is in fact lower in the post-task Fitts' task than in its pre-task equivalent (Figure 39), where movement, while not faster, was more accurate. It is therefore unlikely that increased arousal is a valid candidate explanation.

While the criticisms and inconsistencies of traditional Arousal Theory have been well documented (Hockey and Hamilton, 1983; Hancock and Ganey, 2003; VaezMousavi *et al.*, 2009), current results still fit with an explanation in terms of decreased arousal, which is theoretically also associated with improved response time. This association also lends support to an effort-regulation account, which saw better performance in the group with the lowest task-demand (large road). HRV may provide further insight into this relationship.

The increase in HRV (rMSSD) indicates a significantly lower cognitive effort in the post-task test. HF power response was higher in the post-task test, which indicates a state of elevated parasympathetic activation. Further to this, both LF power and LF power relative to (LF+HF) do not reflect any statistical effects, suggesting that sympathetic activity was not at all dominant during this time. This indicates lower effort and greater parasympathetic dominance during the post-test. Taken together, these results suggest that participants are in a general state of down-regulation, which could potentially explain both the increased target deviation and the fact that response time improves for the *easy* variation but does not change for the *difficult* variation.

Fitts' law describes the inherent trade-off between speed and accuracy in movement. To understand how this law applies in this setting, it is necessary to consider each movement variation from a motor control point of view. Previous research has also linked response time to confidence. Indeed, Doshier (1984) found that participants tended to give accurate memory answers faster than inaccurate one. Applied to motor programming response, the current results are consistent with these principles.

The *easy* variation is represented by every second stimulus, which appears in the same location in the middle of the screen. Therefore, as the participant performs the task, they may start to anticipate that every second stimulus will be in the same location and will begin to anticipate its appearance. On a neural level this translates to the motor program becoming more entrained, developing a generalised motor program (Schmidt and Lee, 2011). On a psychological level it translates to an increase in each participant's confidence in predicting every second stimulus (Robinson *et al.*, 1997). Therefore, it is easy to see how, for the *easy* variation, an increase in response time is accompanied by an increase in target deviation.

On the other hand, the *difficult* variation is characterised by every other stimulus, presented at random locations across the screen. The inherent unpredictability of the stimulus will have the opposite effect on the participant's motor programming and confidence in anticipating the stimulus location. Therefore, even if there were an increased effort, the fact that the location of the stimulus is unpredictable means that there would have to be a reprogramming of the motor system with every new stimulus, and thus a lower confidence in anticipation. The fact that the *difficult* variation did not improve may be explained by a limitation in movement pattern programming. Described by Schmidt and Lee (2005) as the storage problem, the long-term memory is unable to store the programs for all the variations of movements that exist. Thus the neural system is forced to create a new program for each novel movement, and is therefore inherently limited in terms of how fast it can program a new movement pattern. If it is the case that in the pre-task test participants were programming novel movements (difficulty variation) at their fastest, then one would not expect that following an extended drive this limit could be improved upon, despite the decreased effort and decreased interest in the task. Participants are thus unable to generate faster response times. To maintain the response time in the face of a down-regulated neural system, Fitts' law predicts there must be a trade-off, which presents as a cost to accuracy (Figure 37). The integral difference between the two difficulty variations is that the *easy* variation requires a generalised motor program and the *difficult* variation is a novel movement that requires a new program. The above responses point to a decreased need for effort to control performance. It is likely though that the prolonged driving task as well as the extended testing duration will also contribute to this.

HR and blink frequency were the only measures for which there was a significant difference in responses within the groups between pre- and post- Fitts' task (Figure 39 and Figure 42). These effects are difficult to interpret, as they show neither the same nor inverse relationships as one another.

These results suggest that for task whose end goal requires only motor performance, participants in a fatigued state will trade accuracy for speed. Combined with the psychophysiological data, these results speak directly to an effort-regulation account of performance control. If Resource Theory were dominant, one would see an increase in effort and sympathetic arousal to offset performance decrements associated with depleted resources. Thus the performance decrement observed in the simulated drive does not seem to deplete resources linked to motor performance. The following two sections consider these effects for other aspects of information processing.

5.3.2 WORKING MEMORY (DIGIT RECALL TASK)

The purpose of the memory recall test was to assess attentional resources associated with working memory function. Participants were given no other instructions but to recall the digit string as accurately as possible.

Both recall ability (*percentage correct*) and response duration reflected difficulty effects (Table XXXVI and Table XXXVII), confirming that these tasks were in fact differentially taxing on the short-term memory system. As expected, many of the physiological parameters reflect pre/post fatigue effects, however not for the oculomotor system (Table XXXV).

The performance data reveal a differential effect for percentage of digits correctly recalled (Figure 43). That is, there was a significant change in the difference between the *easy* (5-digits) and *difficult* (7-digits) variations from pre- to post-task. This is mainly accounted for by the *difficult* variation trial, which reflected significantly better post-task recall performance, while recall ability in the *easy* variation did not improve from pre- to post-task. At first glance, the combination of these result is unexpected and raises a number of questions:

First, physiological measures point towards participants being in a down-regulated state in the post-task than the pre-task: The lower heart rate indicates lower arousal (Figure 46), while

increased heart rate variability (rMSSD) suggests that participants were investing less effort post-task (Figure 48). Both LF and HF power responses increased (Figure 50 and Figure 51), and as there was no change in the LF:HF ratio (Table XLIV) it points to an interplay between a strengthening of the sympathetic and parasympathetic branches, to provide balance. Therefore, it leads to the tentative suggestion that participants were in a fatigued, if not down-regulated, state. As progressive fatigue states have been shown to impair working memory (Cajochen *et al.*, 2004; Staal, 2004), in the current study one might expect impaired recall ability. Why then does performance actually improve in the *difficult* variation?

Speed-accuracy trade-off posits that if there is an increase in accuracy (recall ability), there must be an associated reduction in speed (response duration) (Wickelgren, 1977). In line with this, response duration increased numerically (Table XXXVII) from pre- to post-task, though there was no group effect. That is, while in the *difficult* variation an increased recall performance was traded off on longer duration, the same did not occur for the *easy* variation, where response duration increased but there was no increase in recall ability.

Even though there is evidence for a post-task performance trade-off in the *difficult* variation, it seems unlikely that pre-task in a non-fatigued state participants would choose speed over accuracy, especially as pre-task HRV responses were lower, indicating greater effort. It may be that participants developed a better recall strategy. That is, over the course of the testing, they may have figured out a more efficient chunking strategy for recall ability. This is more relevant for the *difficult* variation, as the digit string would have taxed the upper 7 ± 2 item capacity of the working memory, while the 5-digit string not. Even though there was a pre-test habituation, individuals may still have been experimenting with different recall strategies in the initial test battery. The question that remains, however, is that if performance for the more challenging task could be traded-off, why did the same trend not occur for the less challenging task?

Miller's law states that working memory capacity is capable of storing, rehearsing and recalling 7 ± 2 items (Miller, 1956). As the *easy* variation required participants to recall only 5 digits, it is characteristically a data-limited task – i.e. Performance is limited by the quality of information, not by the resources involved (Norman and Bobrow, 1975; Wickens, 1984). Thus, even though post-task recall ability improved for the *difficult* variation, as recall

performance in the *easy* variation is already at its upper limit at $\approx 96\%$ during pre-task, it is not plausible that the *easy* variation would show any vast post-task improvements. This explains the non-change in recall ability, but provides no account for why participants would need to take longer to recall the task.

It may be compensation for fatigue. It is possible that fatigue was a contributing factor, but as the *difficult* variation showed that memory capacity was not fundamentally impaired, there is likely to be a behavioural element involved. An effort-regulation account would explain this in terms of participants misperceiving effort or failing to apply appropriate effort to the task (Hancock and Warm, 1989; Matthews and Desmond, 2002), as is evidenced in the increased HRV.

Interestingly, blink duration showed a similar differential effect to that observed for recall ability (Figure 53). Increased recall ability for the *difficult* variation was accompanied by increased blink duration, while the *easy* variation, which showed no change in recall ability, reflected no change in blink duration. In the presence of fatigue or down-regulated state, participants may have used this behaviour as a strategy to reduce the amount of information entering the sensory memory store while rehearsing the 8-digit string. Certainly, learning effects are considered to counteract the effects of mental fatigue by masking the effects of fatigue due to sustained performance (Logan, 1992; Healy *et al.*, 2006). Various authors have associated longer blink durations with higher workload levels (Fogarty and Stern, 1989; Hankins and Wilson, 1998), which is typically itself a compensation for fatigue. It may be that this behaviour inadvertently also contributed to the improved recall ability. However, given the various factors discussed above that may influence performance, it is only a tentative suggestion.

No group effects were observed for any statistical analyses conducted for the memory recall test. This indicates that while the different road widths used in prolonged drive induced different changes in performance and psychophysiological responses between the groups, it had no influence on the participants' recall ability.

As with the Fitts' task, the results from the memory recall task support an effort-regulation account of performance control. However, unlike the Fitts' task, where participants traded accuracy for speed, in the memory recall task speed was traded for accuracy. If a resource

account were to have dominated, one may have seen similar trade-off strategies, but there would have been an associated increase in cognitive effort to compensate for resource depletion. However, such was not the case.

5.3.3 COGNITION (READING TASK)

The task was a visual scanning and object recognition task, implemented to probe resources used in central processing. As per the differential approach, the two difficulties used in the current study were varied according to text resolution. The *easy* variation was a high-resolution text set to 300 dots per inch, and the *difficult* variation was a low-resolution text set to 60 dots per inch (Figure 13 and Figure 14). The texts comprised of both contextual and non-contextual errors.

There was a significant *difficulty* effect observed for all indices of reading performance (Table XLVI), which validates that object recognition for the low-resolution text was more difficult than for the high-resolution text. The significant *difficulty* effect is in line with previous studies (e.g. Ziefle, 1998; Chaplin, 2010), which found poorer image quality (low resolution) to induce greater visual information processing impairments than did better image quality. In contrast, Miyao (1989) found no changes in reading speed between high-resolution and low-resolution text. This is confirmed by differences in all heart rate and heart rate frequency responses, which reflected neither significant nor numerical differences between the *easy* and *difficult* variations (Table XLVI). However, blink behaviour was not sensitive to changes in text resolution (Table LIV and Table LV).

Reading performance improved significantly from pre- to post-task, in the sense that participants read faster (Figure 54) but showed no changes in error recognition (Table XLVI). The reader will recall that the instruction given to the participants was to read as thoroughly as possible, and at the same time as fast as possible.

In all performance tasks, there must be a factor to account for any changes in performance. Typically, these changes are quantified in terms of performance trade-offs. In this way, the speed–accuracy trade-off posits that if there is an increase in reading speed, there should be a concomitant decrease in error recognition (Wickelgren, 1977). However, this trade-off was

not immediately apparent in the reading task, as participants identified the same number of errors post-task while reading speed increased. The question, therefore, is what factors could account for this performance increase? There are two candidate explanations: Either participants invested greater effort or there was a learning effect. To address the effort hypothesis, one must consider the responses of the physiological system.

Changes in cardiovascular responses from pre- to post-reading task mirror exactly the changes in responses seen for the memory task discussed above, which concluded that participants were in a down-regulated state in the post-task than the pre-task. For the reading task, this same trend is evidenced by the decreased heart rate (Figure 57), increased heart rate variability (Figure 58) and balancing of the two branches of the autonomic nervous system (LF and HF power both increased, Figure 60 and Figure 61). There were, however, no changes in oculomotor parameters. Though, as blink behaviour is attention-driven (Schleicher, 2008), and reading performance increased, one would not expect to see impairments in blink behaviour – if anything, one would expect to see improvements. Taken together, these physiological data suggest that it is unlikely that improvements in reading performance are due to increase in cognitive effort, which leaves the suggestion that a combination of learning and task strategy is a more likely explanation. Learning effect refers to participants becoming better adapted to recognising errors in the task. The influence of a learning effect would account for how reading speed increased post-task without impairing error-recognition ability.

While a learning effect is a simple and therefore an attractive explanation for the observed trend, it is questionable whether it is the only factor mediating performance. There is ample evidence to support the notion that in fatigued states individuals alter their adaptive strategies to keep performance at an acceptable level under adverse internal circumstances (see Boksem, 2008 for a review). The learning proposition reintroduces the possibility of a speed-accuracy performance trade-off explanation.

According to the classification set out by Norman and Bobrow (1975), the reading task is data-limited as there is a finite number of errors that can be detected, or there exists an upper limit of performance, if you like. However, unlike the Fitts' and digit recall tasks, the reading task is exclusively self-paced. That is to say, participants were free to choose their own

reading strategy, whether to read slower but more accurately, or to read faster but less accurately. The withdrawal of effort in the post-task may explain a shift in reading strategy, moving towards a prioritisation of reading speed. As intimated before, speed–accuracy trade-off predicts that this should be accompanied by a decrease in error recognition. As a learning effect suggests that participants improve their object recognition ability, it is possible that this might account for why there were no accuracy impairments.

Taken together, these results indicate that prolonged simulated drive does not impair resources utilised in higher order cognitive functions, where the increase in performance is accounted for by a complimentary combination of a shift in task strategies and a learning effect. Thus, the interpretation thereof tentatively supports the hypothesis that performance is controlled via an effort-regulation mechanism (Hockey, 1997). Outside of this interpretation, there are few viable explanations for trends discussed above.

5.4 RESPONSES TO HYPOTHESES

Sub-maximal Drive

1. The null hypothesis states that all performance, psychophysiological and subjective responses will remain unchanged between the beginning and the end of the sub-maximal drive.

Response: Significant differences were established between the beginning and end of the sub-maximal drive for lane deviation, heart rate, heart rate variability (time-domain and frequency-domain), blink frequency, blink duration and Borg CR-10, therefore the null hypothesis is rejected.

2. The null hypothesis states that all performance, psychophysiological and subjective responses between three experimental groups will remain unchanged in the sub-maximal drive.

Response: There was a significant difference calculated between the groups for lane deviation, therefore the null hypothesis is rejected for this measure. Alternately, the null hypothesis is tentatively accepted for all the other measured variables.

