

**A COMPARISON BETWEEN THE RESPONSIVENESS OF SELECTED  
PHYSIOLOGICAL AND SUBJECTIVE MENTAL WORKLOAD INDICATORS  
DURING REAL-WORLD DRIVING SCENARIOS**

**BY**

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## **ABSTRACT**

Sub-optimal levels of mental workload in automobile drivers is a risk factor for road accidents. However, mental workload as a construct cannot be directly measured. Common indicators of mental workload include heart rate frequency and variability, eye motion and subjective rating tools. Namely, the National Aeronautics and Space Administration Task Load Index (NASA-TLX), its modified, unweighted version called the Raw-TLX, and the Rating Scale of Mental Effort (RSME). Comparisons between the suitability and responsiveness of these mental workload indicators have been almost exclusively examined in driving simulators. However, real-world driving research is important as even high-fidelity simulators cannot capture the complexity of driving scenarios. Hence, this research aimed to compare the suitability and responsiveness of these mental workload indicators in response to real-world driving scenarios.

Six participants drove along a set route for an hour while wearing a heart rate monitor and eye tracker. A dashcam was used to capture footage of the different driving scenarios encountered. The set route comprised of driving through the industrial, residential, provincial main road and Rhodes University campus areas. RSME scores were taken during brief stops after driving through each zone. The NASA-TLX questionnaire was administered on completion of the drive and analysed later as the modified Raw-TLX version.

The data collected in response to the encountered driving scenarios were sorted into three meta-groupings. (1) Data was segmented according to the different areas that participants drove through. This was termed Area Events and were long duration scenarios of between five and thirty minutes. These driving scenarios were further segmented into two meta-groups with short duration driving scenarios (< 90 seconds). (2) The Common Events meta-group consisted of driving scenarios that were encountered by all participants. These were scenarios were anticipated by drivers. (3) The All Events meta-group was grouped according to all the driving scenarios that were encountered by participants. It consisted of both anticipated and unanticipated driving scenarios of short durations.

Data were further analysed using a method of systematically selecting a threshold value for each mental workload indicator. Responses to driving scenarios which surpassed the threshold were considered indicative of an increase in mental workload. The total frequency of higher mental workload events was used as a determiner responsiveness (or 'sensitivity') for each mental workload indicator.

Mental workload indicators were evaluated for their responsiveness and suitability for assessing mental workload. Results found blink frequency to be a responsive mental workload indicator for all categories of driving scenarios. Blink frequency and duration were the most responsive short duration mental workload indicators. Furthermore, the indicators were able to distinguish between higher and lower mental workload driving scenarios. However, blink parameters are also sensitive to driver fatigue and drowsiness. Further research on distinguishing mental workload from that of fatigue in response to real-world driving was recommended.

Pupil diameter, fixation duration, saccade duration and saccade amplitude were found to be responsive short duration mental workload indicators. However, these measures were not determined to be suitable for real-world driving applications. Pupil diameter was confounded by changing illumination levels. Fixation and saccade responses were confounded by the driving task itself as gaze could not be accounted for.

For long duration driving scenarios heart rate frequency, heart rate variability: high-frequency power, blink frequency and RSME were found to be responsive and suitable MWL indicators.

The Raw-TLX results could not be assessed for responsiveness as it was administered once. However, it was confirmed as a suitable cumulative mental workload indicator in the application of real-world driving. The moderate levels of workload reported by participants agreed with the experimental protocol that prevented inducing sub-optimal mental workload.

Blink frequency shows promise as a responsive and suitable mental workload indicator for different types of driving scenarios. More research is needed regarding the assessment of mental workload during short durations using blink frequency and blink duration. For driving durations between five and thirty minutes

long, further research into heart rate frequency, heart rate variability: high frequency power, and the RSME was recommended.

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Error bars denote standard deviation. Scenarios consisted of six data points each.  
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## CHAPTER 1 – RESEARCH AIMS

### 1.1 Road Accident Context

The rate of motor vehicle accidents around the world and South Africa are high. Many accidents can be attributed to human error due to too much or too little cognitive workload. Many recent studies have looked at mental workload during simulated driving (Lieberman *et al.*, 2014; Faure *et al.*, 2016; Shakouri *et al.*, 2018; Peruzzini *et al.*, 2019). There is a need to include more studies on mental workload using real vehicles. Therefore, this real-world study measures how indicators of mental workload respond to typical driving scenarios.

South Africa has a higher incidence of traumatic motor vehicle accidents both in comparison to developed countries and to that of other Southern African Development Community (SADC) countries. On average, 14 – 16 000 people per annum are killed and an additional 7 000 per annum are permanently disabled as a result of traffic accidents (Arrive Alive, 2011).

It is estimated that 75-90% of road accidents are due to human factors. 40% of deaths are due to collisions with, or to avoiding, pedestrians and jay-walkers which can be primarily attributed to drivers' lapse in attention which is a function of mental workload (Arrive Alive, 2011; da Silva, 2014). A failure to successfully negotiate hazards while driving can be attributed to either depletion of cognitive resources or a deviation from the optimal mental workload, according to which theory of mental workload is used. In both theories, measuring mental workload is essential to the understanding of information processing and for quantifying driver workloads (Marquart *et al.*, 2015).

To date, the number of driver, vehicle, road and environment studies using driving simulators has increased (Dols *et al.*, 2016). Indeed, numerous studies examining drivers and driving performance, including that of mental workload (MWL), are conducted using driving simulators (Bunce *et al.*, 2012; Zhao *et al.*, 2012; Hughes *et al.*, 2013; Almahasneh *et al.*, 2014; Platten *et al.*, 2014; van Leeuwen *et al.*, 2015; Li *et al.*, 2016; Tjolleng *et al.*, 2017; Kandemir *et al.*, 2018).

There are fewer studies conducted on real-world driving scenarios as simulator studies offer multiple advantages. Simulation studies can be set up to reproduce the stimuli or independent variable(s) in question without the risk of accident and at less cost. Furthermore, simulation studies offer repeatability and control of conditions in comparison to dynamic and unpredictable real-world driving (Dols *et al.*, 2016).

However, driving is inherently a complex multi-component activity and focusing on specific stimuli/variables would not give an overall indication of mental workload responses to driving. Physiological changes in response to simulated driving is not easily transferrable to real-world results (Charles and Nixon, 2019). Bongiorno *et al.* (2017, p.6) argue that using a real vehicle allows for analysis of workload caused by “stresses not preliminary known... in order to favour a natural behaviour of the driver.” This real-world study, therefore, examines how various indicators of mental workload respond to typical driving scenarios.

## **1.2 Background**

### **1.2.1 Driving and Mental Workload**

Several psychological and physiological measures are used to infer mental workload. Typical driving and mental workload studies use multiple measures to infer mental workload and are conducted via a driving simulator task.

Naturalistic driving studies have used the incidence of driver-error as an indication of inappropriate mental workload. No studies, to the author’s best knowledge, have yet examined the typical battery of mental workload indicators used in driving simulator studies in naturalistic driving studies.

However, a notable exception was the measurement of saccade latency and Galvanic Skin Response (GSR) in a naturalistic driving scenario (Bongiorno *et al.*, 2017). The study did not measure subjective feelings of mental workload, Heart Rate Variability (HRV), Heart Rate Frequency (HR), and other typical eye-motion metrics - which are typical mental workload indicators used in simulator studies.

Simulator-based studies do not match the complexity of real-world driving tasks. What can be inferred about mental workload in simulator studies, compared to real-world driving, is incomplete as simulator studies are inherently different from realistic driving (Charles and Nixon, 2019). Real-world driving is more visually complex and elicits different hazard perception in drivers than that of even high-fidelity simulators (Owsley and McGwin, 2010; Underwood *et al.*, 2011).

An exploratory study regarding the behaviour of the mental workload indicators themselves is needed. The outcome of this research is to determine potential areas where future research shows promise regarding the measurement of mental workload during real-world. These types of studies will measure driver workload during real-world conditions, as opposed to the incidence of driving error which presumes problematic mental workload levels. Ultimately, by accurately measuring error-inducing levels of mental workload, solutions can be found to reduce road accidents.

### 1.2.2 The Research Gap

In comparison to simulated driving studies, naturalistic driving studies provide data about driving situations after the fact. This information is representative of the reality of driving which provides an accurate understanding of current driving safety issues.

Mental workload is a crucial factor in understanding the mechanisms behind unsafe driving behaviour. Naturalistic driving studies have focused primarily on the incidence of distraction, collisions and near-crashes and their associated causes.

Factors such as secondary task demands, high traffic density and intersections are typical accident risk factors (Precht *et al.*, 2017). These studies look at links between the externally associated causes of accidents and near-collisions after the fact, and rates of these incidents. While invaluable, these types of naturalistic driving studies typically do not:

- 1) Look at physiological indicators of driver cognitive workload in the context of mental workload theory.

- 2) Compare the responsiveness (sensitivity) of commonly used indicators of mental workload during different real-world driving events.

### **1.3 Research Aims**

This research aimed to compare the responsiveness of mental workload indicators (indices) in response to real-world driving. In addition, it was expected that some indicators of mental workload are more responsive to certain driving scenarios (independent variables) than others.

Therefore, the main research aim was to compare the sensitivity of mental workload indicators in response to different categories of driving scenarios. The findings were then contextualised in terms of theories of mental workload. Secondly, this novel research aimed to address the research gap by identifying areas of future research regarding MWL assessment during real-world driving.

### **1.4 Research Approach: Exploratory Study**

The sensitivity of different indicators of mental workload under real-world conditions has not received due consideration. As such, this study was exploratory and hypothesis generating, as opposed to confirmatory, in approach.

Confirmatory studies are based on null hypotheses that are either accepted or rejected based on empirical data. In contrast, exploratory studies seek to generate hypotheses based on data collection and analysis (Jaeger and Halliday, 1998).

### **1.5 Methodological approach**

The research was exploratory (inductive) in nature intending to inform future studies in the field of driving and mental workload. Participants' physiological and perceptual indicators of mental workload were recorded in response to real-world driving scenarios. The task of driving was conducted on roads in and around the city of Makhanda (named Grahamstown prior to June 2018), Eastern Cape.

## **CHAPTER 2 – REVIEW OF RELATED LITERATURE**

### **2.1 Introduction to Mental Workload**

Mental workload in response to driving has become an increasingly important area of consideration. Traffic density, the use of in-vehicle interfaces and the use of mobile devices are increasing, which makes driving an increasingly complex task. Furthermore, these additional demands on attention can vary during a single driving session causing the driver's mental workload to fluctuate vastly (Brookhuis and de Waard, 1993; Verwey, 2000). There is evidence that the risk of vehicular accidents is a function of the mental workload of the driver as many accidents occur due to lapses in attention (da Silva, 2014).

Academic interest in driving and mental workload began in the late 1970s after the publication of the book "Mental Workload" by Neville Moray in 1979. Initially, mental workload was predominately studied in the context of air traffic controllers and pilots and later in other contexts, notably in professional drivers (da Silva, 2014).

It is in these high-risk applications, where errors can cost a lot in both asset damage and human life, that understanding mental workload became, and remains, an important consideration (da Silva, 2014). In terms of safety, the evaluation of mental workload is almost as critical as, and indeed complementary to, immediate safety concerns such as the driver's vehicle handling knowledge and ability (Pauzié and Manzano, 2007). Understanding the limits of operator mental workload as well as defining adequate and optimal mental workload were, and remain, the aim of research into mental workload (Verwey, 2000; de Waard, 1996).

#### **2.1.1 Defining Mental Workload**

Simplistically, mental workload can be defined as the amount of information processing demands placed on the human. That is the amount of information processing that is used in order to complete a task (Brookhuis and de Waard,

1993). A complete general definition would include the individual workers' capacity as well as the task demands. This makes the concept of mental workload inherently a study about a system as the interaction between human and task, rather than simply being a synonym for 'cognitive task demands' (de Waard, 1996; da Silva, 2014). Mental workload is both a reflection of the tasks' effects and the driver's characteristics, capabilities and knowledge, motivation to perform the task, as well as their general mood and health (Brookhuis *et al.*, 2009; Verwey, 2000).

Thus, quantifiable measurements of mental workload are only possible in response to a task and are not absolute measures themselves. Mental workload has no direct measure, but is inferred by other indicators (Brünken *et al.*, 2003). In the present study, mental workload was measured in response to real-world or field driving conditions.

### 2.1.2 Mental Workload vs. Mental Effort

Mental effort is distinct from mental workload. Conceptually, mental workload occurs whenever there is information processing taking place, regardless of the human's subjective feelings of cognitive exertion. For example, mental workload is incurred both when the driver perceives a driving task as being comfortable and "effortless" and when the driver can feel themselves exerting mental energy. Mental effort is a type of mental workload that is specific to the latter case when the driver is "trying hard" to achieve a goal (Brookhuis and de Waard, 2010).