3. The null hypothesis states that all performance, psychophysiological and subjective responses between three experimental groups will remain unchanged between the beginning and end of the sub-maximal drive.

Response: Significant differences were established between the beginning and end of the sub-maximal drive and between the three experimental groups for lane deviation, heart rate variability (time-domain and frequency-domain), therefore the null hypothesis is rejected for these variables. Alternately, the null hypothesis is tentatively accepted for all the other measured variables.

Maximal Drive

4. The null hypothesis states that there will be no difference between PRE- 1 and PRE- 2 maximal drive tests performance, psychophysiological and subjective responses.

Response: Significant differences were established between PRE- 1 and PRE- 2 for

LF:HF ratio, blink frequency and Borg CR-10, therefore the null hypothesis is rejected for these variables. Alternately, the null hypothesis is tentatively accepted for all the other measured variables.

5. The null hypothesis states that there will be no difference between POST- 1 and POST- 2 maximal drive tests performance, psychophysiological and subjective responses.

Response: Significant differences were established between POST- 1 and POST- 2 for heart rate frequency, LF power, LF:HF ratio and Borg CR-10, therefore the null hypothesis is rejected for these variables. Alternately, the null hypothesis is tentatively accepted for all the other measured variables.

6. The null hypothesis states that there will be no difference between POST- 1 and POST- 2 maximal drive tests performance, psychophysiological and subjective responses.

Response: Significant differences were established between POST- 1 and POST- 2 for heart rate frequency, heart rate variability (time-domain), LF power and Borg CR-10, therefore the null hypothesis is rejected for these variables. Alternately, the null hypothesis is tentatively accepted for all the other measured variables.

Resource Tests

7. The null hypothesis states that there will be no difference in performance responses between pre- and post- for all resource specific-tests.

Response: Significant differences were established for response time and target deviation in the Fitt's tapping task, number of correctly recalled digits in the digit recall task, and reading speed in the reading task, therefore the null hypothesis is rejected for these variables. Alternately, the null hypothesis is tentatively accepted for all the other measured variables.

8. The null hypothesis states that there will be no difference in physiological responses between pre- and post- for all resource-specific tests.

Response: Significant differences were established for physiological responses between pre- and post- for all resource-specific tests, therefore the null hypothesis is rejected for these variables.

9. The null hypothesis states that there will be no difference in oculomotor responses between pre- and post- for all resource-specific tests.

Response: No significant differences were established for oculomotor responses between pre- and post- for all resource-specific tests, therefore the null hypothesis is accepted for these variables.

10. The null hypothesis states that there will be no pre- and post- difference in performance responses between the two difficulty variations for the Fitts' tapping task. I.e. there is no differential effect.

Response: There was a differential effect calculated for response time in the Fitts' tapping task, the null hypothesis is therefore rejected for these variables. Alternately, the null hypothesis is tentatively accepted for all the other measured variables.

11. The null hypothesis states that there will be no pre- and post- difference in performance responses between the two difficulty variations for the digit recall task. I.e. there is no differential effect.

Response: There was a differential effect calculated for percentage digit correctly recalled in the digit recall task, the null hypothesis is therefore rejected for these variables. Alternately, the null hypothesis is tentatively accepted for all the other measured variables.

12. The null hypothesis states that there will be no pre- and post- difference in performance responses between the two difficulty variations for the reading task. I.e. there is no differential effect.

Response: No differential effect was calculated for the reading task, the null hypothesis is therefore accepted for these variables.

CHAPTER VI

CONCLUSION

This chapter brings together the work presented in previous chapters. It highlights the results of this research in light of the original aims of this thesis, discusses some of the issues that have arisen with the methodology, results and interpretation thereof, and suggests directions for future work.

Firstly, a summary of each of the previous chapters is presented. Then, Section 6.2 evaluates the results of this research followed by a section reflecting on potential limitations of the current study. Section 6.4 concludes with an outline of future work that should be addressed to better understand the control mechanisms of driver performance.

6.1 SUMMARY

Chapter 1: Introduction

In Chapter 1, the issue of driver fatigue was introduced through its burden on society in terms of lives lost. Driver error contributes towards 90% of road accidents. Amongst these, fatigue is seen as one of the main contributing factors to accidents. Fatigue can be caused by the body's natural sleep/wake cycle and a lack of sleep, but it can also be caused by characteristics of the task. While many of these task factors have been researched extensively, little research focuses on the processes underlying the control and maintenance of driving performance in these conditions.

With this in mind, the central aims of this thesis were defined to be an investigation into two leading control mechanisms of driver performance, how they relate to the development of fatigue with time on task, and whether they impact on the ability to mobilise resources at the different levels of information processing.

Solving this problem could result in a better ability to predict performance breakdowns in different situations and under different stresses, which would inform more effective fatigue management strategies and countermeasures.

Chapter 2: Review of Literature

In this chapter, fatigue theories were surveyed and fatigue was defined as “a general psychophysiological phenomenon, which diminishes the ability of the individual to perform the driving task”.

The concept of fatigue was unpacked before it was considered within the context of driving. Sources of fatigue were also identified. Amongst them, sleep-related factors, task-related factors and individual differences were explored and have been shown to significantly influence driving performance and fatigue development.

This review further outlines the basic concepts related to information processing, and explains the functioning of the conceptual model of human information processing. Following from this is the description of two candidate mechanisms proposed to underlie the control of driving performance, and how each accounts for performance impairment. These are based on Resource Theory and Effort-Regulation Theory.

Lastly, the various types of measures used to assess the breakdown of performance were explored. These included behavioural measures, psychophysiological assessments and subjective assessments. These variables can be collected during driving and can be used to observe the fatigue state of the driver.

Chapter 3: Methodology

Chapter 3 outlined the experimental concept and the design methodology used in this thesis. It aimed to create driver fatigue due to the prolonged driving task and assess the extent to which this fatigue could be explained by resource depletion theory or Effort-Regulation Theory. Factors influencing sustained attention were controlled, particularly fatigue, time on task and circadian rhythms. All driving scenarios are sustained attention tasks, with driving being reduced to a lane-keeping task at a constant speed. Driver task-demand was varied through the road design (small, medium, or large road width).

Various behavioural, psychophysiological and subjective assessments were used to assess driver fatigue throughout the experiment. These were collected, analysed and presented in

the next chapter. These measures have been shown to modify the onset and manifestations of driver fatigue. They include vehicle control performance, heart rate measures, blink behaviour, resource utilisation and participant factors. All psychophysiological data were collected at a rate that allowed real-time assessment of fatigue development.

This chapter also covered the major components of the implementation of the driving simulator study. Equipment available to implement this study included a low-fidelity driving simulator – which provided the simulated environment as well as the variables from the car. The heart rate device used was a Polar™ T34 heart rate belt and receiver and the temperature devices used were forehead temperature sensor, the measures from which were captured on the Biometrics DataLOG MWX8. The eye-tracking device used was the Dikablis Gaze Analytic System. All psychophysiological data were synchronised, and analysed simultaneously using the Data Reduction and Analysis Tool.

6.2 THESIS OUTCOMES

6.2.1 Original Aims

The original aims stated in Chapter 1 were to investigate the predictions of two leading candidate mechanisms proposed to account for driving performance decrement over time, and to assess whether and to what extent this impacted on information processing.

More precisely, the thesis proposes to answer the following research questions:

- How does the degradation of driving performance in a prolonged simulated driving task manifest in behavioural, psychophysiological and subjective assessments?
- Based on these assessments, which of Resource Theory and Effort-Regulation Theory best accounts for degradation of driving performance in a prolonged simulated driving task?
- Does prolonged driving differentially tax different information processing stages?

By achieving the objectives, this thesis sought to provide greater insight into control mechanisms of driver performance, how they relate to the development of fatigue with time on

task, and whether they impact on the ability to mobilise resources at the different information processing stages.

6.2.2 Proposed Method

The method proposed to achieve this was to induce fatigue in a prolonged simulated driving task. To test the prediction of each theory, participants were divided into three experimental groups for the sub-maximal drive, each of which comprised of a different road width with a different task-demand. In addition to this, a proposed pre/post differential approach was used to assess the impacts of this task on information processing. Each task had two difficulty variations to assess whether any fatigue responses could be isolated to a specific resource. The tests to probe information processing were: a modified Fitts' tapping task for motor programming, a digit recall task for perception, and an object recognition reading task for cognition. In addition to performance variables, cardiovascular and oculomotor measures were recorded continuously.

6.2.3 Conclusions

Although there are studies that have attributed fatigue to both resource depletion (Warm *et al.*, 2008) and effort-regulation (Hancock and Warm, 1989; Fairclough, 2001; Matthews and Desmond, 2002), as well as those that have investigated the impact of resource depletion and effort-regulation on workload transition in automated driving (Funke, 2007), to the author's knowledge the current study is the first to exclusively approach driver fatigue from both theoretical perspectives while taking into account a combination of performance and psychophysical responses. Such a perspective has important implications.

For example, this study has shown that effort-regulation (Hancock and Warm, 1989) dominates the control of performance in prolonged driving. This has the pressing implication that effort-regulation is not dependant on the workload of the task. Rather, time on task seems to be the most important factor in fatigue development.

Further, the finding that information processing was not influenced by the varying task-demands via which fatigue was induced (road widths) indicates that the impact of fatigue is

guided more by task goals and intrinsic motivation than by the manner in which the fatigue state developed.

In this context it is necessary to assume that these factors probably interact to influence task performance. Caution should nonetheless be practiced when seeking to assign causality.

Another interesting implication is that effort-regulation does not impact on resource utilisation for any of the information processing stages. There is a general decrement in performance between pre- and post- resource tests, however this is due in large part to a withdrawal of attentional effort to satisfy goals of personal comfort. Where differential effects did exist, performance was actually seen to improve. The effect was generally accounted for by a limitation in task characteristic, i.e. the tasks were data-limited. This implies that information processing is not fundamentally changed under the type of fatigue observed herein.

6.3 REFLECTION

Although the current study provides some insight into the control mechanisms of driving performance, there were also a number of aspects regarding the methodology, results and interpretation thereof that should be acknowledged.

6.3.1 Sample

Firstly, three independent same groups were used in the current study, which compounded the impact of individual variability, in terms of performance, psychophysiological and behavioural responses. While provision was made to accommodate these variances (time of day, sleep instructions, morningness-eveningness, diet/caffeine restrictions, activity restrictions), not all extraneous variables could be accounted for and delimited. These included such factors as personality type and emotional state. Individuals were, however, excluded from the study if they had a history of sleep disorders, epilepsy, or any attention-related disorders.

Next, a relatively small sample size of 8 participants per group (three conditions = 24 participants) is used in this research due to limitations in both time and participant availability. A repeated-design would have been preferable, as this would have minimised the possible

variance in the data and increased statistical power. However, this was not possible due to issues of deception, ethics and recruitment. Deception of task length and order was a critical aspect of the protocol; knowledge of test length and end-point may have influenced behaviour. Thus, a repeated-design would have invalidated the objectives of the deception. Further, exposing participants to three 2-hour testing sessions raised serious ethical concerns, and would not have been approved by the Ethics Committee. Participants were not given incentives to participate in this study, as it was important that they had no extrinsic motivation to complete the task or change intrinsic task goals. This was an important delimitation that ensured that under the current conditions, resource model and effort-regulation model had the same chance of dominating. However, this factor made it more difficult to recruit participants. University students are over-represented in the samples used in this study. While the consequences of such bias are unclear, it still represents a potential limitation.

Participant chronotype was assessed via an adapted Morningness-Eveningness questionnaire (Horne and Ostberg, 1979). However, as none of the participants were judged as “definitely morning” or “definitely evening” type, this variable was not considered as an important variable, especially as all testing occurred during the day. With regard to testing time, half of the participants performed the experiment between 9:00-11:30am, while the other half were tested between 2:30-5:00pm. Gender was evenly distributed between the groups and between testing times. As all participants fell within a very narrow age range (18–23 years; mean age= 22.50 years, SD=2.87), it was not considered in the group distribution.

6.3.2 Equipment

There was a limitation with regard to the type and amount of equipment at the researcher’s disposal. Given the multidimensional nature of fatigue, it is desirable to use as many assessment tools as possible when studying the phenomenon (Hitchcock and Matthews, 2005). This certainly applies to the psychophysiology of driver fatigue and the mechanisms underlying its development. For example, despite its limitations, EEG has been used extensively and may therefore have provided additional insights into the distinction between resource depletion and effort of regulation on a psychophysiological level (Lal and Craig, 2002; Tejero and Choliz, 2002).

The Polar™ T34 heart rate memory belt used in this study was originally designed for cross training, running etc. and not specifically for general cognitive tasks. While the Polar™ heart rate memory belts have been validated against ECG recordings (Kingsley *et al.*, 2005; Porto and Junqueira, 2009) there is still the likelihood of error. These studies reported that variation in responses in comparison with the conventional ECG machine were $\pm 2 \text{ beats/min}^{-1}$ which, according to Kingsley *et al.* (2005), is sufficient for heart rate variability analysis.

6.3.3 Tasks

For good reason, safety research is inclined to test human capabilities at the maximum limit. However, while the methodologies¹⁰ typically employed in driver fatigue research (e.g. Matthews and Desmond, 2002; Birch, 2012; Robertson, 2012) can boast level of control over extraneous variables, the parameters influencing fatigue development, and safety of the experiment, they often induce fatigue states that are much more severe than what is representative of real-world driving scenarios, or at least achieve a fatigue state much more rapidly (Akerstedt *et al.*, 2005). Certainly, lack of environmental stimulation, such as long straight roads, has been linked to fatigue-related crashes (Thiffault and Bergeron, 2003b; Oron-Gilad and Ronen, 2007). Caution should therefore be used when attempting to extrapolate the results from this study, and indeed similar studies, to real world driving. Naturalistic driving studies are much more suitable in this regard, though the ethical limitations are acknowledged, to say nothing of the complexity inherent in real-world driving.

The nature of fatigue is such that it cannot be measured directly, we can only use indirect measures to infer its presence (Lal and Craig, 2002). Of course, this depends very much on the way in which one defines fatigue, the backdrop against which it is considered, and the particular measures used to assess it (Hitchcock and Matthews, 2005). Given all the factors and combinations thereof, it is difficult to know whether or to what extent the interaction of the mechanisms under investigation (resource and effort-regulation) might function differently under even slightly different conditions from those tested in this study, let alone in vastly different experimental and *in situ* contexts.

¹⁰ Typically, these include simulator characteristics and task duration.

A further limitation relates to the pre/post tasks used to probe resource utilisation. There is evidence to suggest the mere act of switching tasks increases arousal and elevates the level of cerebral activity, which in turn may mask any signs of fatigue (Grandjean, 1979). A dual-task, direct assessment was initially considered for the current study. However, this approach, too, has been shown to have its limitations. For example, in a study investigating the impact of workload on active and passive fatigue in a prolonged driving task, Birch (2012) found driving performance to increase during concurrent attendance to both a digit recall task and a choice response time task. Moreover, a more direct approach would not have allowed for a differential approach to be used, which was an essential aspect to the aims and outcomes of the current study. Nevertheless, if it is the case that a change of task led to a masking of any fatigue-related performance decrements, then it simply points towards a recommendation as a fatigue management strategy.

In terms of the Fitts' task, integrating the two difficulty variations into one task prevented the possibility of attributing any difficulty-related performance changes to specific psychophysiological states. However, analysing the responses according to the well-established Fitts' law tentatively mitigated this limitation.

The resource-specific tests used in the current study, while based on established principles and laws, are not validated in the way that other, more widely used tests are. There was due consideration of such tests, however none of the candidate standard tasks would have allowed for the manipulation of task characteristics in such a way as was necessary to answer the research question. A consequence of using these non-validated tests is that their outcomes cannot easily be compared with other studies of a similar nature.

While the habituation session was used to facilitate familiarisation of the various resource-specific tasks, it was not possible to habituate participants up to the asymptotic performance level. Thus, the influence of learning was an unavoidable factor in the current study.

6.3.4 Individual Differences

Another limitation is that this study cannot answer questions about subjective behavioural responses and individual difference issues. First, there is the question of whether the

assessment used in the current study (CR-10) was able to adequately quantify subjective approach to task control. Indeed, this consideration is not as important to understand the phenomenon from a Kahneman (1973) resource view as it is from the effort-regulation view, which embodies a greater motivational component in its core assumptions. However, various factors prevented a greater subjective assessment: Interaction with participants during the drive had to be limited as much as possible, as the main aim was to assess the development of fatigue from not only a performance point of view, but also a psychophysiological point of view. Extensive subjective assessment during the course of the prolonged drive, as would be required for NASA-TLX workload assessment for instance, may have altered behaviour and therefore confounded results. Indeed, Buck-Gengler and Healy (2001) observed performance improvements after only a brief task interruption after 30 minutes of work. Post-task assessments were not favourable either, as it would have required participants to recall subjective ratings of workload back over an extended protocol that consisted of a number of different tasks, to say nothing of the challenge the participants would face in attempting to recall subjective differences between the difficulty variations.

As the behavioural component of effort-regulation is assumed to be both conscious and subconscious, it begs the question whether subjective ratings would be sensitive enough to isolate any relevant effects. Nonetheless, in the current study, participants reported an increasing investment of subjective effort as time elapsed. However, this is inconsistent with the observations of effort from a psychophysiological point of view, where HRV showed effort to be progressively withdrawn with time on task - in a study on task aversion, Sunshine (2013) found subjective effort to be related to task duration and not changes in task difficulty. This suggests that a subconscious withdrawal of effort may account for why task-demand is said to increase with time on task.

There is some variability between individuals' capacity to resist fatigue (Thiffault and Bergeron, 2003a), especially along the introversion/extroversion dimensions of personality types (Eysenck, 1967). This study did not consider the potential impact that personality types may have on the development of fatigue. Thus, further studies might consider these distinctions in relation to the findings presented herein.

6.3.5 Potential Bias

Hitchcock and Matthews (2005) propose that the range of constructs sampled on different fatigue instruments is highly variable. For example, different measures are sensitive to different effects, thus one would expect different constructs to emerge. In much the same way, as the fatigue induction task used in the current study (sub-maximal drive) may satisfy the concept of underload and overload from an effort-regulation perspective, it may not from a resource perspective. That is, the *small* road condition, while still the most challenging of the three, may not have been sufficiently taxing to induce the extreme resource depletion necessary to be reflected in the resource-specific test-battery. This would render the current methodology inherently biased towards inducing effort-regulation behaviour as opposed to resource depletion behaviour. The reader will recall that the strength of Resource Theory is rooted in its ability to predict performance breakdown in an overload situation (Wickens, 2002). Thus, if this methodology failed to provoke that breakdown it is no fault of the theory, but simply a highlight of its limitation.

6.4 FURTHER WORK

Future work on control of driving performance should assess the impact of knowledge of task endpoint, both on driving control and on whether it may change the extent to which effort-regulation behaviour might dominate. This is relevant, as many current in-vehicle information systems provide real time feedback regarding journey end time based on vehicle location and speed in relation to the destination.

This research has raised questions about the impact of road design on driving performance. It would be informative to assess whether a greater number of stimuli in the road scenery would alter the validity of the two control mechanisms on explaining driving performance.

Previous studies have demonstrated that tasks requiring cognitive engagement during driving may improve driving performance over prolonged drives. However, it is not known whether and to what extent this influences resource allocation and task-directed effort. Therefore, it would be interesting to assess whether intermittent dual-task attendance would alter effort-

regulation. Certainly, resource theories are known to be able to predict performance breakdown in such overload contexts.

Furthermore, and as noted, different personality types have been shown to be differentially sensitive to fatigue. In light of the outcomes of the current study, it would be interesting to assess whether effort-regulation and resource depletion account are more or less valid for the different personality dimensions. In this context, it would be essential to correlate measures of performance, psychophysiology and personality.

A typical fatigue state is usually spawned from a combination of causal factors. These combinations are known to affect varying safety and performance outcomes. Only task-related fatigue was examined in the current study. Thus, it is relevant to investigate whether the mechanism controlling driving performance changes according to the contribution of causal factors to the fatigue state. Indeed, recommendations based on the effort-regulation model may differ according to contributions of sleep-related or task-related factors.

This study shows that effort-regulation dominates over a 90-minute drive. However, as many vehicle crashes occur during micro-sleeps, it would be interesting to examine whether Resource Theory and Effort-Regulation Theory present similar control over performance fluctuations in short-term breakdowns.

Currently, there is no efficient countermeasure against road accidents related to fatigue. While there exists no precise definition of fatigue, the results of this study may help researchers differentiate the several control mechanisms of driving performance. The methodology developed in this study may also provide a means to assess the impact of various stressors on the different levels of human information processing.

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APPENDIX A: GENERAL INFORMATION

1. Letter to the participant
2. Pre-screening questionnaire (including Morningness-Eveningness questionnaire)
3. Informed consent form
4. Ethical clearance

APPENDIX A1: LETTER OF INFORMATION TO THE SUBJECT

Dear _____

Thank you for agreeing to participate in this study, titled “**AN INVESTIGATION INTO CONTROL MECHANISMS OF DRIVING PERFORMANCE: RESOURCE DEPLETION AND EFFORT-REGULATION**”. Your contribution is greatly appreciated. This document contains information regarding the research that will be carried out and how you will be assisting in this regard, as well as the potential risks and benefits involved. Also attached to this document is a consent form that you have to sign prior to commencing with the testing. Please ensure that you read everything carefully before signing. Should you be uncertain about anything or want further explanation, please do not hesitate to contact the researcher, who will attempt to timeously address any queries.

PURPOSE OF RESEARCH/ STUDY

The aim of this study is to determine whether a decrement in prolonged driving is due to cognitive resource depletion or effort-regulation. In driving, fatigue provokes many accidents in otherwise unassuming environments. Some of these fatigue effects can be explained by a lack of sleep, circadian regulation or physical exhaustion. However, there are many instances where drivers present none of these factors, but claim to have fallen asleep behind the wheel, suggesting mental fatigue is to blame. Despite the vast amount of research into driver fatigue, it is still unknown as to whether this type of driver fatigue is due to cognitive down-regulation (your brain “switching off” to conserve energy) or cognitive resource depletion (where your brain no longer has the capacity to maintain attention). If it is resource depletion, we need to know whether it is resource specific or whether it is a general effect, as this has huge implications in terms of how one designs countermeasures. It would also be interesting to understand how the information processing chain is affected if effort-regulation dominated during the task. This study measures the psychophysiological responses, the subjective responses as well as performance output and behaviour in different driving settings to determine if and to what extent performance decrements are due to cognitive resource

depletion or effort-regulation. The findings of this study will assist in determining more efficient fatigue management strategies, and more effectively designed in-vehicle information systems.

PROCEDURES

You will be required to attend two laboratory sessions at the Human Kinetics and Ergonomics Department. In the initial session (lasting no longer than 30 minutes) you will be introduced to the equipment (heart rate monitor and eye tracker) and procedures, and allowed to practice driving on the driving simulator until you feel comfortable enough to perform the task. Any questions or concerns you have about the testing protocol are welcome. The second session will entail driving on the driving simulator continuously for an extended period of time. The heart rate monitor, temperature sensors and eye tracker will be attached and worn throughout the procedure. A perceived effort/fatigue rating will also be asked periodically, where you will be asked to rate the difficulty in maintain effort to perform the task. This will be assessed on a scale of 1 (very easy/alert) to 10 (very hard/struggling to maintain performance). I am not able to give you specific information about task length, as this will influence your subconscious coping strategies, which is what this study is trying to explore. However, testing will not take longer than 3 hours.

RISKS AND BENEFITS

It is unlikely that you will experience any injuries during this study, as the procedures are not considered harmful in any way. Due to the length and nature of the protocol, however, there is a possibility that you may feel slightly dizzy or nauseous. This feeling is transient, and should dissipate once you have stopped the task. If you feel uncomfortable and unable to complete the protocol please note that you are may request to stop the test at any point.

In the unlikely event of incurring an injury during the study as a result of the either the experimental protocol or equipment used, the Department of Human Kinetics and Ergonomics will be liable for any costs which may ensue and will reimburse the participant to the full amount i.e. doctors consultations, etc. The Department will also assist in applying rehabilitation sessions for the injury if need be. The Department will, however, waiver any legal recourse against the researcher or Rhodes University in the event the injury is proved to

be self inflicted or due to negligence on the part of the participant themselves. It is important to reiterate that the likelihood of the incurring injury during this protocol is highly unlikely.

Benefits derived from this study include exposure to equipment and technology that may otherwise be difficult to encounter. You will also contribute to an improved understanding of the demands placed on individuals in a wide array of work situations requiring sustained attention, for example long distance driving, in the hopes of preventing the dangerous performance failures that occur in real-life situations. This will ultimately make the work environment a safer and better place.

OTHER

All data collected will be coded, and thus you will remain anonymous with regards to your data and results. If at any stage you wish to withdraw from the study you may do so without any adverse consequences to you. If there are any queries involving the testing procedures or any other concerns you may have, the researchers details are provided at the end of this letter.

‘Dos’ and ‘Don’ts’

In the interests of limiting the effects of extraneous variables you are asked to please refrain from the following before coming for your data collection:

- Consuming alcohol 24 hours before testing
- Strenuous exercise/ activities 24 hours before testing
- Consuming caffeine 8 hours prior to testing
- Eating one hour before testing
- Medication such as stimulants or performance enhancers (Ritalin, Concerta)

If you do any of the above, please inform the researcher.

Thank you for your time and co-operation.

Yours sincerely,

Tyron Louw, BSc (Hons) (cum laude)

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APPENDIX A2: PRE-SCREENING QUESTIONNAIRE

(values in red for scoring not shown to participants)

Please note that you are exempt from this study if:

- You do not have a **valid driver's license**
- You have any **sleep disorders**
- You have a history of **epilepsy**
- You have **ADHD** or similar disorders

Name: _____

Sex: M / F

Age: _____

How many years driving experience do you have?

0-2 years	2-5 years	5+ years
1	2	3

How often do you drive long distance (over 1.5hours)?

Never	Less than once a month	More than once a month
0	1	2

Have you had any experience with the HKE driving simulator? If yes, how much?

No experience	Less than 1hr experience	More than 1hr experience
0	1	2

How often do you play video games?

Daily	A few times a week	Less than once a week	Never
3	2	1	0

How long do you play video games for at a time on average?

N/A	Less than 1 hour	1 – 3 hours	More than 3 hours
0	1	2	3

Morningness - eveningness Questionnaire

For each question, please select the answer that best describes you by circling the point that best indicates how you have felt in recent weeks.

1. If you were entirely free to plan your evening and had no commitments the next day, at what time would you choose to go to bed?

- 1. 20:00 – 21:00 5
- 2. 21:00 – 22:15 4
- 3. 22:15 – 00:30 3
- 4. 00:30 – 01:45 2
- 5. 01:45 – 03:00 1

2. You have to do 2 hours physically hard work. If you were entirely free to plan your day, in which of the following periods would you choose to do the work?

- 1. 08:00 – 10:00 4
- 2. 11:00 – 13:00 3
- 3. 15:00 – 17:00 2
- 4. 19:00 – 21:00 1

3. For some reason you have gone to bed several hours later than normal, but there is no need to get up at a particular time the next morning. Which of the following is most likely to occur?

- 1. Will wake up at the usual time and not fall asleep again 4
- 2. Will wake up at the usual time and doze thereafter 3
- 3. Will wake up at the usual time but will fall asleep again 2
- 4. Will not wake up until later than usual 1

4. You have a 2 hour test to sit which you know will be mentally exhausting. If you were entirely free to choose, in which of the following periods would you choose to sit the test?