Furthermore, mental effort can be categorised into two modes or degrees, namely 'computational effort' and 'compensatory effort' (Mulder, 1986;). Computational effort refers to a level of mental effort which is enough to perform a task. In contrast, compensatory effort is applied when additional workload demands are made and in order to maintain the original level of performance output. The compensatory effort would then refer to the extra effort required when the complexity of the primary task increases and to execute a secondary task. However, the compensatory effort is not as sustainable as computational effort and leads to a state of fatigue faster (Brookhuis and de Waard, 2010; da Silva, 2014).

## 2.2 Theories of Mental Workload

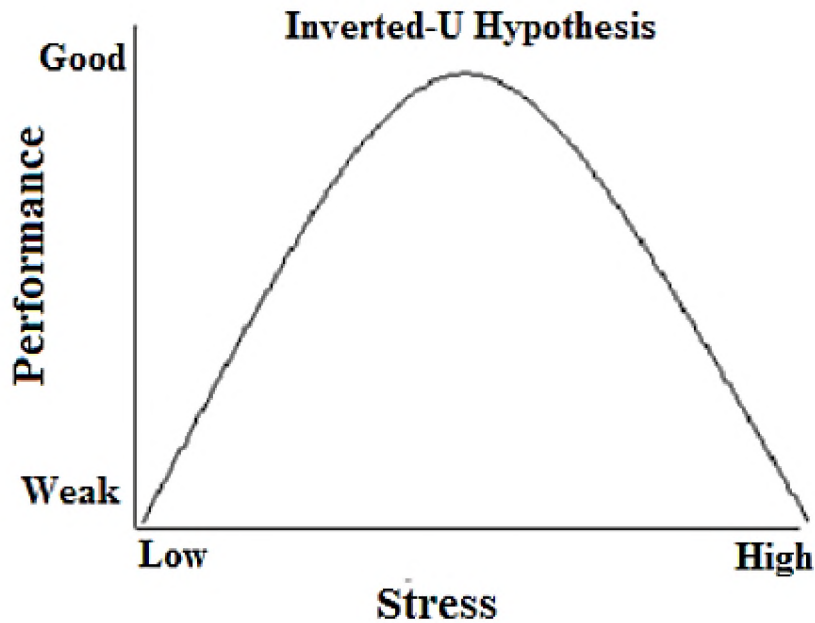
There is no all-encompassing theory of mental workload (Yeh and Wickens, 1988). However, the cognitive energetic theory and the multiple resource theory of mental workload have proved useful in real-world contexts or applications.

It is understood that a multifaceted and dynamic understanding of mental workload is needed, given the complexity of the human driver. There are several psychophysiological systems of the human involved. Mental workload is comprised of neurophysiologic, perceptual and cognitive processes of the human operator (Baldwin and Coyne, 2003).

### 2.2.1 Cognitive Energetic Theory of Mental Workload

Cognitive energetic theory proposes that every human operator has an optimal energetic state in which to execute a specific task (Gaillard and Wientjes, 1994). An optimal energetic state is reached when performance output is good, and the operator feels comfortable and able to meet the demands of the task (Brookhuis and de Waard, 2010; da Silva, 2014).

The cognitive energetic theory is based on the Inverted-U model illustrated in Figure 1. The model's hypothesis is that performance increases as a function of arousal - up to a point. 'Arousal' refers to the physical and mental readiness that occurs in response to psychophysical stress brought on by task demands. If overall arousal increases further than this point, performance drops (U.S. Army Research Laboratory, 2000; Karimi and Kangavari, 2012; Peruzzini *et al.*, 2019).



*Figure 1: The Inverted-U Hypothesis illustrates the cognitive energetic theory of mental workload (taken from Karimi and Kangavari, 2012, p.194).*

The optimal energetic state is achieved when the driver operates from the top of the inverted-U graph (Brookhuis and de Waard, 1993). In terms of mental workload, the top of the curve signifies that the driver's mental workload is ideal and is in-between being too low, as it would be on the left of the graph, or too high as is the case on the right side of the graph.

Underlying this energetic state theory is the hypothesis that the driver has to operate from an ideal level of psychophysiological arousal. Erroneous or potentially harmful behaviours are made when arousal is at a suboptimal or excessive level (Brookhuis and de Waard, 1993).

Causes of underload in driving include alcohol consumption, sleep deprivation and fatigue, mainly induced by long-distance non-urban driving conditions. Driver underload is more prevalent than driver overload, which occurs when additional demands are made on the driver, such as when navigating through a busy intersection (Brookhuis and de Waard, 1993). Operating in-vehicle interfaces such as navigation systems and radios as well as the use of cell phones are generally

reported to increase arousal and mental workload while driving (Klüver *et al.*, 2016).

### 2.2.2 Multiple Resource Model of Mental Workload

Wickens' resource model has been the most widely applied mental workload theory for three decades (Wickens, 2008). The model has been revised since its conception to account for different modes of mental processing. Earlier and simpler resource models depicted all mental resources as a single pool from which any information processing depletes these resources. Wickens' revised theory proposes that not all mental resources can be grouped. This has had implications for dual-tasks in explaining why certain tasks can be successfully done simultaneously and others not (Wickens, 2008). For example, one can lift boxes and hold a conversation because the cognitive processing required to execute a physical manoeuvre is different to that required for producing a verbal output.

Wickens' revised resource theory is conceptualised as a four-dimensional cube which includes the stages of information processing on the x-axis and types of perceptual input on the y and z-axes (refer to the upcoming Figure 2). Information processing steps along the x-axis are Perception, Cognition (analogous to decision making) and Response (or output). Perception is then divided into visual and auditory modes on the y-axis and spatial and verbal on the z-axis. Similarly, Cognition and Responding are both divided into spatial and verbal modes.

This indicates that different cognitive resources will be used to process visual and auditory information (y-axis) and also spatial and verbal information (z-axis). Similarly, different cognitive resources will be used to produce a physical output than it would a verbal output.

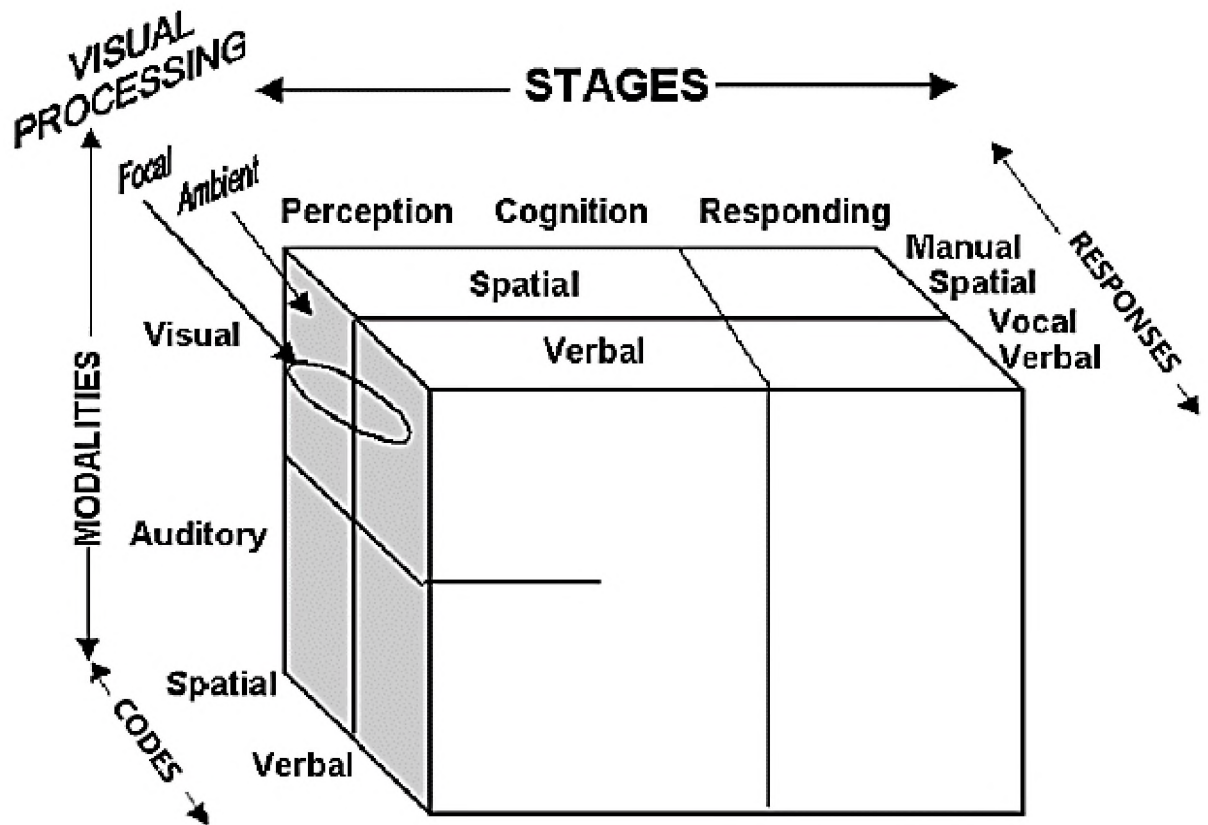


Figure 2: Wickens' 4D resource model of mental workload (taken from Wickens, 2008, p.450).

## 2.3 Driving and Mental Workload Theories

### 2.3.1 Driving Task Demands and Mental Workload

Due to the multidimensional nature of mental workload, the relationship between it and task demands are multipart. It might be expected that as the task demands of driving increases, for example when navigating an intersection, that mental workload would increase linearly to match. However, drivers can employ different strategies to manage demands or may be limited in their capacity to deal with those demands (Yeh and Wickens, 1988; da Silva, 2014).

In some cases, mental workload stays the same or even decreases in response to an increase in task demand. Yeh and Wickens (1988) refer to this scenario as 'dissociation'.

Drivers might invest less mental effort thus reducing workload. Dissociation might also occur in cases where a secondary demand does not compete for the same resources and can be executed efficiently as a result. Both causes of dissociation are especially evident in the case when measuring subjective mental workload (Yeh and Wickens, 1988). However, differences between different mental workload responses help to deduce the operator's true response.

### 2.3.2 Driving as a Complex Task

Driving is a complex activity. Equally, measuring mental workload as well as comprehensively defining it is complex. However, the empirical link between safe driving and the optimal workload is evident (da Silva, 2014; Shakouri *et al.*, 2018). This makes it necessary to understand driving through the lens of mental workload.

Driving is sophisticated as it requires different modes of operation (different kinds of sub-tasks) in a dynamic environment. Mental workload can fluctuate with changing traffic and pedestrian density, use of in-vehicle interfaces (IVIs), mobile phone usage and distraction by passengers (de Waard, 1996; Verwey, 2000; Foy and Chapman, 2018).

Driving is a physical task in that pedals, the steering wheel and gear shaft are manoeuvred. It is a mental task as the driver makes decisions based on external input and internal memory. The visual and mental aspects of driving are closely related as input is primarily visual and decisions are made based on judging space-time relationships (Marquart *et al.*, 2015). Similarly, visual-motor integration is a related cognitive demand (Peruzzini *et al.*, 2019).

The intensive visual scanning of the environment is a demand limited by the driver's cognitive resources. One aspect is that visual short-term memory is limited to one object - when all objects are of the same visual category (Olsson and Poom, 2005). Another limit is that of attention span. When these cognitive resources are overly taxed, a possible consequence is "inattention blindness" which is a driving safety concern (Wiberg *et al.*, 2015).

Furthermore, the tactical and strategic aspects of driving contribute to overall mental workload. Janssen (1979, as cited in de Waard, 1996) describes driving complexity in terms of three hierarchical tiers. Top-level concerns are about strategic decisions about destination and route-choice. The intermediate, manoeuvring level consists of responding to other road users and traffic regulations. The lowest level concerns the operation of the vehicle itself. In experienced drivers, the top and intermediate levels use most cognitive resources (de Waard, 1996).

### 2.3.3 Driving According to the Energetic Theory of Mental Workload

The energetic theory of mental workload is often employed in cases where performance loss due to cognitive underload is a concern.

One example is the problem with partially-automated vehicles. The driver must take manual control of the vehicle when necessary. This poses a problem as driver inactivity during automated driving phases leads to lowered arousal levels. Performance is then compromised when the driver is prompted to take-over control. Responses from the driver are incorrect and/or delayed, compromising safety (Naujoks *et al.*, 2018).

A proposed solution is to increase the energetic cognitive state of the driver by adding a secondary-task. This has been shown to reduce fatigue associated with cognitive underload (Miller *et al.*, 2015). However, an increased response time due to task-switching remains a concern (Körber *et al.*, 2016; Naujoks *et al.*, 2017, 2018).

The energetic cognitive theory of mental workload is also applicable to short-haul light vehicle drivers. In this case, fatigue is caused by cognitive underload from the monotony of driving through rural areas (Friswell and Williamson, 2013).

### 2.3.4 Driving According to the Multiple Resource Model of Mental Workload

The multiple resource theory of mental workload is often used in the context of driving. Firstly, the theory is based on differentiating aspects of mental workload. Driving utilises the visual channel of information processing which is a facet of the

multiple resource theory. The framework of Wickens' theory is useful in that it allows for the differentiation of visual workload as well as providing classification and context of other driving-related sub-tasks. It is a multi-faceted theory which lends itself to conceptualising driving as a complex task.