- 1. 08:00 – 10:00 4
- 2. 11:00 – 13:00 3
- 3. 15:00 – 17:00 2
- 4. 19:00 – 21:00 1

5. If you had no commitments the next day and were entirely free to plan your own day, what time would you get up?

- 1. 05:00 – 06:30 5
- 2. 06:30 – 07:45 4
- 3. 07:45 – 09:45 3
- 4. 09:45 – 11:00 2
- 5. 11:00 – 12:00 1

6. A friend has asked you to join him twice a week for a work-out in the gym. The best time for him is between 10pm - 11pm. Bearing nothing else in mind other than how you normally feel in the evening, how do you think you would perform?

- | | |
|--------------------|---|
| 1. Very well | 1 |
| 2. Reasonably well | 2 |
| 3. Poorly | 3 |
| 4. Very poorly | 4 |

7. One hears about 'morning' and 'evening' types of people. Which of these types do you consider yourself to be?

- | | |
|--|---|
| 1. Definitely morning type | 6 |
| 2. More a morning than an evening type | 4 |
| 3. More an evening than a morning type | 2 |
| 4. Definitely an evening type | 0 |

Morningness - Eveningness Scale

- | | |
|----------------------------------|---------|
| 1. Definitely morning type | 32 - 28 |
| 2. Moderately morning type | 27 - 23 |
| 3. Neither type | 22 - 16 |
| 4. Moderately evening type..... | 15 - 11 |
| 5. Definitely evening type..... | 10 - 6 |

Thank you for your time! I will get hold of you either via email or text message to set up a time for testing!

If you have any questions, please don't hesitate to get hold of me.

Tyron

(071 863 6730; g07l3737@campus.ru.ac.za)

APPENDIX A2: SIGNED CONSENT

I, _____, do hereby consent to participate in the study entitled:

“AN INVESTIGATION INTO CONTROL MECHANISMS OF DRIVING PERFORMANCE: RESOURCE DEPLETION AND EFFORT-REGULATION”

I have read the information sheet and understand the testing procedure that will take place. I have been told about the risks as well as benefits involved, as well as what will be expected of me as a participant. I understand that all information gained from this project will be treated confidentially, that I will remain anonymous at all times and that data obtained may be used and published for statistical or scientific purposes. All testing procedures, associated risks and the benefits from partaking in this study have been verbally explained to me as well in writing. I have had ample opportunity to ask questions and to clarify any concerns or misunderstandings. I am satisfied that these have been answered satisfactorily.

In light of this, and in agreeing to participate in this study, I accept joint responsibility together with the Human Kinetics and Ergonomics Department, in that should any accident or injury occur as a direct result of the protocols being performed during the study, the Human Kinetics and Ergonomics Department will be liable for any costs which may ensue and will reimburse the participant to the full amount. I.e. doctor's consultation, medication, etc. The department will, however, waive any legal recourse against the researchers of Rhodes University, from any and all claims resulting from personal injuries sustained whilst partaking in the investigation due to negligence on the part of the participant or from injuries not directly related to the study itself. This waiver shall be binding upon my heirs and personal representatives.

Please note that if you feel that you need to withdraw from the study, you can do so at any stage. Should you have any questions regarding the study, please do not hesitate to contact the researcher. Thank you again for your participation; your assistance is greatly appreciated.

I have read and understood the above information, as well as the information provided in the letter accompanying this form.

I therefore consent to voluntarily participate in this research study.

Signed at the Department of Human Kinetics and Ergonomics, Rhodes University, on _____
(Date) 2012.

PARTICIPANT

(Print name)

(Sign)

RESEARCHER

(Print name)

(Sign)

WITNESS:

(Print name)

(Sign)

WITNESS:

(Print name)

(Sign)

APPENDIX A4: ETHICAL CLEARANCE



Human Kinetics and Ergonomics Ethics Committee Report



RHODES UNIVERSITY
Where leaders learn

Student Name: Tyron Louw
Type of Research: Masters Research Project
Project Title: DRIVER FATIGUE – EFFORT REGULATION OR RESOURCE DEPLETION?
Supervisor: Dr Zschernack
Report compiled: 27 August 2012

Approved 	Approved, on condition that suggestions have been effected	Request for rework and resubmission	Rejected
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Remark:

The committee has provided ethical clearance for your research.

I wish you luck with your research!

Signed

Al Todd
Chair: Human Kinetics and Ergonomics Ethics Committee

APPENDIX B: DATA COLLECTION

1. Habituation order of procedures
2. Borg CR-10 Scale
3. Driving simulator system parameters
4. Permutation Table

APPENDIX B1: HABITUATION ORDER OF PROCEDURES

- 1. Welcome and Introduction**
- 2. Hand out participant letter**
- 3. Explanation of project**
- 4. Experimental set up; pre- and post- tests**
- 5. Each participant will then be exposed to the equipment and testing procedures for each aspect of the protocol:**
 - a. Heart rate
 - b. Fitts' tapping test
 - c. Reading test
 - d. Digit recall test
 - e. Subjective rate of perceived exertion
 - f. Eye-tracking
- 6. Questions**
- 7. Pre-screening questionnaire: Explanation: answer as honestly as you can**
- 8. Take anthropometrics**
- 9. Don'ts:**
 - a. No alcohol or drugs 48 hours before testing
 - b. No caffeine 24 hours before testing and no caffeine during testing – no energy drinks such as Red Bull or Coffee.
 - c. No alertness enhancing drugs – BioPlus, energy tablets, etc.
 - d. No Smoking
- 10. Do:**
 - a. Get a good night's sleep before your testing day.
 - b. Ask questions
 - c. Feel free to leave the study if you are at any stage not comfortable with the study
 - d. Please report any injuries, illnesses or medicines being take to the researcher
- 11. Set up date and time for testing session**

APPENDIX B2: BORG CR-10 SCALE

rating	description
0	NOTHING AT ALL
0.5	VERY, VERY LIGHT
1	VERY LIGHT
2	FAIRLY LIGHT
3	MODERATE
4	SOMEWHAT HARD
5	HARD
6	
7	VERY HARD
8	
9	
10	VERY VERY HARD (MAXIMAL)

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for more information see <http://www.transdynamics.com/testimonials.htm>

APPENDIX B3: DRIVING SIMULATOR SYSTEM PARAMETERS

Table LVI: Parameters used in the “system parameters” menu.

Parameter	Description	Value
Distance to footprint	Virtual distance of an observer to the arrowhead/bonnet	2,237 m
Viewing skew	Angle of inclination of the image section shown on level	8.5°
Street line width	Width of tracking line	3 Pixel
Object appearance	Colours	R/G/B
Background	Background (sky)	000/176/176
Vehicle	Vehicle (arrow/bonnet color)	253/241/162
Ground Floor	Environment	104/250/060
Street	Street	130/130/130
Street line	Tracking Line	080/080/080

The distance travelled was adjusted according to the settings in the “Driving parameter” with the factors listed in Table LVII.

Table LVII: Parameters used in the “driving parameters” menu.

Parameter	Description	Value
Curve radius	Range of curve radii of the generated curve segments	10-90 m
Curve length	Bandwidth of the length of the curve segments in the square	1°- 3°
Same direction	Number of segments which follow each other in the same direction	1- 4
Segment resolution	Resolution generated for curve radii for each segment	0,5°
Driving speed	Relative value of the road speed	Variable
Street width	Relative value of the width of the road	Small group: 0,5m Maximal Drive and Medium group: 0,8m Large group: 1,1m
Steering wheel	Sensitivity of wheel	0.7

APPENDIX B4: RESOURCE TEST PERMUTATION TABLES

Table LVIII: Resource test permutation tables.

SUBMAX DRIVE GROUP: Small: 0,5m					
1	Fitts	Read 300	Read 60	Mem 7	Mem 5
2	Read 60	Fitts	Mem 7	Mem 5	Read 300
3	Read 300	Mem 7	Fitts	Read 60	Mem 5
4	Mem 7	Mem 5	Read 300	Fitts	Read 60
5	Mem 5	Read 60	Mem 7	Fitts	Read 300
6	Fitts	Mem 7	Read 300	Mem 5	Read 60
7	Read 60	Read 300	Mem 7	Fitts	Mem 5
8	Fitts	Read 300	Mem 7	Mem 5	Read 60

SUBMAX DRIVE GROUP: Medium: 0,8m					
1	Mem 7	Fitts	Read 60	Mem 5	Read 300
2	Mem 5	Read 60	Mem 7	Read 300	Fitts
3	Read 60	Read 300	Fitts	Mem 5	Mem 7
4	Fitts	Mem 7	Read 300	Read 60	Mem 5
5	Fitts	Mem 5	Mem 7	Read 300	Read 60
6	Mem 5	Fitts	Read 300	Read 60	Mem 7
7	Fitts	Read 60	Mem 7	Mem 5	Read 300
8	Read 60	Read 300	Mem 7	Fitts	Mem 5

SUBMAX DRIVE GROUP: Large: 1,1m					
1	Mem 5	Read 60	Read 300	Fitts	Mem 7
2	Read 300	Mem 7	Fitts	Read 60	Mem 5
3	Mem 5	Fitts	Mem 7	Read 300	Read 60
4	Read 60	Read 300	Mem 5	Mem 7	Fitts
5	Read 300	Mem 7	Read 60	Mem 5	Fitts
6	Read 60	Read 300	Mem 5	Fitts	Mem 7
7	Mem 5	Mem 7	Read 300	Read 60	Fitts
8	Fitts	Mem 7	Mem 5	Read 300	Read 60

APPENDIX C: STATISTICS TABLES

APPENDIX C1: Additional Statistical Tables

Sub-maximal drive

Sub-maximal drive: SDNN

Repeated Measures Analysis of Variance (Drive HRV SDNN.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 104.6862

	SS	Degr. of - Freedom	MS	F	p
Intercept	1615089	1	1615089	147.3727	0.000000
Condition	19240	2	9620	0.8778	0.430398
Error	230143	21	10959		
TIME	33670	17	1981	12.1049	0.000000
TIME*Condition	12440	34	366	2.2361	0.000156
Error	58412	357	164		

Sub-maximal drive: PNN30

Repeated Measures Analysis of Variance (Drive HRV PNN30.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 77.67803

	SS	Degr. of - Freedom	MS	F	p
Intercept	945560.4	1	945560.4	156.7086	0.000000
Condition	6938.5	2	3469.2	0.5750	0.571339
Error	126711.4	21	6033.9		
TIME	3680.5	17	216.5	5.4084	0.000000
TIME*Condition	1486.2	34	43.7	1.0919	0.337269
Error	14291.0	357	40.0		

Sub-maximal drive: PNN50

Repeated Measures Analysis of Variance (Drive HRV PNN50.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 81.31298

	SS	Degr. of - Freedom	MS	F	p
Intercept	331209.0	1	331209.0	50.09361	0.000001
Condition	2996.3	2	1498.1	0.22658	0.799176
Error	138847.8	21	6611.8		
TIME	4241.6	17	249.5	7.68452	0.000000
TIME*Condition	1407.3	34	41.4	1.27482	0.145305
Error	11591.4	357	32.5		

Sub-maximal drive: HF Centre frequency

Repeated Measures Analysis of Variance (Drive HRV HF Centre Freq.sta) Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: .0926198

	SS	Degr. of - Freedom	MS	F	p
Intercept	25.09933	1	25.09933	2925.863	0.000000
Condition	0.01599	2	0.00799	0.932	0.409544
Error	0.18015	21	0.00858		
TIME	0.02355	17	0.00139	8.222	0.000000
TIME*Condition	0.00740	34	0.00022	1.292	0.133023
Error	0.06016	357	0.00017		

Sub-maximal drive: HF Centre frequency

Repeated Measures Analysis of Variance (Drive HRV LF Centre Frequency.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0194191

	SS	Degr. of - Freedom	MS	F	p
Intercept	3.293480	1	3.293480	8733.624	0.000000
Condition	0.001476	2	0.000738	1.956	0.166282
Error	0.007919	21	0.000377		
TIME	0.001060	17	0.000062	1.785	0.028330
TIME*Condition	0.001619	34	0.000048	1.363	0.089860
Error	0.012470	357	0.000035		

Resource Tests

SDNN: Fitts' tapping task

Repeated Measures Analysis of Variance (Tests HRV SDNN.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 26.52151

	SS	Degr. of - Freedom	MS	F	p
Intercept	89042.06	1	89042.06	126.5897	0.000000
Condition	741.73	2	370.86	0.5273	0.597835
Error	14771.21	21	703.39		
PREPOST	2913.93	1	2913.93	9.4751	0.005703
PREPOST*Condition	817.21	2	408.61	1.3286	0.286199
Error	6458.24	21	307.54		

SDNN: Maximal drive

Repeated Measures Analysis of Variance (Tests HRV SDNN.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 42.72524

	SS	Degr. of - Freedom	MS	F	p
Intercept	234246.7	1	234246.7	128.3230	0.000000
Condition	1957.5	2	978.7	0.5362	0.592782
Error	38334.4	21	1825.4		
PREPOST	7864.1	1	7864.1	20.8219	0.000169
PREPOST*Condition	2861.8	2	1430.9	3.7886	0.039364
Error	7931.3	21	377.7		
R1VSR2	66.1	1	66.1	0.6234	0.438594
R1VSR2*Condition	473.0	2	236.5	2.2305	0.132318
Error	2226.6	21	106.0		
PREPOST*R1VSR2	0.0	1	0.0	0.0001	0.992222
PREPOST*R1VSR2*Condition	150.0	2	75.0	0.7963	0.464149
Error	1978.0	21	94.2		

SDNN: Reading task

Repeated Measures Analysis of Variance (Tests HRV SDNN.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 39.72749

	SS	Degr. of - Freedom	MS	F	p
Intercept	222270.1	1	222270.1	140.8311	0.000000
Condition	2400.0	2	1200.0	0.7603	0.479954
Error	33143.8	21	1578.3		
PREPOST	6226.2	1	6226.2	16.1968	0.000613
PREPOST*Condition	299.0	2	149.5	0.3889	0.682558
Error	8072.6	21	384.4		
EASYDIFF	288.4	1	288.4	3.0647	0.094606
EASYDIFF*Condition	222.1	2	111.1	1.1804	0.326710
Error	1975.9	21	94.1		
PREPOST*EASYDIFF	3.3	1	3.3	0.0655	0.800559
PREPOST*EASYDIFF*Condition	77.9	2	39.0	0.7726	0.474508
Error	1058.8	21	50.4		

SDNN: Digit recall task

Repeated Measures Analysis of Variance (Tests HRV SDNN.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 46.99047

	SS	Degr. of - Freedom	MS	F	p
Intercept	284290.1	1	284290.1	128.7484	0.000000
Condition	2534.1	2	1267.1	0.5738	0.571957

Error	46370.2	21	2208.1		
PREPOST	9388.0	1	9388.0	24.9028	0.000061
PREPOST*Condition	1100.2	2	550.1	1.4592	0.255044
Error	7916.7	21	377.0		
EASYDIFF	1097.8	1	1097.8	11.7440	0.002532
EASYDIFF*Condition	371.9	2	185.9	1.9890	0.161791
Error	1963.1	21	93.5		
PREPOST*EASYDIFF	28.8	1	28.8	0.5944	0.449323
PREPOST*EASYDIFF*Condition	25.6	2	12.8	0.2634	0.770956
Error	1019.1	21	48.5		

PNN30: Fitts' tapping task

Repeated Measures Analysis of Variance (Tests HRV PNN30.STA) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 26.81365

	SS	Degr. of - Freedom	MS	F	p
Intercept	70280.68	1	70280.68	97.75159	0.000000
Condition	1526.68	2	763.34	1.06171	0.363710
Error	15098.42	21	718.97		
PREPOST	1600.01	1	1600.01	13.57710	0.001377
PREPOST*Condition	804.05	2	402.03	3.41145	0.052129
Error	2474.77	21	117.85		

PNN30: Maximal Drive

Repeated Measures Analysis of Variance (Tests HRV PNN30.STA) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 41.52572

	SS	Degr. of - Freedom	MS	F	p
Intercept	232739.3	1	232739.3	134.9694	0.000000
Condition	1306.9	2	653.4	0.3789	0.689171
Error	36212.1	21	1724.4		
PREPOST	1249.1	1	1249.1	11.1930	0.003065
PREPOST*Condition	39.4	2	19.7	0.1765	0.839397
Error	2343.5	21	111.6		
R1VSR2	52.7	1	52.7	0.9998	0.328736
R1VSR2*Condition	411.2	2	205.6	3.8975	0.036347
Error	1107.7	21	52.7		
PREPOST*R1VSR2	23.2	1	23.2	0.4346	0.516914
PREPOST*R1VSR2*Condition	18.6	2	9.3	0.1739	0.841581
Error	1123.1	21	53.5		

PNN30: Digit recall task

Repeated Measures Analysis of Variance (Tests HRV PNN30.STA) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 40.98338

	SS	Degr. of - Freedom	MS	F	p
Intercept	211645.2	1	211645.2	126.0065	0.000000
Condition	1032.9	2	516.4	0.3075	0.738562
Error	35272.4	21	1679.6		
PREPOST	4076.4	1	4076.4	57.1735	0.000000
PREPOST*Condition	42.9	2	21.4	0.3006	0.743471
Error	1497.3	21	71.3		
EASYDIFF	232.4	1	232.4	2.3758	0.138163
EASYDIFF*Condition	41.2	2	20.6	0.2105	0.811891
Error	2054.1	21	97.8		
PREPOST*EASYDIFF	77.6	1	77.6	1.3026	0.266594
PREPOST*EASYDIFF*Condition	64.1	2	32.0	0.5382	0.591630
Error	1250.3	21	59.5		

PNN30: Reading task

Repeated Measures Analysis of Variance (Tests HRV PNN30.STA) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 42.77039

	SS	Degr. of - Freedom	MS	F	p
Intercept	231342.2	1	231342.2	126.4644	0.000000
Condition	582.0	2	291.0	0.1591	0.853945
Error	38415.4	21	1829.3		
PREPOST	4253.4	1	4253.4	34.6082	0.000008
PREPOST*Condition	458.7	2	229.3	1.8659	0.179515
Error	2580.9	21	122.9		
EASYDIFF	33.5	1	33.5	0.8423	0.369161
EASYDIFF*Condition	88.9	2	44.5	1.1180	0.345639
Error	835.2	21	39.8		
PREPOST*EASYDIFF	2.3	1	2.3	0.0808	0.779057
PREPOST*EASYDIFF*Condition	51.3	2	25.7	0.8932	0.424344
Error	603.5	21	28.7		

PNN50: Fitts' tapping task

Repeated Measures Analysis of Variance (Tests HRV PNN50.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 26.26378

	SS	Degr. of - Freedom	MS	F	p
Intercept	21163.39	1	21163.39	30.68108	0.000017
Condition	1058.79	2	529.40	0.76748	0.476767
Error	14485.52	21	689.79		
PREPOST	1293.60	1	1293.60	11.06190	0.003209
PREPOST*Condition	441.21	2	220.60	1.88644	0.176421
Error	2455.78	21	116.94		

PNN30: Maximal Drive

Repeated Measures Analysis of Variance (Tests HRV PNN50.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 45.27053

	SS	Degr. of - Freedom	MS	F	p
Intercept	114110.5	1	114110.5	55.67938	0.000000
Condition	10735.4	2	5367.7	2.61914	0.096490
Error	43037.9	21	2049.4		
PREPOST	0.2	1	0.2	0.00011	0.991911
PREPOST*Condition	3237.3	2	1618.7	0.85574	0.439263
Error	39722.1	21	1891.5		
R1VSR2	5.1	1	5.1	0.15022	0.702228
R1VSR2*Condition	278.2	2	139.1	4.11824	0.030981
Error	709.2	21	33.8		
PREPOST*R1VSR2	0.0	1	0.0	0.00035	0.985191
PREPOST*R1VSR2*Condition	195.6	2	97.8	1.54635	0.236323
Error	1328.1	21	63.2		

PNN30: Reading task

Repeated Measures Analysis of Variance (Tests HRV PNN50.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 93.21057

	SS	Degr. of - Freedom	MS	F	p
Intercept	142074.6	1	142074.6	16.35257	0.000585
Condition	9557.8	2	4778.9	0.55005	0.585012
Error	182452.4	21	8688.2		
PREPOST	21874.1	1	21874.1	3.66167	0.069408
PREPOST*Condition	12179.3	2	6089.7	1.01939	0.377987
Error	125449.7	21	5973.8		
EASYDIFF	5771.7	1	5771.7	1.02415	0.323057
EASYDIFF*Condition	11076.4	2	5538.2	0.98272	0.390858
Error	118347.8	21	5635.6		

PREPOST*EASYDIFF	5974.7	1	5974.7	1.14056	0.297657
PREPOST*EASYDIFF*Condition	11132.6	2	5566.3	1.06260	0.363416
Error	110005.8	21	5238.4		

PNN50: Digit recall task

Repeated Measures Analysis of Variance (Tests HRV PNN50.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 39.91187

	SS	Degr. of - Freedom	MS	F	p
Intercept	81752.02	1	81752.02	51.32089	0.000000
Condition	1076.39	2	538.19	0.33786	0.717103
Error	33452.12	21	1592.96		
PREPOST	4092.47	1	4092.47	28.33525	0.000028
PREPOST*Condition	38.82	2	19.41	0.13440	0.874990
Error	3033.04	21	144.43		
EASYDIFF	264.94	1	264.94	3.24799	0.085885
EASYDIFF*Condition	98.21	2	49.10	0.60196	0.556920
Error	1713.01	21	81.57		
PREPOST*EASYDIFF	37.77	1	37.77	0.87215	0.360974
PREPOST*EASYDIFF*Condition	28.65	2	14.33	0.33079	0.722033
Error	909.48	21	43.31		

LF Centre Frequency: Fitts 'tapping task

Repeated Measures Analysis of Variance (Tests HRV LF CENTRE.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0096446

	SS	Degr. of - Freedom	MS	F	p
Intercept	0.376703	1	0.376703	4049.727	0.000000
Condition	0.000009	2	0.000005	0.051	0.950569
Error	0.001953	21	0.000093		
PREPOST	0.000023	1	0.000023	0.440	0.514487
PREPOST*Condition	0.000090	2	0.000045	0.876	0.430959
Error	0.001082	21	0.000052		

LF Centre Frequency: Maximal Drive

Repeated Measures Analysis of Variance (Tests HRV LF CENTRE.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0094552

	SS	Degr. of - Freedom	MS	F	p
Intercept	0.757231	1	0.757231	8469.974	0.000000
Condition	0.000285	2	0.000142	1.592	0.227044
Error	0.001877	21	0.000089		
PREPOST	0.000055	1	0.000055	0.616	0.441381

PREPOST*Condition	0.000038	2	0.000019	0.214	0.808996
Error	0.001868	21	0.000089		
R1VSR2	0.000000	1	0.000000	0.003	0.957472
R1VSR2*Condition	0.000242	2	0.000121	2.411	0.114164
Error	0.001053	21	0.000050		
PREPOST*R1VSR2	0.000126	1	0.000126	1.679	0.209092
PREPOST*R1VSR2*Condition	0.000072	2	0.000036	0.479	0.626069
Error	0.001575	21	0.000075		

LF Centre Frequency: Digit recall task

Repeated Measures Analysis of Variance (Tests HRV LF CENTRE.sta) Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: .0172221

	SS	Degr. of - Freedom	MS	F	p
Intercept	0.697626	1	0.697626	2352.069	0.000000
Condition	0.001048	2	0.000524	1.767	0.195327
Error	0.006229	21	0.000297		
PREPOST	0.001332	1	0.001332	5.140	0.034062
PREPOST*Condition	0.000173	2	0.000087	0.335	0.719338
Error	0.005442	21	0.000259		
EASYDIFF	0.000135	1	0.000135	0.637	0.433841
EASYDIFF*Condition	0.000348	2	0.000174	0.821	0.453821
Error	0.004453	21	0.000212		
PREPOST*EASYDIFF	0.000201	1	0.000201	1.124	0.301027
PREPOST*EASYDIFF*Condition	0.000607	2	0.000304	1.699	0.207077
Error	0.003752	21	0.000179		

LF Centre Frequency: Reading task

Repeated Measures Analysis of Variance (Tests HRV LF CENTRE.sta) Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: .6137076

	SS	Degr. of - Freedom	MS	F	p
Intercept	2.218749	1	2.218749	5.890948	0.024301
Condition	0.773384	2	0.386692	1.026697	0.375480
Error	7.909378	21	0.376637		
PREPOST	0.376223	1	0.376223	1.006804	0.327092
PREPOST*Condition	0.744949	2	0.372475	0.996772	0.385869
Error	7.847297	21	0.373681		
EASYDIFF	0.000006	1	0.000006	0.063299	0.803801
EASYDIFF*Condition	0.000322	2	0.000161	1.613268	0.222969
Error	0.002098	21	0.000100		
PREPOST*EASYDIFF	0.000079	1	0.000079	0.808918	0.378638

PREPOST*EASYDIFF*Condition	0.000215	2	0.000108	1.095294	0.352800
Error	0.002063	21	0.000098		

HF Centre Frequency: Fitts' tapping task

Repeated Measures Analysis of Variance (Tests HRV HF CENTRE FREQ.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0377748

	SS	Degr. of - Freedom	MS	F	p
Intercept	3.036038	1	3.036038	2127.662	0.000000
Condition	0.004051	2	0.002026	1.420	0.264090
Error	0.029966	21	0.001427		
PREPOST	0.000064	1	0.000064	0.413	0.527346
PREPOST*Condition	0.000302	2	0.000151	0.972	0.394853
Error	0.003267	21	0.000156		

HF Centre Frequency: Maximal Drive

Repeated Measures Analysis of Variance (Tests HRV HF CENTRE FREQ.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0493414

	SS	Degr. of - Freedom	MS	F	p
Intercept	6.423332	1	6.423332	2638.375	0.000000
Condition	0.003176	2	0.001588	0.652	0.531107
Error	0.051126	21	0.002435		
PREPOST	0.011022	1	0.011022	21.644	0.000137
PREPOST*Condition	0.001251	2	0.000626	1.229	0.312881
Error	0.010694	21	0.000509		
R1VSR2	0.001096	1	0.001096	3.171	0.089409
R1VSR2*Condition	0.000957	2	0.000479	1.384	0.272499
Error	0.007260	21	0.000346		
PREPOST*R1VSR2	0.000345	1	0.000345	0.984	0.332583
PREPOST*R1VSR2*Condition	0.000197	2	0.000098	0.280	0.758228
Error	0.007363	21	0.000351		

LF Centre Frequency: Reading task

Repeated Measures Analysis of Variance (Tests HRV HF CENTRE FREQ.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0472790

	SS	Degr. of - Freedom	MS	F	p
Intercept	6.586471	1	6.586471	2946.555	0.000000
Condition	0.009701	2	0.004850	2.170	0.139112
Error	0.046942	21	0.002235		
PREPOST	0.000447	1	0.000447	0.756	0.394530
PREPOST*Condition	0.000875	2	0.000438	0.739	0.489491

Error	0.012429	21	0.000592		
EASYDIFF	0.001477	1	0.001477	6.020	0.022966
EASYDIFF*Condition	0.000459	2	0.000229	0.935	0.408438
Error	0.005154	21	0.000245		
PREPOST*EASYDIFF	0.000076	1	0.000076	0.318	0.578757
PREPOST*EASYDIFF*Condition	0.000049	2	0.000025	0.104	0.902046
Error	0.005016	21	0.000239		

HF Centre Frequency: Digit recall task

Repeated Measures Analysis of Variance (Tests HRV HF CENTRE FREQ.sta) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: .0646051

	SS	Degr. of - Freedom	MS	F	p
Intercept	6.196109	1	6.196109	1484.517	0.000000
Condition	0.002281	2	0.001141	0.273	0.763528
Error	0.087650	21	0.004174		
PREPOST	0.000175	1	0.000175	0.096	0.759881
PREPOST*Condition	0.003418	2	0.001709	0.935	0.408466
Error	0.038401	21	0.001829		
EASYDIFF	0.000216	1	0.000216	1.064	0.313936
EASYDIFF*Condition	0.001798	2	0.000899	4.421	0.024988
Error	0.004270	21	0.000203		
PREPOST*EASYDIFF	0.000107	1	0.000107	0.448	0.510793
PREPOST*EASYDIFF*Condition	0.000130	2	0.000065	0.271	0.765232
Error	0.005020	21	0.000239		