Furthermore, the fourth dimension of Wickens' theory divides visual perception into focal and peripheral. It is an essential division for driving, as both types of visual perception are utilised while scanning the environment (Ma *et al.*, 2018). In this regard, the multi-resource theory also hypothesises that focal and peripheral visual input draws on different (though highly related) cognitive resources.

Secondly, multiple resource theory is useful in the study of IVI usage and driver distraction. It hypothesises which kinds of secondary tasks compete for the same resources as the primary driving task. However, even theoretically non-competing secondary tasks (e.g. talking) compromises the driver's visual attention (Ma *et al.*, 2018). This is due to limits of attention span which is responsible for the conscious allocation of mental resources (Patten *et al.*, 2004; Stapel *et al.*, 2019).

De Waard (1996) used the multiple resource model to explain that driving increasingly taxes auditory resources. Mobile phones and more recently Global Positioning System devices and IVI alerts have audio outputs.

In conclusion, both the energetic and multiple resource theories describe the same underlying construct that is mental workload. The use of either theory is based on which aspect of mental workload and driving is of particular concern. Cognitive underload issues are best understood in terms of the energetic theory, whereas driving as a visually-based task or driving distraction and IVI usage are suited to Wickens' multiple resource theory of mental workload.

## **2.4 Measuring Mental Workload**

Indicators of mental workload fall into three main categories: performance, physiological and subjective measures. Measures of performance are an important component in the assessment of mental effort. In cases of high task demand, performance declines or the operator compensates by reducing the task

demands. In the case of driving, compensation or lowering task demands is done by reducing vehicle velocity (de Waard *et al.*, 1995).

However, performance Indicators have received less consideration than physiological and subjective mental workload Indicators (Jorna, 1992; Brookhuis and de Waard, 1993; Verwey and Veltman, 1996). Furthermore, using driving performance as a mental workload indicator was beyond the scope of the research given the experimental effort needed to do so.

Therefore, the research represented in this thesis aimed to compare a selection of physiological and subjective mental workload indicators. Physiological indicators consisted of heart rate, Heart Rate Variability (HRV) and eye motion Indicators.

## **2.5 Heart Rate and Heart Rate Variability**

### 2.5.1 Physiological Basis

Electrocardiogram-based (ECG) measures are the most commonly used physiological indicator of mental workload (Charles and Nixon, 2019). Before details of these indicators are individually discussed, the physiology responsible for the link between these ECG indicators and mental workload warrants discussion.

Heart rate pacing is initiated by the sinoatrial node of the heart where the pacemaker cells are located. The sinoatrial node is innervated by both sympathetic and parasympathetic branches of the autonomic nervous system (ANS), as well as by the heart itself (Pumprija *et al.*, 2002; Thayer *et al.*, 2009).

An increase in heart rate frequency can occur when the activity of the sympathetic nervous system (SNS) is increased, and the parasympathetic nervous system (PNS) activity is diminished. In this case, alertness is increased by an increase in heart rate and metabolic activity. Conversely, lower SNS and higher PNS activity lead to cardio-deceleration and a “rest and digest” state (Acharya *et al.*, 2006; Hoover *et al.*, 2012; Marinescu *et al.*, 2016). However, both the SNS and PNS can be activated at the same time, and at varying degrees, in the heart and other

organs. Thus, determining the domination of either nervous system branch is not simple or direct (Berntson *et al.*, 1994).

The SNS is mediated by the release of the neurotransmitter noradrenaline, which is relatively slowly metabolised. The PNS is regulated on a quicker, beat-to-beat basis, as the fast-acting neurotransmitter acetylcholine controls it. Therefore, the SNS and PNS operate at different frequencies making it possible to distinguish their distinct influences (Acharya *et al.*, 2006).

There is a physiologically direct and indirect manner by which mental workload influences HRV. Indirectly, an increase in mental workload is physiologically arousing as greater alertness is required to meet task demands (Thayer and Lane, 2009; Shakouri *et al.*, 2018).

The neurovisceral integration model is the basis for understanding the direct link. The model is based on evidence that the brain's prefrontal cortex is linked to the ANS - which is ultimately responsible for the heart's pacing. It is the prefrontal cortex which is responsible for executive (higher) cognitive ability (Fallahi *et al.*, 2016; Luque-Casado *et al.*, 2016).

### 2.5.2 Heart Rate

Heart rate frequency (HR) is measured as the number of heart beats per minute, though other periods can be used (Charles and Nixon, 2019). HR has been found to increase in response to an increase in mental workload (De Rivecourt *et al.*, 2008; Mulder *et al.*, 2009; Brookhuis and de Waard, 2010). The increase in HR has been observed explicitly in response to conditions with multiple tasks (Mehler *et al.*, 2011; Charles and Nixon, 2019).

However, according to Brookhuis and de Waard (2010), HR is better suited to measure physical rather than mental activity. Indeed many researchers of mental workload exclude it entirely in favour of HRV (Pumppla *et al.*, 2002; Hoover *et al.*, 2012; Luque-Casado *et al.*, 2016).

In the context of real-world driving, Mehler *et al.* (2011) argue that HR should not be discounted. The authors found HR to be more sensitive than HRV to the

change from low to moderate workload during real-world driving. The authors thus advocate for the use of both HR and HRV in assessing mental workload.

It is worth noting, however, that mental workload was increased by adding a secondary, memory recall task while driving and not due to an increase in driving demands. Similarly, Wiberg *et al.* (2015) found HR to be a particularly sensitive measure of increased mental workload during city-driving.

### 2.5.3 Heart Rate Variability

HRV is derived via calculation from recorded information of the heart's electrical activity over time (Hoover *et al.*, 2012; Shakouri *et al.*, 2018; Charles and Nixon, 2019).

HRV is defined as the variation in the duration (in ms) between each heartbeat over time (Pumprla *et al.*, 2002; Acharya *et al.*, 2006). Specifically, this inter-beat-interval (IBI) is the duration between each successive heart beat's peak point, R, of the QRS complex. The QRS complex refers to the electrocardiograph depiction of the electrical activity of one cardiac cycle (Shakouri *et al.*, 2018). These R-R durations vary over time due to the modulating effect of the ANS (Acharya *et al.*, 2006).

The use of HRV as a measure of mental workload has two main advantages. Firstly, there is good physiological and empirical evidence of HRV as a meaningful measure of mental workload. Secondly, it is a non-invasive, relatively inexpensive and easy measure to attain (Fallahi *et al.*, 2016; Luque-Casado *et al.*, 2016).

However, HRV readings are influenced by the length of the sample duration. It is therefore advised to compare samples with the same durations (Task Force of the European Society of Cardiology, 1996; Charles and Nixon, 2019).

### 2.5.4 HRV: Time Domain Analysis

Time domain analysis of HRV calculates the total variability of R-R intervals over a period. These periods are typically short (between 0.5 and 5 minutes) given the heart's responsiveness to stress (Acharya *et al.*, 2006). Time domain analysis is thus a measure of the amount of variability of IBIs (Pumprla *et al.*, 2002).

There are two primarily used time domain indices. The first calculation is the standard deviation of the differences between all N-N intervals, abbreviated as 'SDNN' (Acharya *et al.*, 2006; Charles and Nixon, 2019). N-N stands for 'normal to normal' intervals as abnormal heartbeats (such as missed beats) are excluded from the equation (Charles and Nixon, 2019). The second index is the root mean square of successive differences between normal IBI, abbreviated as rMSSD (Pumprla *et al.*, 2002; Acharya *et al.*, 2006; Tjolleng *et al.*, 2017).

SDNN is the most straightforward HRV measure (Shakouri *et al.*, 2018). It is also suitable for assessing HRV for ultra-low duration samples of 30 seconds (Castaldo *et al.*, 2019).

rMSSD is considered the more robust HRV measure as it is a beat-to-beat measure – unlike the more summative SDNN index. Furthermore, rMSSD can indicate the PNS influence on the heart's pacing as it is a beat-to-beat measure (Mehler *et al.*, 2011; Shakouri *et al.*, 2018).

Lastly, both time domain measures typically decrease in response to increased mental workload (Brookhuis and de Waard, 2010; Tjolleng *et al.*, 2017 Charles and Nixon, 2019).

#### 2.5.5 HRV: Frequency Domain Analysis

Spectral analysis of IBIs is used to separate HRV frequency bands. These frequency bands differentiate between the influence of PNS or SNS in response to mental workload (Acharya *et al.*, 2006). While a valuable measure in this regard, frequency domain analysis is influenced directly by movement and respiration (Hsu *et al.*, 2015).

The high-frequency band (0.15 – 0.4 Hz) is associated with PNS influence, given that the rapidly acting neurotransmitter, acetylcholine, modulates the PNS. The high-frequency band is also influenced by respiration. An increase in mental workload is expected to result in a decrease of high-frequency power (Hoover *et al.*, 2012; Fallahi *et al.*, 2016; Tjolleng *et al.*, 2017).

The low-frequency band (0.04 – 0.15 Hz) is associated with the dominance of SNS activity, as well as the influence of the baroreflex mechanism (Pumprla *et al.*, 2002; Acharya *et al.*, 2006).

Power measures of the low-frequency band also correlate with direct measures of the muscle's sympathetic nerve activity. This correlation supports the association between the low-frequency band of HRV and physiological arousal stemming from SNS influence (Pumprla *et al.*, 2002).

It then follows that the low-frequency band is expected to increase in response to increasing mental workload (Pumprla *et al.*, 2002; Fallahi *et al.*, 2016; Shakouri *et al.*, 2018). It should be noted that the frequency ranges defining each band is not standard and differs slightly amongst researchers (Charles and Nixon, 2019).

However, spectral analyses requires a different “moving window technique” on intervals less than two minutes long, especially the low-frequency power band (Stuiver *et al.*, 2012). In this technique, power is calculated by overlapping time segments of 30 second intervals. When using straight-forward computations, time domain analyses are suitable for short time excerpts (Castaldo *et al.*, 2019).

Furthermore, longer sample durations increase the variability of time domain results. Thus, the results of long and short sample durations should be analysed separately, and the mental workload inferences of these results cannot be directly compared (Charles and Nixon, 2019).

## **2.6 Eye Motion Metrics**

Eye motion metrics are measurements of the movements of the eyeballs, lids and changes in pupil size. Core movements of the eyeballs are fixation and saccades. Blink parameters, such as frequency and duration, are measures obtained from the endogenous opening and closing of the eyelids (Marquart *et al.*, 2015). These parameters have been shown to respond to changes in cognitive demands (Van Orden *et al.*, 2000; Ahlstrom and Friedman-Berg, 2006).

Recent technological advancement has made tracking eye motion parameters easier and affordable. According to Charles and Nixon (2019), this accessibility explains the recent popularity of eye movements as a mental workload indicator.

In addition to being accessible, eye motion measures offer a relatively reliable measure of mental workload. In particular, pupil size and eye blink measures have been frequently and reliably used to measure overall mental workload (Kramer, 1990; Charles and Nixon, 2019). Saccade and fixation parameters are lesser used measures of mental workload.

Furthermore, eye motion measures are responsive to changes in mental workload over short intervals in the order of milliseconds. It detects fluctuations in mental workload not reflected by longer-duration subjective measures. Eye motion measures are taken continuously, eliminating the need to interrupt the task (Van Orden *et al.*, 2000; Ahlstrom and Friedman-Berg, 2006; Marchitto *et al.*, 2016). This makes eye motion a good measure for real-world experiments.

However, eye motion measures are affected by other factors. Pupil size is affected by changes in ambient illumination, emotional state and drug use. Eye blinks can be affected by air quality, drowsiness or fatigue - which may not necessarily be caused by the task in question (Kramer, 1990; Charles and Nixon, 2019).

Furthermore, eye motion can be reflexive to the type of task being performed as opposed to purely indicative of mental workload. When eye motion occurs in the absence of an identifiable stimulus it can reflect endogenously occurring cognitive workload (Marquart *et al.*, 2015). Thus, care must be exercised when inferring mental workload from eye motion measures.

There are mixed results in the literature regarding whether higher or lower values indicate an increase in mental workload. The differences due to the type of tasks performed (e.g. vigilance, simulation, real-world, long-duration tasks) could account for the contradictions in the findings.

### 2.6.1 Fixations and Saccades

Eye movements offer an indication of underlying cognitive processes as the eyes move from one interest point to the next (Zeghal *et al.*, 2002). Core ocular

movements comprise fixations and saccades. Fixations occur as the eye stops to focus on a point and are performed to relay visual information to the retina for further cognitive processing (Marquart *et al.*, 2015). However, seeing does not necessarily guarantee cognitive processing and substantial increase in mental workload. Therefore, an additional measure of mental workload is useful for clarification (Zeghal *et al.*, 2002).

Saccades are rapid eye movements that orientate the eye to fixation points (Goldberg and Kotval, 1999; Marquart *et al.*, 2015). Unlike fixations, visual information is not perceived during saccades; however it is an essential aspect of ocular-motor coordination (Goldberg and Kotval, 1999; Marquart *et al.*, 2015). There are a few variables related to the saccadic movement which will be outlined below.