APPENDIX C2: POST-HOC ANALYSES

Sub-maximal Drive – Lane Deviation post-hoc analysis

Tukey HSD test; variable DV_1 (Driving Lane Dev.sta) Approximate Probabilities for Post- Hoc Tests Error: Within MSE = .00018, df = 340.00

	TIM E	{1} - .03278	{2} - .03519	{3} - .03721	{4} - .03724	{5} - .04198	{6} - .04004	{7} - .04217	{8} - .04535	{9} - .05096	{10} - .04932	{11} - .05201	{12} - .04729	{13} - .04638	{14} - .04719	{15} - .05109	{16} - .04883	{17} - .05709	{18} - .05417
1	0-5		1.00000 0	0.99966 8	0.99963 5	0.63011 3	0.92263 5	0.59134 8	0.10603 7	0.00041 4	0.002668	0.000131	0.021124	0.046877	0.022968	0.000356	0.004548	0.000036	0.000040
2	5-10	1.00000 0		1.00000 0	1.00000 0	0.95684 5	0.99892 4	0.94438 9	0.43881 0	0.00612 5	0.029693	0.001956	0.147724	0.259619	0.157022	0.005348	0.045414	0.000038	0.000169
3	10-15	0.99966 8	1.00000 0		1.00000 0	0.99911 7	0.99999 9	0.99854 1	0.81671 8	0.04134 5	0.145543	0.015907	0.453212	0.632711	0.470944	0.036944	0.200360	0.000074	0.001660
4	15-20	0.99963 5	1.00000 0	1.00000 0		0.99918 8	1.00000 0	0.99865 2	0.82143 6	0.04247 7	0.148708	0.016395	0.459386	0.638936	0.477179	0.037971	0.204345	0.000076	0.001720
5	20-25	0.63011 3	0.95684 5	0.99911 7	0.99918 8		1.00000 0	1.00000 0	0.99999 3	0.67131 8	0.914189	0.462033	0.996706	0.999681	0.997314	0.646007	0.952411	0.011761	0.137825
6	25-30	0.92263 5	0.99892 4	0.99999 9	1.00000 0	1.00000 0		1.00000 0	0.99671 1	0.30211 5	0.611795	0.160146	0.923020	0.977048	0.930700	0.281327	0.706308	0.001499	0.029575
7	30-35	0.59134 8	0.94438 9	0.99854 1	0.99865 2	1.00000 0	1.00000 0		0.99999 7	0.70805 9	0.931309	0.500549	0.997893	0.999826	0.998305	0.683581	0.963475	0.014219	0.157337
8	35-40	0.10603 7	0.43881 0	0.81671 8	0.82143 6	0.99999 3	0.99671 1	0.99999 7		0.99382 7	0.999922	0.963383	1.000000	1.000000	1.000000	0.992022	0.999988	0.185907	0.701045
9	40-45	0.00041 4	0.00612 5	0.04134 5	0.04247 7	0.67131 8	0.30211 5	0.70805 9	0.99382 7		1.000000	1.000000	0.999975	0.999488	0.999964	1.000000	1.000000	0.983723	0.999996
10	45-50	0.00266 8	0.02969 3	0.14554 3	0.14870 8	0.91418 9	0.61179 5	0.93130 9	0.99992 2	1.00000 0		1.000000	1.000000	0.999999	1.000000	1.000000	1.000000	0.867739	0.998912
11	50-55	0.00013 1	0.00195 6	0.01590 7	0.01639 5	0.46203 3	0.16014 6	0.50054 9	0.96338 3	1.00000 0	1.000000		0.999217	0.993614	0.999004	1.000000	0.999997	0.998059	1.000000
12	55-60	0.02112 4	0.14772 4	0.45321 2	0.45938 6	0.99670 6	0.92302 0	0.99789 3	1.00000 0	0.99997 5	1.000000	0.999217		1.000000	1.000000	0.999959	1.000000	0.507438	0.950659
13	60-65	0.04687 7	0.25961 9	0.63271 1	0.63893 6	0.99968 1	0.97704 8	0.99982 6	1.00000 0	0.99948 8	0.999999	0.993614	1.000000		1.000000	0.999264	1.000000	0.337603	0.865819
14	65-70	0.02296 8	0.15702 2	0.47094 4	0.47717 9	0.99731 4	0.93070 0	0.99830 5	1.00000 0	0.99996 4	1.000000	0.999004	1.000000	1.000000		0.999942	1.000000	0.489403	0.944598
15	70-75	0.00035 6	0.00534 8	0.03694 4	0.03797 1	0.64600 7	0.28132 7	0.68358 1	0.99202 2	1.00000 0	1.000000	1.000000	0.999959	0.999264	0.999942		1.000000	0.986996	0.999998
16	75-80	0.00454 8	0.04541 4	0.20036 0	0.20434 5	0.95241 1	0.70630 8	0.96347 5	0.99998 8	1.00000 0	1.000000	0.999997	1.000000	1.000000	1.000000	1.000000		0.798466	0.996498
17	80-85	0.00003 6	0.00003 8	0.00007 4	0.00007 6	0.01176 1	0.00149 9	0.01421 9	0.18590 7	0.98372 3	0.867739	0.998059	0.507438	0.337603	0.489403	0.986996	0.798466		0.999999
18	85-90	0.00004 0	0.00016 9	0.00166 0	0.00172 0	0.13782 5	0.02957 5	0.15733 7	0.70104 5	0.99999 6	0.998912	1.000000	0.950659	0.865819	0.944598	0.999998	0.996498	0.999999	

Sub-maximal Drive – Heart rate frequency post-hoc analysis

Tukey HSD test; variable DV_1 (Drive HR Freq.sta) Approximate Probabilities for Post- Hoc Tests Error: Within MSE = 8.8945, df = 323.00

	TI	{1} - 73.523	{2} - 73.201	{3} - 73.925	{4} - 72.675	{5} - 72.175	{6} - 72.348	{7} - 73.133	{8} - 72.716	{9} - 72.916	{10} - 72.057	{11} - 71.005	{12} - 70.060	{13} - 70.186	{14} - 70.032	{15} - 69.011	{16} - 69.324	{17} - 69.102	{18} - 68.54
1	0-5		1.000000	1.000000	0.999956	0.985508	0.996863	1.000000	0.999978	1.000000	0.966503	0.238871	0.007296	0.012842	0.006420	0.000057	0.000182	0.000073	0.0000
2	5-10	1.000000		0.999996	1.000000	0.999414	0.999952	1.000000	1.000000	1.000000	0.997706	0.491114	0.029283	0.047816	0.026178	0.000190	0.000944	0.000298	0.0000
3	10-15	1.000000	0.999996		0.993576	0.853627	0.935267	0.999983	0.995598	0.999526	0.773681	0.067893	0.001004	0.001911	0.000870	0.000037	0.000047	0.000038	0.0000
4	15-20	0.999956	1.000000	0.993576		1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	0.896720	0.182106	0.256975	0.167933	0.002785	0.012056	0.004324	0.0002
5	20-25	0.985508	0.999414	0.853627	1.000000		1.000000	0.999763	1.000000	0.999994	1.000000	0.997005	0.563611	0.675457	0.538546	0.026694	0.086316	0.038241	0.0032
6	25-30	0.996863	0.999952	0.935267	1.000000	1.000000		0.999985	1.000000	1.000000	1.000000	0.986015	0.410358	0.521051	0.387152	0.012842	0.046224	0.018954	0.0013
7	30-35	1.000000	1.000000	0.999983	1.000000	0.999763	0.999985		1.000000	1.000000	0.998925	0.552679	0.038365	0.061580	0.034422	0.000267	0.001343	0.000424	0.0000
8	35-40	0.999978	1.000000	0.995598	1.000000	1.000000	1.000000	1.000000		1.000000	0.999999	0.875878	0.161511	0.230781	0.148551	0.002273	0.010054	0.003550	0.0002
9	40-45	1.000000	1.000000	0.999526	1.000000	0.999994	1.000000	1.000000	1.000000		0.999947	0.740824	0.084908	0.128597	0.077122	0.000818	0.003955	0.001305	0.0000
10	45-50	0.966503	0.997706	0.773681	1.000000	1.000000	1.000000	0.998925	0.999999	0.999947		0.999193	0.668987	0.771489	0.644795	0.042593	0.127500	0.059740	0.0057
11	50-55	0.238871	0.491114	0.067893	0.896720	0.997005	0.986015	0.552679	0.875878	0.740824	0.999193		0.999801	0.999973	0.999706	0.671507	0.891115	0.746433	0.2749
12	55-60	0.007296	0.029283	0.001004	0.182106	0.563611	0.410358	0.038365	0.161511	0.084908	0.668987	0.999801		1.000000	1.000000	0.999221	0.999994	0.999761	0.9537
13	60-65	0.012842	0.047816	0.001911	0.256975	0.675457	0.521051	0.061580	0.230781	0.128597	0.771489	0.999973	1.000000		1.000000	0.996863	0.999944	0.998816	0.9089
14	65-70	0.006420	0.026178	0.000870	0.167933	0.538546	0.387152	0.034422	0.148551	0.077122	0.644795	0.999706	1.000000	1.000000		0.999448	0.999997	0.999839	0.9609
15	70-75	0.000057	0.000190	0.000037	0.002785	0.026694	0.012842	0.000267	0.002273	0.000818	0.042593	0.671507	0.999221	0.996863	0.999448		1.000000	1.000000	1.0000
16	75-80	0.000182	0.000944	0.000047	0.012056	0.086316	0.046224	0.001343	0.010054	0.003955	0.127500	0.891115	0.999994	0.999944	0.999997	1.000000		1.000000	0.9999
17	80-85	0.000073	0.000298	0.000038	0.004324	0.038241	0.018954	0.000424	0.003550	0.001305	0.059740	0.746433	0.999761	0.998816	0.999839	1.000000	1.000000		1.0000
18	85-90	0.000037	0.000044	0.000036	0.000252	0.003244	0.001363	0.000048	0.000206	0.000086	0.005736	0.274905	0.953797	0.908939	0.960962	1.000000	0.999986	1.000000	

Sub-maximal Drive – rMSSD post-hoc analysis

Tukey HSD test; variable DV_1 (Drive HRV RMSSD.sta) Approximate Probabilities for Post- Hoc Tests Error: Within MSE = 224.18, df = 323.00

	TIM E	{1} - 56.843	{2} - 58.683	{3} - 59.970	{4} - 66.967	{5} - 67.192	{6} - 70.882	{7} - 76.320	{8} - 74.993	{9} - 82.519	{10} - 81.697	{11} - 80.527	{12} - 85.470	{13} - 82.706	{14} - 85.208	{15} - 86.000	{16} - 91.115	{17} - 89.846	{18} - 87.282
1	0-5		1.00000 0	1.00000 0	0.65211 4	0.61224 0	0.10390 7	0.00093 4	0.00353 8	0.00003 6	0.000037	0.000041	0.000036	0.000036	0.000036	0.000036	0.000036	0.000036	0.000036
2	5-10	1.00000 0		1.00000 0	0.90603 4	0.88423 8	0.29842 4	0.00578 4	0.01877 9	0.00004 0	0.000049	0.000094	0.000036	0.000039	0.000036	0.000036	0.000036	0.000036	0.000036
3	10-15	1.00000 0	1.00000 0		0.97953 6	0.97199 9	0.51107 8	0.01816 9	0.05210 8	0.00005 9	0.000103	0.000306	0.000036	0.000054	0.000036	0.000036	0.000036	0.000036	0.000036
4	15-20	0.65211 4	0.90603 4	0.97953 6		1.00000 0	0.99998 7	0.77766 4	0.92732 7	0.03480 6	0.064513	0.140938	0.002503	0.030008	0.003237	0.001471	0.000039	0.000051	0.000391
5	20-25	0.61224 0	0.88423 8	0.97199 9	1.00000 0		0.99999 4	0.80989 7	0.94305 7	0.04146 5	0.075708	0.161581	0.003126	0.035866	0.004027	0.001849	0.000040	0.000056	0.000494
6	25-30	0.10390 7	0.29842 4	0.51107 8	0.99998 7	0.99999 4		0.99883 0	0.99997 3	0.38561 7	0.528437	0.732544	0.071424	0.355320	0.085675	0.048574	0.000426	0.001578	0.017404
7	30-35	0.00093 4	0.00578 4	0.01816 9	0.77766 4	0.80989 7	0.99883 0		1.00000 0	0.99440 3	0.998981	0.999962	0.806683	0.992188	0.841087	0.726906	0.061598	0.143889	0.501982
8	35-40	0.00353 8	0.01877 9	0.05210 8	0.92732 7	0.94305 7	0.99997 3	1.00000 0		0.95873 7	0.986816	0.998545	0.589424	0.948466	0.636033	0.494250	0.021992	0.059063	0.285577
9	40-45	0.00003 6	0.00004 0	0.00005 9	0.03480 6	0.04146 5	0.38561 7	0.99440 3	0.95873 7		1.000000	1.000000	1.000000	1.000000	1.000000	0.999998	0.875140	0.967839	0.999791
10	45-50	0.00003 7	0.00004 9	0.00010 3	0.06451 3	0.07570 8	0.52843 7	0.99898 1	0.98681 6	1.00000 0		1.000000	0.999992	1.000000	0.999997	0.999949	0.768065	0.917676	0.998370
11	50-55	0.00004 1	0.00009 4	0.00030 6	0.14093 8	0.16158 1	0.73254 4	0.99996 2	0.99854 5	1.00000 0	1.000000		0.999657	1.000000	0.999835	0.998733	0.569491	0.782637	0.985719
12	55-60	0.00003 6	0.00003 6	0.00003 6	0.00250 3	0.00312 6	0.07142 4	0.80668 3	0.58942 4	1.00000 0	0.999992	0.999657		1.000000	1.000000	1.000000	0.998144	0.999935	1.000000
13	60-65	0.00003 6	0.00003 9	0.00005 4	0.03000 8	0.03586 6	0.35532 0	0.99218 8	0.94846 6	1.00000 0	1.000000	1.000000	1.000000		1.000000	0.999999	0.894372	0.974967	0.999879
14	65-70	0.00003 6	0.00003 6	0.00003 6	0.00323 7	0.00402 7	0.08567 5	0.84108 7	0.63603 3	1.00000 0	0.999997	0.999835	1.000000	1.000000		1.000000	0.996803	0.999854	1.000000
15	70-75	0.00003 6	0.00003 6	0.00003 6	0.00147 1	0.00184 9	0.04857 4	0.72690 6	0.49425 0	0.99999 8	0.999949	0.998733	1.000000	0.999999	1.000000		0.999463	0.999990	1.000000
16	75-80	0.00003 6	0.00003 6	0.00003 6	0.00003 9	0.00004 0	0.00042 6	0.06159 8	0.02199 2	0.87514 0	0.768065	0.569491	0.998144	0.894372	0.996803	0.999463		1.000000	0.999990
17	80-85	0.00003 6	0.00003 6	0.00003 6	0.00005 1	0.00005 6	0.00157 8	0.14388 9	0.05906 3	0.96783 9	0.917676	0.782637	0.999935	0.974967	0.999854	0.999990	1.000000		1.000000
18	85-90	0.00003 6	0.00003 6	0.00003 6	0.00039 1	0.00049 4	0.01740 4	0.50198 2	0.28557 7	0.99979 1	0.998370	0.985719	1.000000	0.999879	1.000000	1.000000	0.999990	1.000000	