#### 2.6.2 Saccade Amplitude

Saccade amplitude refers to the angular distance the eye has moved during a saccade. Saccade amplitude was found to decrease as aircraft were added to an air traffic control simulation (Ahlstrom and Friedman-Berg, 2006).

Ahlstrom and Friedman-Berg (2006) argued that the decreased saccade amplitude was not a reflection of the decreased distances between aircraft as aircraft density increased. Traffic density did not “contribute to a linear decrease in distances between aircraft” (Ahlstrom and Friedman-Berg, 2006, p.631). Complex relationships between traffic density and weather movements, runway selection and traffic flow adjustments accounted for this. Therefore, the decrease in saccade amplitude indicated an increase in mental workload, rather than just being a result of the gaze activity required by the task.

A study of motorcycle driving around a track found that saccade amplitude remained constant through light and heavy cognitive load conditions. However, a decrease in saccade velocity was found during the higher cognitive load condition. An unchanging saccade amplitude coupled with decreased saccade velocity suggested to the researchers that less visual information was gathered during the higher mental workload condition (Ohtsuka *et al.*, 2015).

### 2.6.3 Saccade Duration

Increases in workload during an air traffic control task resulted in shorter saccade durations (Ahlstrom and Friedman-Berg, 2006).

However, saccade duration increased over time during a visual vigilance task (Schmidt *et al.*, 1979; McGregor and Stern, 1996). Visual fatigue may decrease saccade duration whereas task complexity may increase it. The differences in these findings suggest that changes in saccade duration are determined by task kind.

### 2.6.4 Saccade Velocity

Average saccade velocities can reach  $900^{\circ} \cdot s^{-1}$  and can be influenced by fatigue, arousal and task difficulty (Marchitto *et al.*, 2016).

Older studies have found saccade velocity to decrease as a function of time-on-task during a visually-based vigilance task (Schmidt *et al.*, 1979; McGregor and Stern, 1996). However, McGregor and Stern (1996) caution against using average saccade velocity as a measure of fatigue as its decrease is a consequence of increased blink frequency.

During an air traffic control simulation, Marchitto *et al.* (2016) found a decrease in the saccade velocity of larger saccades as task complexity increased. The researchers reasoned that the decrease in velocity was due to a need for greater precision requiring more “cognitive control” - cutting down on cognitive costs.

### 2.6.5 Fixation Duration

There are opposing findings of the effect of mental workload on fixation duration. In one study, fixation duration decreased with task load in pilots during a flight task (De Rivecourt *et al.*, 2008). Similarly, fixation duration decreased as errors increased during a tracking task. The increase in errors was indicative of loss of performance due to fatigue (Van Orden *et al.*, 2000).

Fixation duration increased during a driving simulation when a hazard was approached. The reasoning, in this case, was that fixation duration increased as

drivers needed to spend more time visually processing the hazardous situation (Underwood *et al.*, 2011). Similarly, Marchitto *et al.* (2016) saw an increase in fixation duration during complex conflict detection conditions in an air traffic control simulation.

De Rivecourt *et al.* (2008) determined that an increase in task demands and visual complexity resulted in a decrease in fixation duration. However, in cases where a secondary task was added, fixation duration increased.

### 2.6.6 Blink Frequency and Duration

A blink is defined by Benedetto *et al.* (2011) as the rapid opening and subsequent closing of the eye. Blink rate is the number of blinks occurring during a set period and blink duration refers to the time of a single blink.

Recarte *et al.* (2008) discussed the difficulty in interpreting increased blink rate as it happens due to fatigue (low activation state) as well as due to an increase in visual task demand (high activation state).

Recarte *et al.* (2008) found a decrease in blink rate during a simulated driving task, which the authors theorised was the case to meet the visual-processing demands of driving. This can be attributed to an increase in attention or due to more information needing to be processed (Veltman and Gaillard, 1998; Faure *et al.*, 2016). Faure *et al.* (2016) conclude that a decrease in blink rate is a mechanism employed to reduce the risk of missing visual information during increased task demand.

In contrast, blink frequency was found to increase with cumulative time on task during a driving simulation task (Benedetto *et al.*, 2011). Furthermore, Faure *et al.* (2016) found an increase in blink frequency when a secondary cognitive task was added to the primary simulator driving task. This suggests that blink rate may increase in response to high cognitive demand due to long task duration (fatigue) or multiple task demands.

Blink duration has been found to increase in response to drowsiness and fatigue and decrease in response to sustained attention or information processing (Ahlstrom and Friedman-Berg, 2006; Faure *et al.*, 2016).

### 2.6.7 Pupil Diameter

Pupil diameter ranges from 2 to 8 mm and controls the amount of light the retina receives. Pupil size is controlled by a group of antagonistic muscles that are innervated by nerve fibres from the sympathetic and parasympathetic nervous system (Kramer, 1990). As with heart rate variability, nervous system control explains the link between cognition and its effect on physiological responses.

Pupil size is affected by illumination, working memory and mental workload (Benedetto *et al.*, 2011). The two main functions of the pupil are to protect the retina from over-exposure to light and to assist in focusing objects viewed at a distance by increasing field depth. In these two cases, the change in pupil size is greater than in response to mental workload (Kramer, 1990; Marquart *et al.*, 2015).

Small changes in pupil size are generally indicative of cognitive processing whereas more substantial changes in pupil size (> 0.5 mm) are due to changes in illumination (Marquart *et al.*, 2015). The former is known as the task-evoked pupillary response (TEPR). However, distinguishing TEPR from illumination responses can be challenging, thereby requiring additional assessment techniques. For example, the Index of Cognitive Activity (ICA) is a signal-processing technique that can separate the two causes (Marquart *et al.*, 2015). However, pupil size can be a reliable and even immediate indication of mental workload when illumination is controlled (Iqbal *et al.*, 2005).

In general, pupil diameter increases with cognitive processing demands (Van Orden *et al.*, 2000; Zeghal *et al.*, 2002; Lin *et al.*, 2003; Iqbal *et al.*, 2005; Ahlstrom and Friedman-Berg, 2006). An increase in pupil diameter was observed in response to tasks involving planning and visual attention (Causse *et al.*, 2010). During another driving simulator study, increased pupil diameter was found to be more sensitive to increasing cognitive demands than increased blink rate (Niezgoda *et al.*, 2015).

However, Van Orden *et al.* (2000) found that pupil diameter did not increase with minor increases in task difficulty during a vigilance task requiring visual attention.

Furthermore, Van Orden *et al.* (2000) found pupil diameter to decrease due to drowsiness.

## **2.7 Subjective Measures of Mental Workload**

Subjective mental workload measures aim to assess the feelings of cost that the operator experiences by executing a task (Hart and Staveland, 1988).

Commonly used subjective measures are the National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire and Rating Scale of Mental Effort (RSME) (Charles and Nixon, 2019). As subjective measures they share the following general advantages and disadvantages.

Subjective mental workload measures are cost-effective and non-intrusive (Wiebe *et al.*, 2010). They are also easy to implement and there is evidence for subjective mental workload measures being sensitive to changes in task difficulty (Rubio *et al.*, 2004).

However, they can be difficult to execute in real-world driving scenarios (Pauzié and Manzano, 2007; da Silva, 2014). Furthermore, they are subjective and rely on the memory of the operator (Marinescu *et al.*, 2016). However, differences between subjective and more objective measures helps to deduce the driver's true mental workload response.

Psychophysiological measures have the advantage of assessing mental workload timeously and objectively (Niezgoda *et al.*, 2015). Sometimes physiological and subjective mental workload results diverge (Faure *et al.*, 2016). However, during an in-vehicle interface driving simulator study, blink rate and duration were corroborated by both NASA-TLX and RSME scores (Benedetto *et al.*, 2011).

### **2.7.1 NASA-TLX and Raw-TLX**

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) is a widely implemented mental workload questionnaire. Published in 1988, it has proved empirically useful in assessing mental workload in several areas of application such as driving, air traffic control, aviation piloting, and even remote-

controlled robotics (Hart, 2006; Luque-Casado *et al.*, 2016). The NASA-TLX is used mainly as a comparative measure where the results of a baseline task are compared to those of the focal task (Bustamante and Spain, 2008).

The NASA-TLX is multi-dimensional in that it evaluates six aspects of mental workload perception. Participants rate their experience of mental demand, physical demand, temporal demand, performance, effort and frustration (Hart, 2006; Wiebe *et al.*, 2010). By using a combination of six subscales associated with the experience of workload, it is theorised that the outcome would be representative of the overall total mental workload (Hart, 2006).

There is a total of 21 rating gradations for each subscale; 10 on the “very high” side and 10 on the “very low” side with a middle demarcation of one (refer to Appendix A, Figure 30).

Some aspects (sub-scales) are then weighted. After a rating of each sub-scale is made, they are compared to one another in terms of relevance to the task. The participant chooses which subscale was more pertinent to the task through 15 pairwise comparisons. The number of times that a sub-scale was chosen over other subscales is multiplied by the given rating. An overall mental workload rating is calculated by adding the results and dividing by 15 (Hart and Staveland, 1988; Rubio *et al.*, 2004; Bustamante and Spain, 2008).

A common modification to the NASA-TLX is the elimination of the weighted scales. This version is called the Raw Task Load Index (typically called the Raw-TLX and RTLX) and has gained popularity due to its ease of use and lower time cost (de Waard, 1996; Hart, 2006). Another common change is to exclude the overall rating in favour of comparing subscale results (Hart, 2006).

Hart (2006) reports mixed findings regarding the correlation of RTLX results with those of the NASA-TLX. However, the exercise of determining weightings introduces a source of measurement error (Bustamante and Spain, 2008; Wiebe *et al.*, 2010). This, in addition to the ease of use, may make the RTLX a favourable measure.

### 2.7.2 NASA-TLX Advantages and Limitations

As with other self-reported measures, the rationale behind using the NASA-TLX is that the driver's subjective experience of the different aspects of mental workload is an accurate indicator of mental strain (de Waard, 1996; da Silva, 2014).

There is evidence that the NASA-TLX is a good measure of cumulative mental workload. It is not a sensitive measure to slight increases in mental workload (Brookhuis *et al.*, 2009; da Silva, 2014).

The extensive usage of the NASA-TLX to assess mental workload since the 1980s in numerous different applications is testament to its utility (Hart, 2006). The NASA-TLX is also non-invasive and, if the task is continuous as in the case of real-world driving, it can be done on task completion. This is beneficial as it does not interrupt the task and risk confounding workload measures (Rubio *et al.*, 2004).

However, NASA-TLX scores can be influenced by factors which are unrelated to the task in question such as prior caffeine and alcohol consumption, stress and illness. Nevertheless it is still considered to be a reliable measure (Rubio *et al.*, 2004; Hart, 2006).

### 2.7.3 RSME

The Rating Scale of Mental Effort was developed in the Netherlands by F.R.H. Zijlstra as part of a doctoral thesis (Zijlstra, 1993; de Waard, 1996). In contrast to the NASA-TLX, the RSME is unidimensional as it does not differentiate between aspects of mental workload. The scale is displayed in

Figure 3 on the next page. The scale ranges from 0 to 150 and is divided into increments of 10. Some descriptions are given along the scale which ranges from "extreme effort" to "absolutely no effort" (Jansen *et al.*, 2016; Sartang *et al.*, 2016).

The RSME has been widely used in driving research as a workload indicator (Brookhuis and de Waard, 2010; Benedetto *et al.*, 2011; da Silva, 2014). It was found to be a sensitive measure of mental workload, both in laboratory

experiments and real-world scenarios (Verwey and Veltman, 1996; Mulder *et al.*, 2009; Widyanti *et al.*, 2013).

As with other subjective measures of workload, the RSME is easy to use, inexpensive and non-intrusive. The RSME, in particular, has the advantage of taking less than a minute to complete (Widyanti *et al.*, 2013; Hsu *et al.*, 2015). De Waard (1996) argues that the RSME is good for self-reporting because it asks users to rate their “invested effort” rather than abstract aspects of mental workload (e.g. the NASA-TLX’s “mental demand” sub-scale).

The unidimensional scale lacks in that it does not diagnose exact causes for changes in mental workload. For example, it would not be clear whether an increase in mental workload was due to time pressure or frustration. Instead the RSME is better suited to give an overall indication of the perception of mental workload (Widyanti *et al.*, 2013).

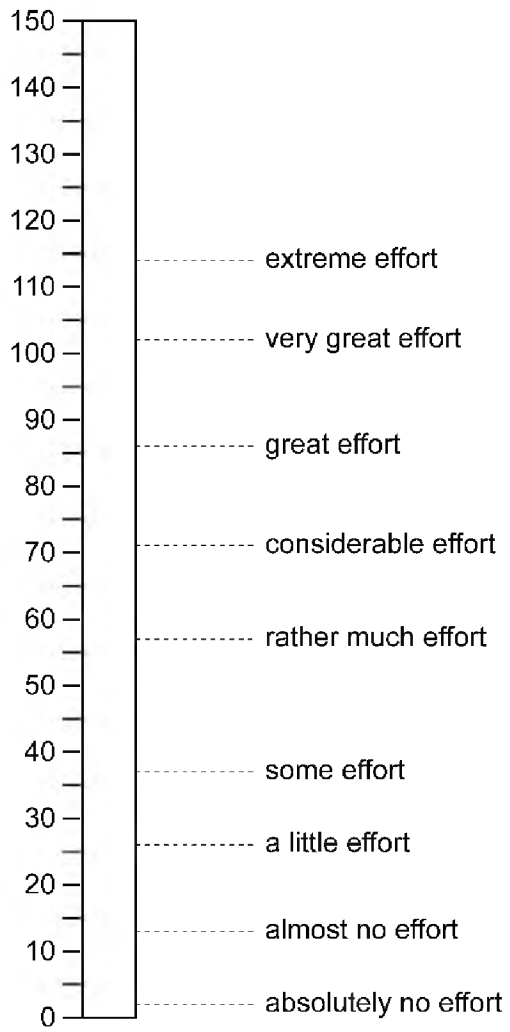


Figure 3: The Rating Scale of Mental Effort (taken from Jansen et al., 2016, p.25).

## CHAPTER 3 – RESEARCH METHODOLOGY

The first half of this chapter contains the research methodology from use of variables to the experimental protocol. The second part of the chapter (section 3.9 onwards) explains the data analysis process undertaken from processing and sorting the raw data to the generation of bar graphs.

### 3.1 Independent Variables

Driving comprises several sub-actions taken by the driver in response to a variety of external conditions (Bongiorno *et al.*, 2017). Given the naturalistic nature of this study, there are a variety of independent variables (external conditions or task demands) – where an independent variable refers to a scenario with the potential to elicit a change in the driver’s mental workload.

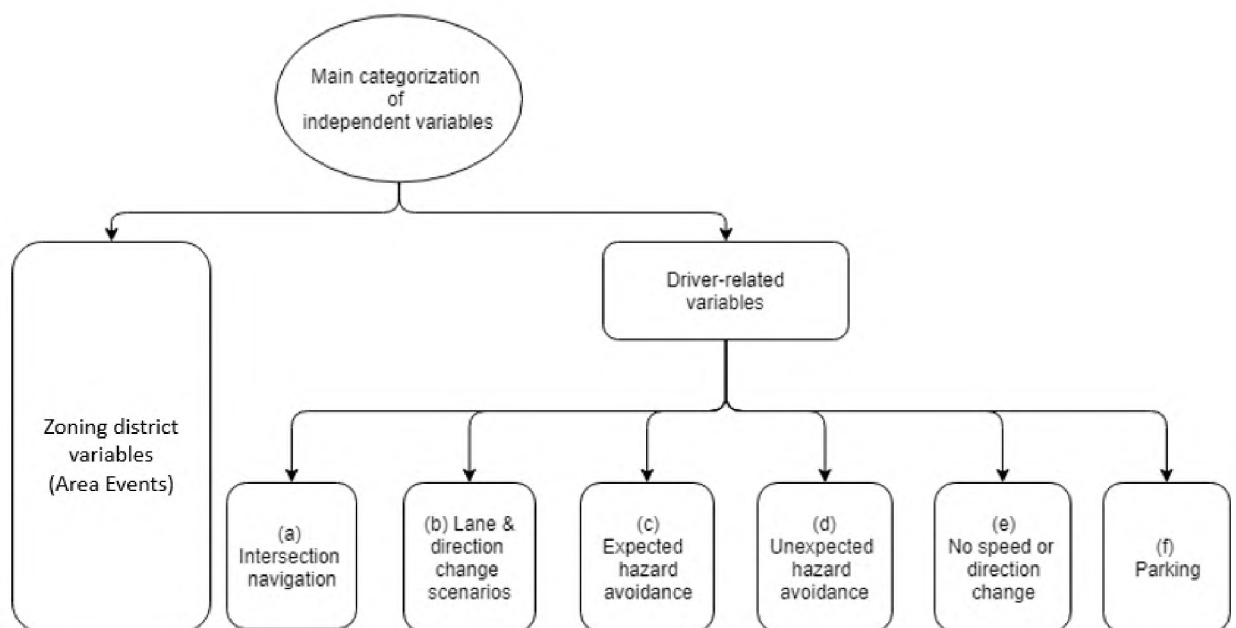


Figure 4: Categorization schema of all independent variables.

By categorizing the potential independent variables according to type, they can be defined and described. Figure 4 depicts the categorization schema of independent variables. The two global categories of independent variables are zoning-district variables and driver-related variables. The zoning district variables refers to the

type of location which participants drive through. Driver-related variables refer to the prompt and subsequent action taken by the driver to navigate to the destination. The driver-related variables are further divided into six categories which group similar driving scenarios and their associated subtasks together.

### 3.1.1 Zoning District Independent Variables

Environmental complexity is often related to road type, as urban areas with higher traffic density are associated with increased mental workload in comparison to rural or freeway driving (Törnros and Bolling, 2006; Ariën *et al.*, 2013; Paxion *et al.*, 2014). It is notable that this association is especially made in driving simulator studies. The relation is not strictly established, however, as other interactional factors (such as road geometry, road condition) may change the expected road complexity (Faure *et al.*, 2016).

However, road type has a well reported influence on driver workload, whether by increasing or decreasing task demand. As such, road type is included in this study as independent variables that elicit change in mental workload. The route that participants drove through consisted of the following defined zoning district variables:

1. Town area (Central Business District)
2. Suburban or residential area
3. Small-scale, light industrial area
4. Provincial Road R350 (agricultural area)

The town and residential areas were chosen as independent variables because they constituted the majority of zoned areas in the city of Makhanda (formerly Grahamstown). While un-tarred roads are common in the Eastern Cape, South Africa, they were excluded as an independent variable in favour of the tarred road in the light industrial area. Tarred roads are preferable for drivers as it reduces vibration, limits the wear on the research vehicle and lowers fuel consumption (Mansfield *et al.*, 2015; Blekhman and Kremer, 2017).

National highways were excluded to minimize participant risk. The combination of higher traffic volumes and speed is a risk factor for collision and near-crashes (Hamzeie *et al.*, 2017, Wang *et al.*, 2017). Furthermore, Christoforou *et al.* (2011) found that highway driving accidents are associated with more multiple-car crashes than driving in other districts. A provincial road with a lower speed limit was chosen to replace highway driving and thereby reduce risk to the participant.

### 3.1.2 Selection of Driver-related Independent Variables.

Driver-related independent variables refer to the sub-actions taken by the participant to accomplish the task of driving the defined route. The exact incidence and order of the driver-related variables are dynamic, and their sequence is not strictly predictable or controllable. Thus, record of these scenarios was made with a mounted dash camera and then matched with the resulting dependent variable responses.

The choice of driver-related independent variables was informed by the Official South African K53 driving manual (Barfield & Grobler, 2013). The K53 refers to a particular method of “defensive driving” that is taught and tested as a necessary requirement for a driver’s license. The manual includes the driving test procedure and hence which actions the candidate is required to execute successfully to pass the test.

A category of driver actions outlined in the K53 manual have been excluded. Excluded actions are those related to the use of vehicle controls - such as indicating, steering and changing gears. For experienced drivers these actions operate from the lowest or automatic level of information processing to execute.

The categorization of driver actions is based on the degree of cognitive processing that they entail. The complex actions that constitute driving have been compartmentalized into three hierarchical information processing categories by several authors (Michon, 1985; de Waard, 1996; Paxion *et al.*, 2014). The intermediate and high-level task processes refer to conscious controlled and serial actions in comparison to the largely automated low-level tasks (Paxion *et al.*, 2014).

Furthermore, low level tasks such as signalling and changing gears can occur concurrently or in parallel to other driving subtasks. The intermediate level describes cognitive processes when drivers respond to other drivers, road users and traffic signs. The highest level comprises strategic decision-making while driving, such as choosing a route and a goal destination (de Waard, 1996).

It is the tactical, intermediate level sub-tasks which are the focus of this research. Hence, the driver-related independent variables consist of sub-tasks from this response-based intermediate level. This study aims to examine the sensitivity of measures of mental workload in response to real-world driving conditions.

The high-level strategic decision-making sub-tasks, while also conscious, controlled and serially occurring, are excluded. The testing route and destination is set to provide a controlled variable to the study. It also limits the chance of inducing excessive amounts of mental workload in participants, which is a near-crash and crash risk factor (U.S. Department of Transportation: National Highway Traffic Safety Administration, 2006a; U.S. Department of Transportation: National Highway Traffic Safety Administration, 2006b; Faure *et al.*, 2016).

### 3.1.3 Schematic of Potential Independent Variables.

Selected K53 driver actions pertaining to the intermediate cognitive-processing level were categorised into six broad categories of potential external prompts:

- a. Intersection navigation
- b. Lane and direction change scenarios
- c. Expected hazard avoidance
- d. Unexpected hazard avoidance
- e. No substantial speed or direction change required
- f. Parking

Road markings, signs, traffic lights, road configurations, road conditions and the behaviour of other road users comprise the external prompts. They prompt the driver to act accordingly in response, by stopping, manoeuvring the vehicle in a different direction or maintaining the current state of motion.

Figures 5, 6 and 7 list sets of external prompts according to the category they fall under. As several external prompts could result in the same specific driver action, each action is linked to multiple potential prompts. For example, a stop sign, or a red traffic light are two different prompts requiring the same driver action of stopping.

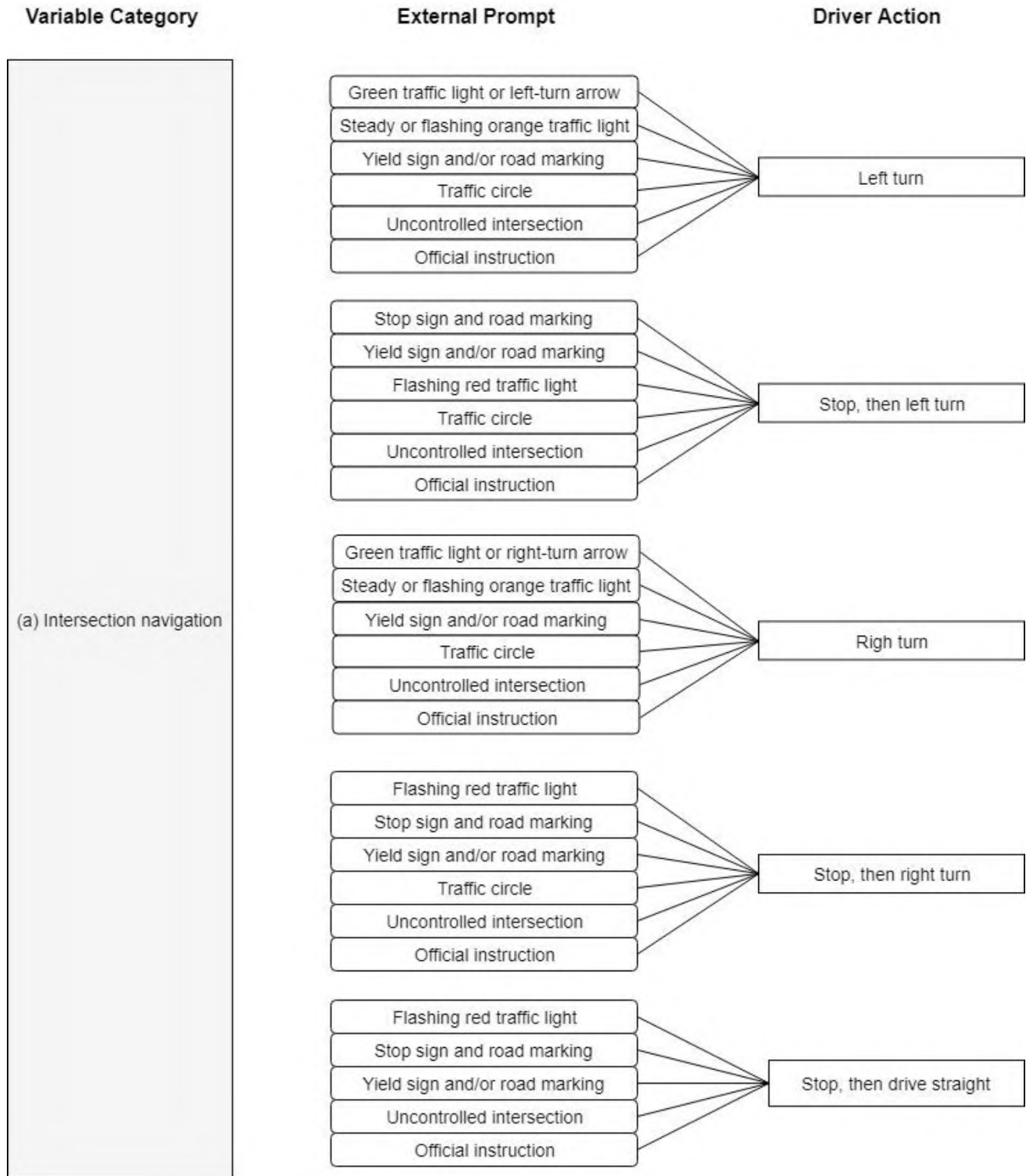


Figure 5: Categorization of driver-related independent variables (1/3).