Sub-maximal Drive – HF Power post-hoc analysis

Tukey HSD test; variable DV_1 (Drive HRV HF Power.sta) Approximate Probabilities for Post- Hoc Tests Error: Within MSE = 1916E2, df = 357.00

	TIM E	0-5	{2} - 813.04	{3} - 693.51	{4} - 722.81	{5} - 802.46	{6} - 835.51	{7} - 866.07	{8} - 936.07	{9} - 1094.6	{10} - 1004.4	{11} - 1061.1	{12} - 1261.5	{13} - 1218.6	{14} - 1274.4	{15} - 1187.9	{16} - 1247.2	{17} - 1317.2	{18} - 1226.4
1	0-5	5-10	1.00000 0	0.99999 9	1.00000 0	1.00000 0	1.00000 0	1.00000 0	0.99950 2	0.58398 8	0.963584	0.776341	0.020292	0.063657	0.013945	0.129372	0.030292	0.003638	0.052397
2	5-10	10-15		0.99997 5	1.00000 0	1.00000 0	1.00000 0	1.00000 0	0.99996 2	0.73511 6	0.989767	0.886870	0.041029	0.115868	0.029038	0.216704	0.059198	0.008301	0.097297
3	10-15	15-20	0.99997 5		1.00000 0	0.99999 4	0.99972 8	0.99683 1	0.90491 5	0.12782 5	0.560944	0.247371	0.000981	0.004250	0.000622	0.011206	0.001620	0.000144	0.003286
4	15-20	20-25	1.00000 0	1.00000 0		1.00000 0	0.99998 9	0.99969 5	0.96920 9	0.22935 0	0.734478	0.396634	0.002701	0.010727	0.001741	0.026240	0.004347	0.000386	0.008447
5	20-25	25-30	1.00000 0	0.99999 4	1.00000 0		1.00000 0	1.00000 0	0.99988 1	0.67506 4	0.982005	0.846404	0.030925	0.091267	0.021609	0.176752	0.045251	0.005955	0.075991
6	25-30	30-35	1.00000 0	0.99972 8	0.99998 9	1.00000 0		1.00000 0	0.99999 8	0.84460 3	0.997538	0.948329	0.072261	0.185005	0.052546	0.320201	0.101037	0.016336	0.158272
7	30-35	35-40	1.00000 0	0.99683 1	0.99969 5	1.00000 0	1.00000 0		1.00000 0	0.94213 0	0.999808	0.987504	0.143913	0.319253	0.108906	0.494211	0.192166	0.038286	0.280656
8	35-40	40-45	0.99996 2	0.90491 5	0.96920 9	0.99988 1	0.99999 8	1.00000 0		0.99887 4	1.000000	0.999953	0.471917	0.729557	0.396181	0.873360	0.559683	0.192226	0.685414
9	40-45	45-50	0.73511 6	0.12782 5	0.22935 0	0.67506 4	0.84460 3	0.94213 0	0.99887 4		1.000000	1.000000	0.997860	0.999958	0.994871	0.999999	0.999301	0.954066	0.999901
10	45-50	50-55	0.98976 7	0.56094 4	0.73447 8	0.98200 5	0.99753 8	0.99980 8	1.00000 0	1.00000 0		1.000000	0.852704	0.967952	0.794943	0.993599	0.904278	0.549798	0.955321
11	50-55	55-60	0.88687 0	0.24737 1	0.39663 4	0.84640 4	0.94832 9	0.98750 4	0.99995 3	1.00000 0	1.000000		0.983350	0.998958	0.969099	0.999943	0.992464	0.856697	0.998105
12	55-60	60-65	0.04102 9	0.00098 1	0.00270 1	0.03092 5	0.07226 1	0.14391 3	0.47191 7	0.99786 0	0.852704	0.983350		1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
13	60-65	65-70	0.11586 8	0.00425 0	0.01072 7	0.09126 7	0.18500 5	0.31925 3	0.72955 7	0.99995 8	0.967952	0.998958	1.000000		1.000000	1.000000	1.000000	0.999999	1.000000
14	65-70	70-75	0.02903 8	0.00062 2	0.00174 1	0.02160 9	0.05254 6	0.10890 6	0.39618 1	0.99487 1	0.794943	0.969099	1.000000	1.000000		1.000000	1.000000	1.000000	1.000000
15	70-75	75-80	0.21670 4	0.01120 6	0.02624 0	0.17675 2	0.32020 1	0.49421 1	0.87336 0	0.99999 9	0.993599	0.999943	1.000000	1.000000	1.000000		1.000000	0.999924	1.000000
16	75-80	80-85	0.05919 8	0.00162 0	0.00434 7	0.04525 1	0.10103 7	0.19216 6	0.55968 3	0.99930 1	0.904278	0.992464	1.000000	1.000000	1.000000	1.000000		1.000000	1.000000
17	80-85	85-90	0.00830 1	0.00014 4	0.00038 6	0.00595 5	0.01633 6	0.03828 6	0.19222 6	0.95406 6	0.549798	0.856697	1.000000	0.999999	1.000000	0.999924	1.000000		1.000000
18	85-90	97	0.0523 7	0.09729 7	0.00328 6	0.00844 7	0.07599 1	0.15827 2	0.28065 6	0.68541 4	0.99990 1	0.955321	0.998105	1.000000	1.000000	1.000000	1.000000	1.000000	

Sub-maximal Drive – LF Power post-hoc analysis

Tukey HSD test; variable DV_1 (Drive HRV LF Power.sta) Approximate Probabilities for Post- Hoc Tests Error: Within MSE = 2471E3, df = 357.00

	TIM E	{1} - 1130.9	{2} - 1372.1	{3} - 1513.7	{4} - 1785.5	{5} - 1805.4	{6} - 2038.3	{7} - 2271.8	{8} - 2724.5	{9} - 3489.6	{10} - 2866.8	{11} - 2561.8	{12} - 2708.0	{13} - 2737.7	{14} - 2944.4	{15} - 2786.4	{16} - 2800.4	{17} - 3130.6	{18} - 2794.9
1	0-5		1.00000 0	0.99999 5	0.99402 1	0.99166 0	0.86997 5	0.51910 3	0.04636 6	0.00006 2	0.015515	0.135003	0.052156	0.042121	0.008073	0.029304	0.026330	0.001450	0.027468
2	5-10	1.00000 0		1.00000 0	0.99998 5	0.99997 1	0.99272 8	0.87793 4	0.20949 4	0.00045 5	0.091008	0.436971	0.228210	0.195230	0.053942	0.148798	0.137147	0.012880	0.141648
3	10-15	0.99999 5	1.00000 0		1.00000 0	1.00000 0	0.99960 4	0.97205 4	0.40282 9	0.00182 3	0.208696	0.676279	0.429498	0.381880	0.135177	0.309556	0.290297	0.039141	0.297795
4	15-20	0.99402 1	0.99998 5	1.00000 0		1.00000 0	1.00000 0	0.99985 7	0.83414 1	0.02005 8	0.621072	0.964948	0.853506	0.817601	0.488468	0.750138	0.729054	0.217650	0.737436
5	20-25	0.99166 0	0.99997 1	1.00000 0	1.00000 0		1.00000 0	0.99991 9	0.85728 6	0.02346 7	0.654401	0.972644	0.874979	0.842052	0.522324	0.778908	0.758878	0.240888	0.766857
6	25-30	0.86997 5	0.99272 8	0.99960 4	1.00000 0	1.00000 0		1.00000 0	0.98994 1	0.11942 9	0.937039	0.999615	0.992291	0.987653	0.871298	0.975439	0.970600	0.602363	0.972586
7	30-35	0.51910 3	0.87793 4	0.97205 4	0.99985 7	0.99991 9	1.00000 0		0.99994 7	0.39167 4	0.998049	1.000000	0.999969	0.999920	0.991912	0.999693	0.999563	0.915056	0.999619
8	35-40	0.04636 6	0.20949 4	0.40282 9	0.83414 1	0.85728 6	0.98994 1	0.99994 7		0.96945 6	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	0.999989	1.000000
9	40-45	0.00006 2	0.00045 5	0.00182 3	0.02005 8	0.02346 7	0.11942 9	0.39167 4	0.96945 6		0.996633	0.847404	0.962630	0.974215	0.999347	0.986942	0.989451	0.999998	0.988515
10	45-50	0.01551 5	0.09100 8	0.20869 6	0.62107 2	0.65440 1	0.93703 9	0.99804 9	1.00000 0	0.99663 3		1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
11	50-55	0.13500 3	0.43697 1	0.67627 9	0.96494 8	0.97264 4	0.99961 5	1.00000 0	1.00000 0	0.84740 4	1.000000		1.000000	1.000000	0.999995	1.000000	1.000000	0.998883	1.000000
12	55-60	0.05215 6	0.22821 0	0.42949 8	0.85350 6	0.87497 9	0.99229 1	0.99996 9	1.00000 0	0.96263 0	1.000000	1.000000		1.000000	1.000000	1.000000	1.000000	0.999980	1.000000
13	60-65	0.04212 1	0.19523 0	0.38188 0	0.81760 1	0.84205 2	0.98765 3	0.99992 0	1.00000 0	0.97421 5	1.000000	1.000000	1.000000		1.000000	1.000000	1.000000	0.999993	1.000000
14	65-70	0.00807 3	0.05394 2	0.13517 7	0.48846 8	0.52232 4	0.87129 8	0.99191 2	1.00000 0	0.99934 7	1.000000	0.999995	1.000000	1.000000		1.000000	1.000000	1.000000	1.000000
15	70-75	0.02930 4	0.14879 8	0.30955 6	0.75013 8	0.77890 8	0.97543 9	0.99969 3	1.00000 0	0.98694 2	1.000000	1.000000	1.000000	1.000000	1.000000		1.000000	0.999999	1.000000
16	75-80	0.02633 0	0.13714 7	0.29029 7	0.72905 4	0.75887 8	0.97060 0	0.99956 3	1.00000 0	0.98945 1	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000		1.000000	1.000000
17	80-85	0.00145 0	0.01288 0	0.03914 1	0.21765 0	0.24088 8	0.60236 3	0.91505 6	0.99998 9	0.99999 8	1.000000	0.998883	0.999980	0.999993	1.000000	0.999999	1.000000		0.999999
18	85-90	0.02746 8	0.14164 8	0.29779 5	0.73743 6	0.76685 7	0.97258 6	0.99961 9	1.00000 0	0.98851 5	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	0.999999	

Sub-maximal Drive – LF Power relative to (LF+HF) post-hoc analysis

Tukey HSD test; variable DV_1 (Drive HRV LF power relative to (LF+HF) [%].sta) Approximate Probabilities for Post- Hoc Tests Error: Within MSE = 54.921, df = 357.00