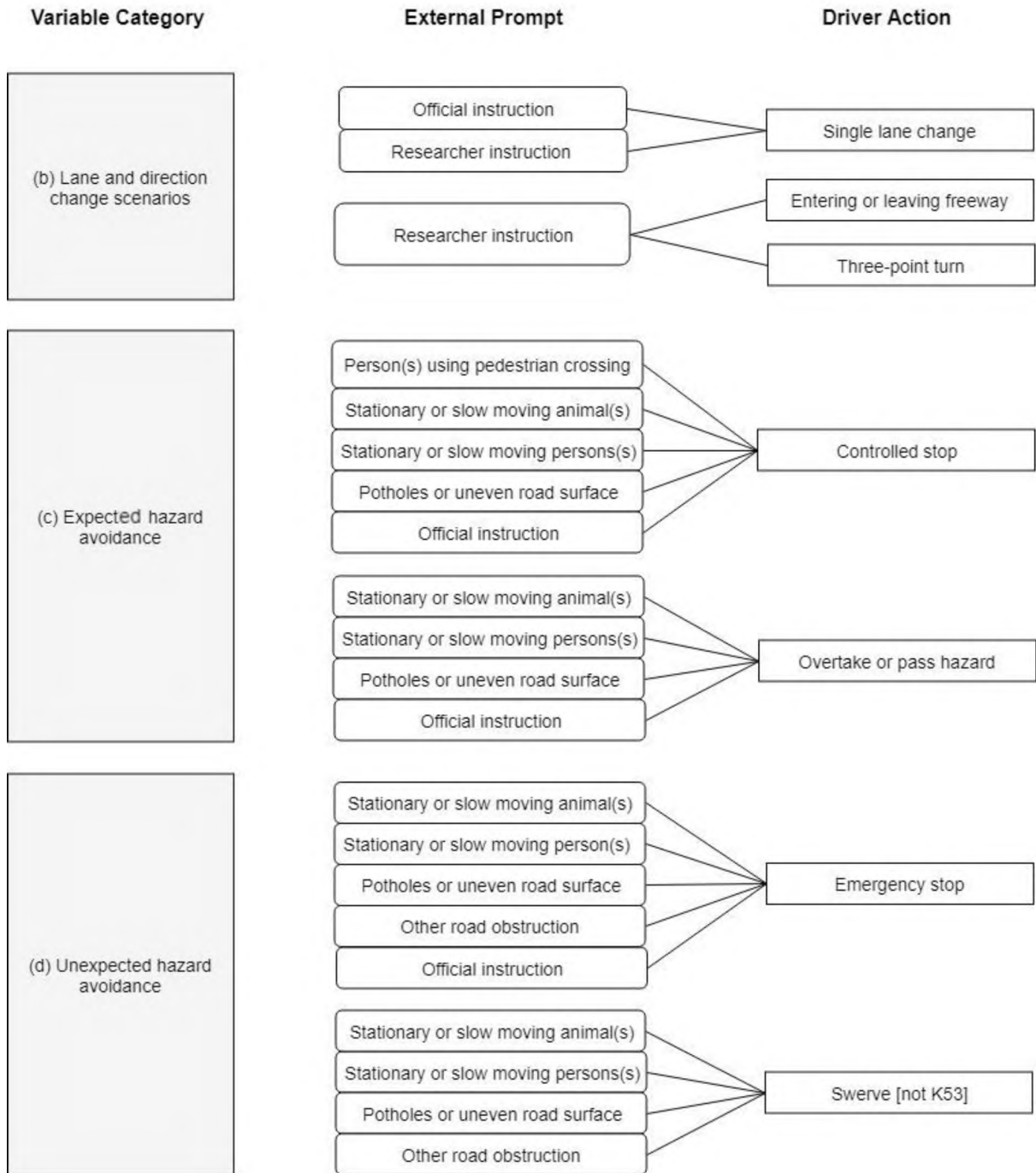


Figure 6: Categorization of driver-related independent variables (2/3).

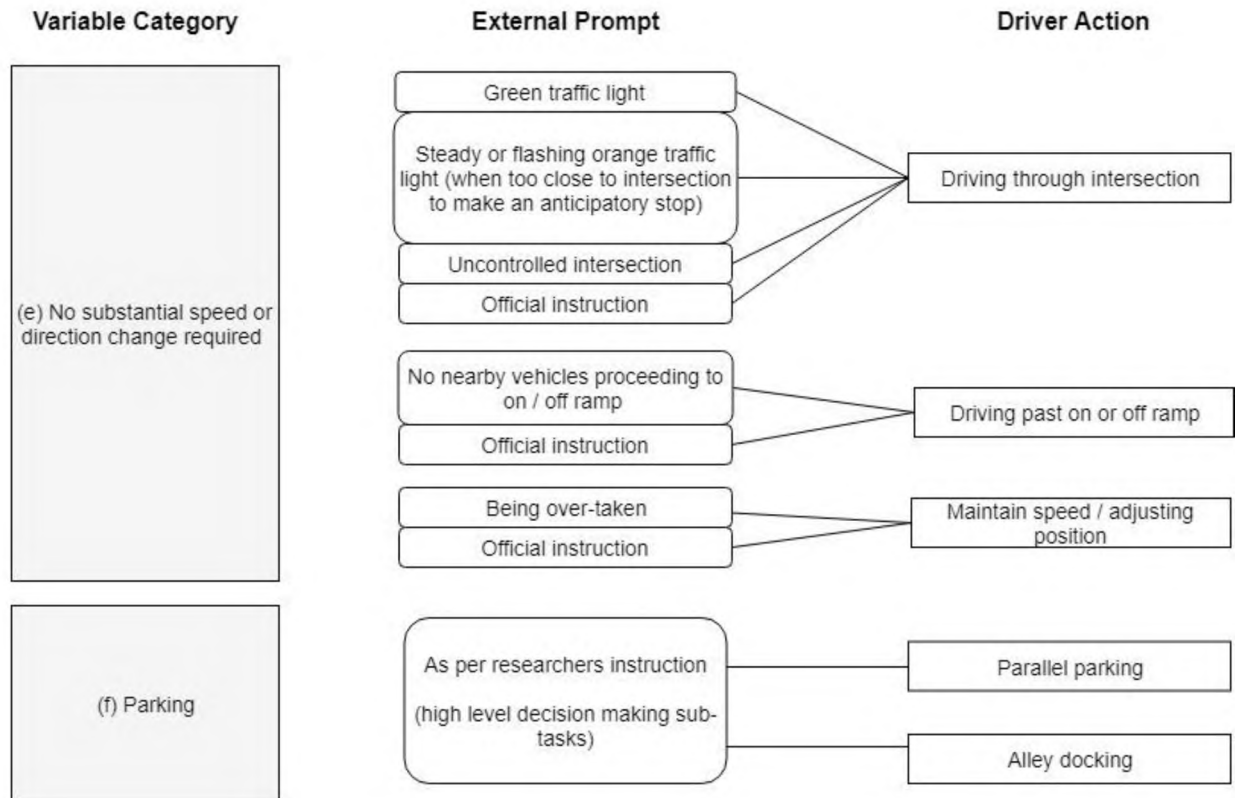


Figure 7: Categorization of driver-related independent variables (3/3).

It is unclear whether different prompts resulting in the same action would illicit the same mental workload change in the driver. As such, the independent variable necessitates being defined both in terms of driver action and the prompt initiating that action.

Thus, Figures 5 to 7 list all driver-related independent variables with two parts: the external prompt and associated driver action. For example, an independent variable is turning left at a green traffic light, while another is turning left at a yield sign.

Intersection navigation refers to scenarios such as yielding, stopping, turning and giving way as commanded by a road sign, marking, traffic light or official instruction. A majority of these commands direct traffic flow at intersections, i.e. where two roads meet.

Lane or direction change scenarios refer to the driver changing the trajectory of the vehicle. These scenarios occur when the driver is required to change lanes in

order to anticipate turning and/or to allow faster traffic to pass. The three-point turn is part of the K53 driver's test, requiring the driver to manoeuvre the car 180°.

Expected obstacle avoidance refers to the driver stopping or swerving the vehicle to avoid collision with an obstacle on the road that the driver has anticipated. In this case the obstacle is visible further along the driver's intended path. The driver has had time to decide on an action to take (or not take) to avoid collision as well as not creating a potentially hazardous situation for surrounding road users.

In the case of an unexpected obstacle appearing on the driver's path, there is less time for the driver to decide on the most appropriate action. The driver is required to act quickly by stopping or swerving the vehicle, to avoid collision. This time pressure is theorized to increase mental workload as a higher amount of information needs to be processed per time unit (Rendon-Velez *et al.*, 2016). With this comes a higher probability of human error and thus a greater potential for collision. Unexpected obstacles include a pedestrian, animal, vehicular or other obstacle suddenly appearing along the driver's path.

The category of 'no speed or direction change required' refers to K53 stipulated scenarios which don't require an overt change in speed or orientation of the vehicle when the scenario prompt is presented. However, these scenarios still require the driver to be vigilant to the need to potentially respond by changing speed or direction. For example, it's not necessary to change speed or direction when proceeding straight through an intersection with a green traffic light. However, the driver is still required to check that there is no approaching cross traffic at the intersection. This vigilance requirement may impact mental workload even without overt driver action.

As parking is an essential part of typical driving, participants were asked to park nearing the end of the driving route. Participants were asked to parallel park on Prince Alfred Street on Rhodes University campus which has a dedicated parking area and cars are required to drive slowly. As South Africans drive on the left side of the road parallel parking was performed on the left side of the road. Alley docking followed at the Rhodes University gym parking lot as the last sub-task of the testing session.

Official instructions by traffic officers also serve as potential external prompts to the participant and are thereby constituted as part of an independent variable. In other cases, official instruction may be given by road maintenance workers to redirect traffic.

Under the South African National Road Traffic Act 93, traffic officers have the right to assert that a driver stops their vehicle in cases of a suspected traffic violation and/or to verify legal documentation (Minister of Transport, 1996). Hence, official instruction was included as a prompt in scenarios pertaining to stopping or traffic flow regulations. Furthermore, traffic officers may request that the driver/participant perform an unlisted action.

### **3.2 Dependent Variables**

Mental workload is a consequence of the interaction between external task demands and the driver's attentional and cognitive resources (Hart and Staveland, 1988; de Waard, 1996; Faure *et al.*, 2016). As such the measurement of mental workload is inferred rather than direct.

Measures of mental workload fall into three main categories: performance, physiological and subjective mental workload indicators. Studies, however, have predominately used physiological and subjective indicators of mental workload (Brookhuis and de Waard, 2002; Paxion *et al.*, 2014; Charles and Nixon, 2019). The low usage of performance as a mental workload indicator in real-world driving studies can be attributed to it being a more indirect indicator of workload than physiological and subjective indicators (da Silva, 2014).

Driving performance measures typically include lateral deviation of the vehicle and the indirect measure of performance on a secondary task (da Silva, 2014). Measuring lateral deviation during real-world driving is not feasible for this study. Determining the lateral deviation for the total distance driven of each drive would require a large degree of experimental effort and additional resources.

Furthermore, Törnros and Östlund (2002, as cited in da Silva, 2014) found in a naturalistic driving study that the accuracy of measurement would be compromised by intersections and narrow roads. Performance measured via a

secondary task would be a confounding factor for other measures of mental workload.

Given the challenges associated with using driving performance as mental workload indicator, it was excluded as an option for this study. The comparatively more direct physiological and subjective mental workload indicators were used. Of these, the physiological measures chosen were eye motion and heart rate metrics. The use of electroencephalogram (EEG) and respiration rate both came second in popularity after the use of heart and eye-motion metrics reported in literature (Charles and Nixon, 2019).

However, EEG and respiration measures were not used in the present study. Recording physiological data on drivers is logistically difficult in real-world driving situations. It would also generate a large amount of data to analyse and compare, which would exceed the timeline of this study.

For subjective measures the NASA Task Load Index questionnaire was administered (and later analysed using the modified Raw-TLX version) in addition to the Rating Scale of Mental Effort.

These mental workload indicators of eye motion, heart rate, NASA-TLX (the Raw-TLX) and the Rating Scale of Mental Effort are elaborated on in Sections 3.2.1 to 3.2.4 below.

### 3.2.1 Eye Motion Metrics

Visual and mental tasks while driving are closely linked. The environment is constantly scanned for visual cues and appropriate actions are decided on. Eye motion measurements are thus suited to study mental workload while driving (Benedetto *et al.*, 2011; Marquart *et al.*, 2015).

Data of seven commonly-used eye motion variables collected throughout the whole journey:

- Blink frequency
- Blink duration
- Pupil diameter

- Saccade duration
- Saccade amplitude (length)
- Saccade velocity
- Fixation duration

Saccade latency was not measured as defined fixation points are needed for its measurement. The unpredictable nature of real-world driving makes defining set fixation points for all driving sessions impossible.

Eye motion was measured using the Dikablis Eye Tracker that consisted of a field camera and a camera that tracks the movement and diameter of the left pupil. The unit is supported by the nose bridge that it is mounted on and secured on the head with the attached headband. Measurement is continuous, and the data are digitized and saved on computer.

### 3.2.2 Heart Rate Metrics

Cardiovascular measures have long been used as a measure of physical as well as cognitive workload (Brookhuis and de Waard, 1993, Brookhuis and de Waard, 2010, Hoover *et al.*, 2012). Both heart rate and heart rate variability have been shown to respond reliably to an increase in mental workload (Grassmann *et al.*, 2017).

The heart rate related measures that were taken were:

- Heart rate frequency
- The standard deviation of inter-beat-intervals (SDNN)
- The root mean square of the successive differences of R-R intervals (rMSSD)
- High frequency band
- Low frequency band
- Frequency band ratio

Heart rate variability measures are derived using heart rate metrics of time (ms) between consecutive heart beats. Time domain analyses provide information

regarding change in mental workload. Frequency domain analyses provide information about mental workload with reference to the influence of the Autonomic Nervous System (ANS). The link between the different frequency bands to branches of the ANS can help to identify physiological arousal and alertness, or lower arousal states.

Heart rate and heart rate variability were measured using a Polar V800 watch and a Polar H7 Heart Rate Sensor belt. The belt was fastened around the participant's chest at the level of the heart. The belt was then synced to the watch which was used to control the belt's mode and duration of recording. On task completion, the belt was removed, and the watch synced up to a computer for data retrieval.

### 3.2.3 NASA-TLX and RTLX

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire has been extensively used for the subjective measurement of mental workload (Hart, 2006). The printed questionnaire was filled in by the participant on completion of the baseline tracking task and the drive.

The NASA-TLX is a multi-dimensional questionnaire as it investigates six factors of mental workload. These factors are mental workload, physical workload, temporal demand, perception of task performance, effort and frustration. Each factor is represented as a rating scale ranging from "Very Low" to "Very High", with the exception of the performance scale, which ranges from "Perfect" to "Failure" (Hart and Staveland, 1988).

Participants provided their perceptual ratings using the NASA-TLX questionnaire (refer to Appendix A, Figure 1). However, a modified version known as the Raw-TLX (RTLX) was used to analyse these ratings as the pairwise comparisons of subscales for determining weightings were excluded. The simpler RTLX method (Hart, 2006) of analysis was more suitable than the NASA-TLX because of the exploratory nature of this study.

### 3.2.4 Rating Scale of Mental Effort (RSME)

While mental effort and mental workload are understood by some researchers to be different, RSME has been widely used in driving research as a subjective indicator of mental workload (Brookhuis and de Waard, 2010; Benedetto *et al.*, 2011; da Silva, 2014).

The RSME is a one-dimensional, self-reported scale that participants used to grade their perception of the proportion of mental effort invested in a task. The scale consists of a 150mm line with length demarcations drawn in at millimetre intervals. Nine labels describing a continuum of mental effort is listed along several demarcated points alongside the line (Sartang *et al.*, 2016). The scale was administered to the participants six times in total. First on completion of the baseline task, and then after driving through each zoning district along the set route; namely the industrial, provincial road, residential, town, and campus zones.

Refer to Section 2.7.3, Figure 3 of the Review of Literature for the RSME chart.

### 3.3 Controlled Variables

The exploratory nature of the study necessitated minimal control over the independent conditions. However, some variables were controlled to reduce risk and to decrease some degree of variability.

Testing occurred on weekdays and did not coincide with periods of higher traffic volumes within the town centre and surrounding areas. Habituation and the main driving task were done between 8h30 and 13h00 as well as from 14h00 to 16h30. The total driving duration was limited to a total of 90 minutes. However, participants completed the drive in about an hour.

No testing was commenced on days where rain or fog was heavy enough to impede visibility and/or reduce the tyres' grip on the road.

The participants were aware of the general planned driving route but they were instructed not to memorise it. While participants drove, the researcher alerted them about upcoming turns and changes in direction. All participants were

instructed in a similar matter, to standardize the influence of the researcher's instruction.

The total driving and parking time was limited to 90 minutes which is below several countries' and states' recommended 120 minute continuous driving limit. In the United Kingdom, The Official Highway Code (rule 91) stipulates that drivers take a 15-minute break from driving every two hours (UK Driving Standards Agency and Department of Transport, 2015). The Queensland government and the South African long-running governmental campaign, Arrive Alive, make the same recommendation (Arrive Alive, 2011; Department of Transport and Main Roads Queensland, 2016).

The 90 minute limit serves to reduce the participant's driver fatigue and subsequent risk. Requirements for participation included driving fairly regularly, in addition to having a valid driver's license. Hence the driving task did not place the participant under risk of fatigue and/or a driving accident that they would not typically take themselves.

### **3.4 List of Equipment**

- Polar V800 watch and Polar H7 Heart Rate Sensor belt
- Dikablis Cable Eye Tracker (model number V 3.0.770988-0001)
- Dell laptop with Dikablis software
- HP Inc. Compaq CQ58 Laptop with low-fidelity tracking task program.
- Africa Longhorn G50 Mini Dashcam (1080P video recorder, 30fps)
- 7-seater Toyota Avanza or a Toyota Hilux (single-cabin pickup truck)

### **3.5 Recording from Equipment**

Recordings were initiated in the following order before the driver turned on the ignition. A few seconds elapsed between commencing the recordings of the heart rate monitor and eye tracker, and then the eye tracker and dashcam.

Heart rate data was set to record first. The Polar heart rate monitor's watch was used to initiate the continuous recording of R-R intervals and heart rate. Data were

saved to the watch and later retrieved by the Polar Flow website and downloaded as a .txt file.

The eye tracker was then set to record continuously the eye motion of the left eye during the drive. Eye tracker data for each drive were saved on the connected laptop by the Dikablis recording software as .txt files.

Lastly, the dashcam was set to record continuously footage of the road ahead at a resolution of 720p. The video recordings were saved onto a mini SD card with each frame time and date stamped by the dashcam.

### **3.6 Participant Characteristics**

The sample was drawn from the student and staff body of Rhodes University who qualified to drive a university owned vehicle. Six participants, comprising four women and two men, completed the research protocol. The average age of participants was 24 years.

Due to irreparable failure of the eye tracker, the original sample size aim of between 10 to 15 participants was not met.

All participants had a valid South African driver's license for light motor vehicles with a manual transmission (code B). Participants had driving experience of at least two years or a total distance of 5000 km driven. All participants had their own vehicle and drove at least twice a week.

Participants did not have any major health concerns (e.g. epilepsy, stroke, heart conditions) or cognitive impairments. They did not take chronic pain management or sedative medications; nor were they undergoing treatments which caused drowsiness and/or impaired motor control.

### **3.7 Research Protocol**

#### **3.7.1 Informed Consent**

Prior to the commencement of the research, all recruited participants were informed about the research tasks and measures, and that they were free to withdraw from participation at any stage. Furthermore, they were informed of the potential risks and benefits of participating and that their information would be kept anonymous. The information was provided in writing and verbally.

Upon agreement to partake in the research, participants signed the informed consent form.

#### **3.7.2 Rhodes University Driving Test**

The participant was required to pass the Rhodes University driving test in order to drive a Rhodes University vehicle. Participants were asked to fill out a driving test application form. The researcher submitted the form to the Rhodes University traffic department and obtained a date for the participant to take the test. Tests were conducted on Tuesdays at 14h00 on University campus and took less than 20 minutes.

#### **3.7.3 Habituation Session**

The habituation session provided an opportunity for the participant to familiarize themselves to the testing setup.

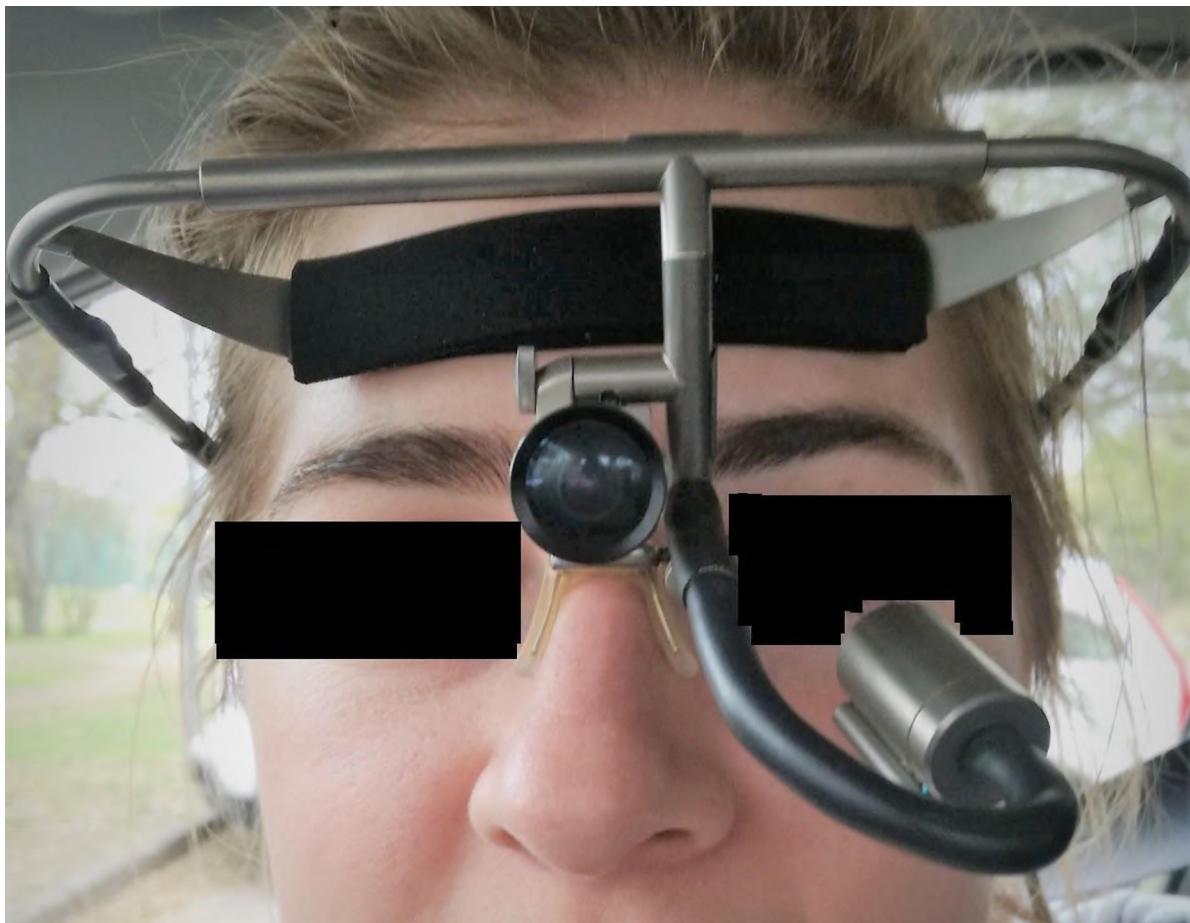
The participant drove the vehicle around a low-traffic area with the researcher in the passenger seat. The participant first drove around without wearing any equipment to familiarize themselves with the handling of the vehicle.

On confirmation that the participant was comfortable with operating the vehicle itself, they were instructed to drive to the department of Human Kinetics and Ergonomics (HKE).

At the department, the participant was fitted with the Polar H7 heart rate sensor belt and the Dikablis eye tracker.

For the fitting of the heart rate sensor around the chest, participants were led to a private room in the department. The participant was asked to lift their garments high enough so that the heart rate sensor could be secured around the chest in the lower rib area. Participants of the opposite sex to the researcher were offered the option of being fitted with the belt by someone of the same sex.

The participant then proceeded to sit in the driver's seat of the vehicle for fitting and calibration of the eye tracker. The eye tracker consisted of an eye and field camera whose weight was supported by the nose support. Figure 8 demonstrates the eye tracker being worn. The nose support was first placed on the bridge of the nose and then the unit was secured around the participant's head by the unit's head band. The head band was then adjusted to be secure but not tight.



*Figure 8: The weight of the eye tracker was supported by the forehead rest and by the nose bridge. The forehead rest was secured with by the attached head band at the back of the head. The field camera sat directly on top of the nose bridge.*

*The eye camera was positioned at the bottom of the left eye and pointed slightly upward.*

The eye tracker was connected to two cables which transmitted data to the laptop which was held by the researcher in the passenger seat.

At this point the researcher calibrated the eye tracker. Calibration required that the participant look to each quadrant of their visual field while the head remained in a set position. Once calibrated, the participant was asked to drive *while wearing the equipment* for ten minutes.

To conclude the habituation session, the participant drove back to the HKE department. The eye tracker was removed by the researcher in the parking lot. The participant returned to the private room and had the heart rate belt removed.