	TIM E	{1} - 63.161	{2} - 64.295	{3} - 68.394	{4} - 72.565	{5} - 69.878	{6} - 72.030	{7} - 74.361	{8} - 74.318	{9} - 75.857	{10} - 73.157	{11} - 71.655	{12} - 69.184	{13} - 70.118	{14} - 71.831	{15} - 70.746	{16} - 70.099	{17} - 71.335	{18} - 71.187
1	0-5		1.00000 0	0.57238 9	0.00152 5	0.14011 5	0.00442 0	0.00005 7	0.00006 0	0.00003 6	0.000443	0.008943	0.302903	0.102756	0.006466	0.041529	0.105409	0.015801	0.020359
2	5-10	1.00000 0		0.90621 9	0.01335 8	0.44599 7	0.03276 3	0.00038 2	0.00041 8	0.00004 4	0.004477	0.058274	0.694112	0.364608	0.044738	0.192342	0.370846	0.091835	0.111975
3	10-15	0.57238 9	0.90621 9		0.89259 8	1.00000 0	0.96700 4	0.31946 9	0.33276 1	0.04998 3	0.735979	0.989021	1.000000	0.999998	0.981014	0.999797	0.999998	0.996566	0.998152
4	15-20	0.00152 5	0.01335 8	0.89259 8		0.99885 6	1.00000 0	0.99999 6	0.99999 7	0.98784 5	1.000000	1.000000	0.984004	0.999658	1.000000	0.999995	0.999621	1.000000	1.000000
5	20-25	0.14011 5	0.44599 7	1.00000 0	0.99885 6		0.99994 0	0.81926 9	0.83075 7	0.31581 5	0.988375	0.999996	1.000000	1.000000	0.999985	1.000000	1.000000	1.000000	1.000000
6	25-30	0.00442 0	0.03276 3	0.96700 4	1.00000 0	0.99994 0		0.99982 1	0.99986 1	0.94732 5	1.000000	1.000000	0.997675	0.999989	1.000000	1.000000	0.999987	1.000000	1.000000
7	30-35	0.00005 7	0.00038 2	0.31946 9	0.99999 6	0.81926 9	0.99982 1		1.00000 0	1.00000 0	1.000000	0.998749	0.592514	0.877684	0.999468	0.968828	0.873514	0.995220	0.991816
8	35-40	0.00006 0	0.00041 8	0.33276 1	0.99999 7	0.83075 7	0.99986 1	1.00000 0		1.00000 0	1.000000	0.998978	0.608184	0.886796	0.999575	0.972244	0.882820	0.995953	0.992971
9	40-45	0.00003 6	0.00004 4	0.04998 3	0.98784 5	0.31581 5	0.94732 5	1.00000 0	1.00000 0		0.998780	0.886282	0.147834	0.392492	0.918855	0.616288	0.386094	0.808539	0.765101
10	45-50	0.00044 3	0.00447 7	0.73597 9	1.00000 0	0.98837 5	1.00000 0	1.00000 0	1.00000 0	0.99878 0		1.000000	0.927330	0.994989	1.000000	0.999718	0.994616	0.999995	0.999983
11	50-55	0.00894 3	0.05827 4	0.98902 1	1.00000 0	0.99999 6	1.00000 0	0.99874 9	0.99897 8	0.88628 2	1.000000		0.999609	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
12	55-60	0.30290 3	0.69411 2	1.00000 0	0.98400 4	1.00000 0	0.99767 5	0.59251 4	0.60818 4	0.14783 4	0.927330	0.999609		1.000000	0.999050	0.999999	1.000000	0.999941	0.999979
13	60-65	0.10275 6	0.36460 8	0.99999 8	0.99965 8	1.00000 0	0.99998 9	0.87768 4	0.88679 6	0.39249 2	0.994989	1.000000	1.000000		0.999998	1.000000	1.000000	1.000000	1.000000
14	65-70	0.00646 6	0.04473 8	0.98101 4	1.00000 0	0.99998 5	1.00000 0	0.99946 8	0.99957 5	0.91885 5	1.000000	1.000000	0.999050	0.999998		1.000000	0.999997	1.000000	1.000000
15	70-75	0.04152 9	0.19234 2	0.99979 7	0.99999 5	1.00000 0	1.00000 0	0.96882 8	0.97224 4	0.61628 8	0.999718	1.000000	0.999999	1.000000	1.000000		1.000000	1.000000	1.000000
16	75-80	0.10540 9	0.37084 6	0.99999 8	0.99962 1	1.00000 0	0.99998 7	0.87351 4	0.88282 0	0.38609 4	0.994616	1.000000	1.000000	1.000000	0.999997	1.000000		1.000000	1.000000
17	80-85	0.01580 1	0.09183 5	0.99656 6	1.00000 0	1.00000 0	1.00000 0	0.99522 0	0.99595 3	0.80853 9	0.999995	1.000000	0.999941	1.000000	1.000000	1.000000	1.000000		1.000000
18	85-90	0.02035 9	0.11197 5	0.99815 2	1.00000 0	1.00000 0	1.00000 0	0.99181 6	0.99297 1	0.76510 1	0.999983	1.000000	0.999979	1.000000	1.000000	1.000000	1.000000	1.000000	

Sub-maximal Drive – Blink duration post-hoc analysis

Tukey HSD test; variable DV_1 (Drive Eye BlinkDuration.sta) Approximate Probabilities for Post- Hoc Tests Error: Within MSE = 708.78, df = 323.00

	TIM E	{1} - 150.88	{2} - 168.75	{3} - 171.35	{4} - 169.67	{5} - 167.77	{6} - 183.88	{7} - 179.21	{8} - 187.48	{9} - 183.97	{10} - 184.88	{11} - 178.23	{12} - 181.93	{13} - 177.71	{14} - 183.13	{15} - 187.71	{16} - 175.98	{17} - 176.84	{18} - 174.27
1	0-5		0.66438 0	0.40625 2	0.57295 3	0.75543 4	0.00236 4	0.02563 7	0.00029 7	0.00224 0	0.001338	0.039673	0.006782	0.049553	0.003567	0.000261	0.098572	0.070763	0.179504
2	5-10	0.66438 0		1.00000 0	1.00000 0	1.00000 0	0.88434 8	0.99695 7	0.57927 9	0.87871 7	0.817205	0.999088	0.964168	0.999559	0.922497	0.556067	0.999977	0.999888	1.000000
3	10-15	0.40625 2	1.00000 0		1.00000 0	1.00000 0	0.97796 2	0.99992 4	0.81720 5	0.97623 2	0.954128	0.999989	0.996500	0.999996	0.988296	0.799463	1.000000	1.000000	1.000000
4	15-20	0.57295 3	1.00000 0	1.00000 0		1.00000 0	0.92984 6	0.99900 9	0.67044 5	0.92578 6	0.879213	0.999758	0.982324	0.999897	0.956260	0.648070	0.999997	0.999980	1.000000
5	20-25	0.75543 4	1.00000 0	1.00000 0	1.00000 0		0.81877 5	0.99151 7	0.48005 6	0.81149 2	0.735542	0.996942	0.931901	0.998348	0.870087	0.457362	0.999862	0.999482	0.999995
6	25-30	0.00236 4	0.88434 8	0.97796 2	0.92984 6	0.81877 5		1.00000 0	1.00000 0	1.00000 0	1.000000	0.999999	1.000000	0.999998	1.000000	1.000000	0.999919	0.999984	0.998912
7	30-35	0.02563 7	0.99695 7	0.99992 4	0.99900 9	0.99151 7	1.00000 0		0.99984 8	1.00000 0	0.999999	1.000000	1.000000	1.000000	1.000000	0.999780	1.000000	1.000000	1.000000
8	35-40	0.00029 7	0.57927 9	0.81720 5	0.67044 5	0.48005 6	1.00000 0	0.99984 8		1.00000 0	1.000000	0.999332	1.000000	0.998666	1.000000	1.000000	0.991032	0.996267	0.963311
9	40-45	0.00224 0	0.87871 7	0.97623 2	0.92578 6	0.81149 2	1.00000 0	1.00000 0	1.00000 0		1.000000	0.999999	1.000000	0.999997	1.000000	1.000000	0.999905	0.999981	0.998769
10	45-50	0.00133 8	0.81720 5	0.95412 8	0.87921 3	0.73554 2	1.00000 0	0.99999 9	1.00000 0	1.00000 0		0.999993	1.000000	0.999979	1.000000	1.000000	0.999593	0.999896	0.996368
11	50-55	0.03967 3	0.99908 8	0.99998 9	0.99975 8	0.99694 2	0.99999 9	1.00000 0	0.99933 2	0.99999 9	0.999993		1.000000	1.000000	1.000000	0.999088	1.000000	1.000000	1.000000
12	55-60	0.00678 2	0.96416 8	0.99650 0	0.98232 4	0.93190 1	1.00000 0	1.00000 0	1.00000 0	1.00000 0	1.000000	1.000000		1.000000	1.000000	0.999999	0.999999	1.000000	0.999947
13	60-65	0.04955 3	0.99955 9	0.99999 6	0.99989 7	0.99834 8	0.99999 8	1.00000 0	0.99866 6	0.99999 7	0.999979	1.000000	1.000000		1.000000	0.998225	1.000000	1.000000	1.000000
14	65-70	0.00356 7	0.92249 7	0.98829 6	0.95626 0	0.87008 7	1.00000 0	1.00000 0	1.00000 0	1.00000 0	1.000000	1.000000	1.000000	1.000000		1.000000	0.999980	0.999997	0.999615
15	70-75	0.00026 1	0.55606 7	0.79946 3	0.64807 0	0.45736 2	1.00000 0	0.99978 0	1.00000 0	1.00000 0	1.000000	0.999088	0.999999	0.998225	1.000000		0.988900	0.995223	0.956995
16	75-80	0.09857 2	0.99997 7	1.00000 0	0.99999 7	0.99986 2	0.99991 9	1.00000 0	0.99103 2	0.99990 5	0.999593	1.000000	0.999999	1.000000	0.999980	0.988900		1.000000	1.000000
17	80-85	0.07076 3	0.99988 8	1.00000 0	0.99998 0	0.99948 2	0.99998 4	1.00000 0	0.99626 7	0.99998 1	0.999896	1.000000	1.000000	1.000000	0.999997	0.995223	1.000000		1.000000
18	85-90	0.17950 4	1.00000 0	1.00000 0	1.00000 0	0.99999 5	0.99891 2	1.00000 0	0.96331 1	0.99876 9	0.996368	1.000000	0.999947	1.000000	0.999615	0.956995	1.000000	1.000000	

Sub-maximal Drive – Blink frequency post-hoc analysis

Tukey HSD test; variable DV_1 (Drive Eye BlinkFrequency.sta) Approximate Probabilities for Post- Hoc Tests Error: Within MSE = 5.1218, df = 357.00

	TIM E	{1} - 14.398	{2} - 14.170	{3} - 15.360	{4} - 15.861	{5} - 16.683	{6} - 15.974	{7} - 17.342	{8} - 17.671	{9} - 17.045	{10} - 17.419	{11} - 17.254	{12} - 17.625	{13} - 18.158	{14} - 17.742	{15} - 17.792	{16} - 18.167	{17} - 17.764	{18} - 17.608
1	0-5		1.00000 0	0.99254 9	0.72761 8	0.04869 0	0.59861 9	0.00093 7	0.00010 9	0.00648 9	0.000551	0.001694	0.000142	0.000037	0.000077	0.000063	0.000037	0.000070	0.000158
2	5-10	1.00000 0		0.93833 7	0.46192 7	0.01432 4	0.33738 7	0.00019 9	0.00004 6	0.00148 2	0.000124	0.000356	0.000052	0.000036	0.000041	0.000039	0.000036	0.000040	0.000054
3	10-15	0.99254 9	0.93833 7		0.99999 9	0.85724 8	0.99997 7	0.18392 1	0.04260 6	0.46822 6	0.135353	0.252299	0.053509	0.002472	0.029538	0.022565	0.002341	0.026201	0.058140
4	15-20	0.72761 8	0.46192 7	0.99999 9		0.99882 7	1.00000 0	0.70776 3	0.33187 5	0.94072 1	0.619282	0.797220	0.379927	0.045656	0.264361	0.222203	0.043786	0.244807	0.398595
5	20-25	0.04869 0	0.01432 4	0.85724 8	0.99882 7		0.99983 1	0.99993 8	0.98994 8	1.00000 0	0.999718	0.999992	0.994052	0.713682	0.979306	0.967513	0.704558	0.974505	0.995170
6	25-30	0.59861 9	0.33738 7	0.99997 7	1.00000 0	0.99983 1		0.82070 0	0.45565 2	0.97673 5	0.746067	0.888449	0.509378	0.078666	0.376329	0.324315	0.075701	0.352457	0.529671
7	30-35	0.00093 7	0.00019 9	0.18392 1	0.70776 3	0.99993 8	0.82070 0		1.00000 0	1.00000 0	1.000000	1.000000	1.000000	0.998920	1.000000	1.000000	0.998774	1.000000	1.000000
8	35-40	0.00010 9	0.00004 6	0.04260 6	0.33187 5	0.98994 8	0.45565 2	1.00000 0		0.99997 0	1.000000	1.000000	1.000000	0.999999	1.000000	1.000000	0.999999	1.000000	1.000000
9	40-45	0.00648 9	0.00148 2	0.46822 6	0.94072 1	1.00000 0	0.97673 5	1.00000 0	0.99997 0		1.000000	1.000000	0.999990	0.966338	0.999867	0.999662	0.963890	0.999796	0.999994
10	45-50	0.00055 1	0.00012 4	0.13535 3	0.61928 2	0.99971 8	0.74606 7	1.00000 0	1.00000 0	1.00000 0		1.000000	1.000000	0.999703	1.000000	1.000000	0.999655	1.000000	1.000000
11	50-55	0.00169 4	0.00035 6	0.25229 9	0.79722 0	0.99999 2	0.88844 9	1.00000 0	1.00000 0	1.00000 0	1.000000		1.000000	0.996289	0.999999	0.999997	0.995871	0.999999	1.000000
12	55-60	0.00014 2	0.00005 2	0.05350 9	0.37992 7	0.99405 2	0.50937 8	1.00000 0	1.00000 0	0.99999 0	1.000000	1.000000		0.999997	1.000000	1.000000	0.999996	1.000000	1.000000
13	60-65	0.00003 7	0.00003 6	0.00247 2	0.04565 6	0.71368 2	0.07866 6	0.99892 0	0.99999 9	0.96633 8	0.999703	0.996289	0.999997		1.000000	1.000000	1.000000	1.000000	0.999995
14	65-70	0.00007 7	0.00004 1	0.02953 8	0.26436 1	0.97930 6	0.37632 9	1.00000 0	1.00000 0	0.99986 7	1.000000	0.999999	1.000000	1.000000		1.000000	1.000000	1.000000	1.000000
15	70-75	0.00006 3	0.00003 9	0.02256 5	0.22220 3	0.96751 3	0.32431 5	1.00000 0	1.00000 0	0.99966 2	1.000000	0.999997	1.000000	1.000000	1.000000		1.000000	1.000000	1.000000
16	75-80	0.00003 7	0.00003 6	0.00234 1	0.04378 6	0.70455 8	0.07570 1	0.99877 4	0.99999 9	0.96389 0	0.999655	0.995871	0.999996	1.000000	1.000000	1.000000		1.000000	0.999994
17	80-85	0.00007 0	0.00004 0	0.02620 1	0.24480 7	0.97450 5	0.35245 7	1.00000 0	1.00000 0	0.99979 6	1.000000	0.999999	1.000000	1.000000	1.000000	1.000000	1.000000		1.000000
18	85-90	0.00015 8	0.00005 4	0.05814 0	0.39859 5	0.99517 0	0.52967 1	1.00000 0	1.00000 0	0.99999 4	1.000000	1.000000	1.000000	0.999995	1.000000	1.000000	0.999994	1.000000	