#### 3.7.4 Main Experimental Procedure Overview

The main experiment was conducted on a separate day to that of the habituation session.

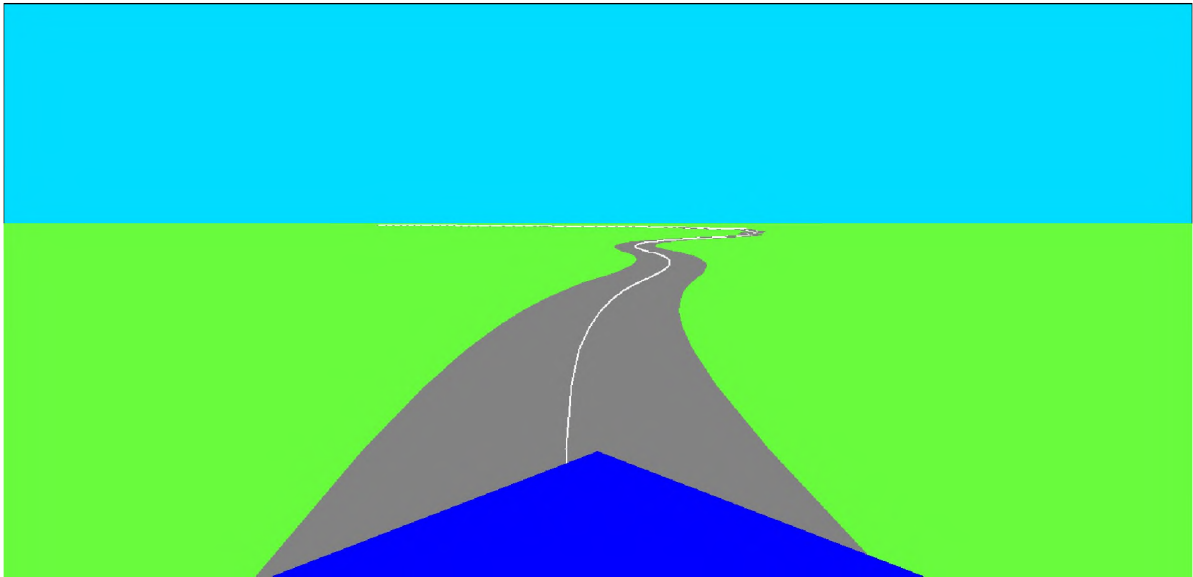
On arrival, the participant was informed once more of the experimental protocol and the driving route (which they did not to memorize). The potential risks and benefits as well as the participant's right to stop testing at any time was reiterated.

Next, the participant proceeded to a private room in the HKE department and was fitted with the Polar H7 heart rate sensor belt. As in the habituation session, the participant was required to lift their garments so that the belt can be fitted around the chest – level with the apex of the left ventricle of the heart.

Then, while still in the HKE department, the researcher fitted and calibrated the Dikablis eye tracker as was done in the habituation session.

#### 3.7.5 Computer Tracking Task

While wearing both the heart rate monitor and eye tracker, the participant was asked to perform a two-minute-long tracking task on a laptop. The tracking task was administered to get baseline data of the dependent variables.



*Figure 9: The tracking task was performed by controlling the top of the blue triangle with the cursor. The goal was to remain as close to the white line as possible as it changed direction.*

The task consisted of a central line on the screen that moves towards the viewer at a constant rate and originating at a horizon point. The mouse input was used to control the cursor (which looks like a triangle at the bottom of the monitor in Figure 9). The objective was to maintain the cursor on the central line as the line progresses and changes direction.

On completion of the tracking task, the eye tracker was removed, and the heart rate recording stopped.

At this point, the participant was asked to rate their workload perceptions. The Rating Scale of Mental Effort (RSME) was administered first followed by the National Aeronautics and Space Administration Task Load Index (NASA-TLX) questionnaire. The RSME and NASA-TLX were both administered using paper and pen.

### 3.7.6 The Driving Task

The participant and researcher proceeded to the vehicle outside. Inside the vehicle, the eye tracker was once again fitted and calibrated. The heart rate monitor was set to record, followed by the eye tracker and dashcam.

The participant started the ignition and pulled off, following the beginning of the set route. Directions were given by the researcher.

The driving task consisted of driving through parts of the Industrial Area, R350 Provincial Road, Residential Area and Town Area of Makhanda (formerly Grahamstown). Please refer to Appendix C: Information to Participants for a summarized version of the route. A more detailed description of the route is given in Appendix E. After driving through each area, participants were instructed to pull over and provide a rating of their mental effort on the RSME scale.

The route took around an hour to complete which was below the recommended time before taking a break. The route looped back to the starting point on campus. The eye tracker recording was stopped, and the participant was instructed to turn off the ignition. The heart rate recording was stopped, and the eye tracker equipment removed.

Participants were asked to provide their final RSME rating and complete the NASA-TLX questionnaire for the entire drive.

At this point, the participant and researcher proceeded back to the HKE department where the heart rate monitor belt and watch were removed.

### **3.8 Research Risk Management**

#### **3.8.1 Inherent Driving Risk**

Driving itself carries an inherent risk of injury, property damage and loss of life. Accidents occur as a result of the interaction between variables, such as road geometry, driver characteristics and behaviour, traffic volume and speed, weather, and other environmental factors (Christoforou *et al.*, 2011).

Driving risk is primarily related to collisions involving other vehicles, pedestrians, cyclists, and animals on the road. Collision types include head-on, rear-end, side-on, and side-sweep collisions (Arrive Alive, 2018a). Vehicle rollover crashes may result because of the collisions and typically cause the greatest damage.

The research reported here was concerned with the driver's cognitive load in response to the task demands of driving. The fundamental reason for examining mental workload during real-world driving is to reduce risk at the human-machine level of interaction.

Given the multivariate causation of vehicle accidents, the inherent risks of driving itself cannot be minimized beyond efforts already put in place by car manufacturers, legislation, the K53 defensive driving strategy and personal responsibility of road users.

Participants consenting to drive in this study were accepting of the inherent risk. It is one that they would consent to themselves under normal circumstances as experienced and regular drivers. Furthermore, drivers who exhibited characteristics of accident risk factors were excluded from participation. These risk factors were inexperience, intoxication, sedative medications, age-related visual and cognitive decline and medical conditions such as a history of heart disease, stroke and epilepsy (European University Association, 2010; Rolison *et al.*, 2018).

Furthermore, speeding, reckless driving and not wearing a seatbelt increases accident risk significantly (Hamzeie *et al.*, 2017; Arrive Alive, 2018b; Rolison *et al.*, 2018). Thus participants were required, in line with SA legislation, to obey speed limits, adhere to the rules of the road, wear a seatbelt, and not engage in reckless driving.

### 3.8.2 Risk Associated with Experimental Design

The risk itself of driving cannot be reduced. However, risks related to the experimental design were minimized. Methods of risk reduction were undertaken to reduce risk created by the experimental design. As a result, the risk that was taken by participants did not substantially exceed the inherent driving risk.

#### Risk Due to Driving Location

Driving on national highways were excluded to reduce the risk of collision. The greater speed limit and traffic density on such roads are collision risk factors (Hamzeie *et al.*, 2017; Wang *et al.*, 2017).

The provincial road towards Port Alfred was excluded as an out-of-town driving option due to the multiple curves along the road. Drivers may drift out or deviate more from the center line while steering and managing speed changes along curves (Ariën *et al.*, 2013). The R350 Provincial Road towards Fort Beaufort was chosen instead.

#### Risk Due to Driver Fatigue

The total driving and parking time were planned not to exceed 90 minutes, i.e. well within the recommended 120 minute continuous driving limit (refer to the second half of Section 3.3 'Controlled Variables' for more details). However, this limit only applies to long-distance driving, as driving-time recommendations in urban areas have not been reported.

Participants were regular drivers and had a valid driver's license. Therefore, the driving task did not place the participant under greater risk of fatigue and/or driving accident than they would typically take themselves.

The participant was directed along the route by the researcher, to minimize added decision-making workload (European University Association, 2010). This reduced error risk associated with heightened levels of mental workload.

#### Risk Due to Driving an Unaccustomed Vehicle

Participants had the opportunity to familiarise themselves with the vehicle's controls, and the general 'feel' and 'responsiveness' of the car. The habituation session served to reduce error and accident risk related to the driver being unaccustomed to the Rhodes University vehicle. Participants drove the same car for the habituation and main experiment.

#### Risks Related to Route Navigation and Driver Distraction

No tasks secondary to driving the vehicle were added. Lapses in driver attention were reduced by banning the use of in-vehicle interfaces such as radio/GPS devices, as well as cell-phones.

Furthermore, instructions and directions along the driving route were given in a clear and timeous manner and repeated once again just before the action is to be

taken. For example, it was announced beforehand that the driver was to turn left at the upcoming intersection. The instruction was repeated closer to the intersection.

### 3.8.3 Risk Due to Measuring Equipment

Eye motion and heart rate were measured continuously throughout the testing session. The NASA-TLX questionnaire was taken after performing the two-minute tracking task (before driving) and again at the end of the driving route. RSME measures were taken after driving through each area, with the participant pulling over to give a rating.

#### Eye-motion Tracker

The primary risk concerning participants wearing the eye-motion tracker while driving was the obstruction of peripheral vision. This obstruction, however, is similar to that of wearing framed eye-glasses as the camera unit is located under the left eye and its weight supported by the nose bridge and head band. The top of the camera unit can be seen in peripheral vision, but most of the visual field remains unobstructed.

Wearing the eye tracker feels unusual though is not uncomfortable when adjusted correctly. The potential distraction caused by the foreign sensation of wearing the eye-tracker was reduced in the habituation session.

Over time there may have been some discomfort on the bridge of the nose from supporting the weight of the eye tracker. This discomfort was temporary and quickly resolved when the tracker was removed.

#### Heart Rate Sensor Belt

The sensor belt sits around the chest at the level of the apex of the left ventricle of the heart for the testing duration. Fitting the belt requires the participant to lift or remove their shirt. This may make the participant feel embarrassed or uneasy. Steps were taken to reduce this by fitting the belt in a private room. Male participants were asked if they would prefer a male researcher to put on the belt.

Fitting the belt takes less than a minute so the discomfort was limited to a short period of time.

The belt is soft and flexible so that wearing it was comfortable. The belt may have been slightly irritating or have made the skin underneath it feel itchy. In this case, participants re-adjusted the belt. The cause of possible skin irritation or itchiness was removed when the belt was removed.

### NASA-TLX and RSME Questionnaires

The questionnaires enquire about the participants' perceptions of mental effort and workload. This information is personal but not to the extent that would be sensitive or embarrassing.

The NASA-TLX comprises six questions which participants may find tedious or cognitively fatiguing to complete. Clarification was provided to minimize this if necessary.

Both questionnaires were completed when the participant was not driving so as not to be a driving distraction.

#### 3.8.4 Liability and Risk of Property Damage

Participants were not under any financial risk. The vehicles used in this study were Rhodes University assets. In the event of an accident, vehicular and third-party property damages would have been paid for by Rhodes University's insurance company. Furthermore, the participant was not responsible for fuel and other potential vehicle maintenance costs.

However, in the unlikely event of a traffic violation the participant/driver would be liable for legal charges made against them consequently. The risk of traffic violation was managed by careful selection of participants and by the researcher's instruction during driving.

#### 3.8.5 Risk of Permanent Harm

Driving is inherently risky, but it is a risk that regular drivers (the participants) would have experience in managing. In the event of a catastrophic collision, some

injuries could be permanent, but care was taken to reduce the risk as much as possible.

Risks due to the experimental design itself were reversible. That is, the discomfort of wearing the eye-tracker and heart rate sensor belt were reversible, as were potential risks of answering the questionnaires.

#### 3.8.6 Participant Anonymity

Participants were not named. Instead a code was used to identify data sets. The information linking the code to the participant was kept for the duration of the project. This information will be destroyed after final corrections have been made to the project.

### **3.9 Data Analysis Overview**

This section describes the data analysis as depicted in the upcoming flowchart, Figure 10 in section 3.11. Six steps were taken to process the data outputted from the eye tracker and heart rate monitor, to that visualised in the bar graphs of Appendix F. Each step of the flowchart is elaborated on in the following sections. In addition, the rationale behind splitting the independent variables into 'meta-groups' is addressed.

#### **3.10 Step 1: Identification of Independent Variables**

A challenge of real-world driving studies is the lack of control regarding the incidence and duration of independent variables (and extraneous variables). Hence, the independent variables encountered, and their details, were only determined after experimentation. A general schema of possible independent variables (also referred to as 'driving scenarios' or 'events') was created before experimentation in anticipation of their potential occurrence. The schema can be referred to from Figures 5 to 7 in the Section 3.1.3 of the Methodology Chapter.

Two timelines of independent variables were made for each drive by using the dashcam footage. One timeline consisted of short duration driving scenarios, and the other of long duration scenarios. The timelines were made up of short descriptions of the driving scenarios and its durations.

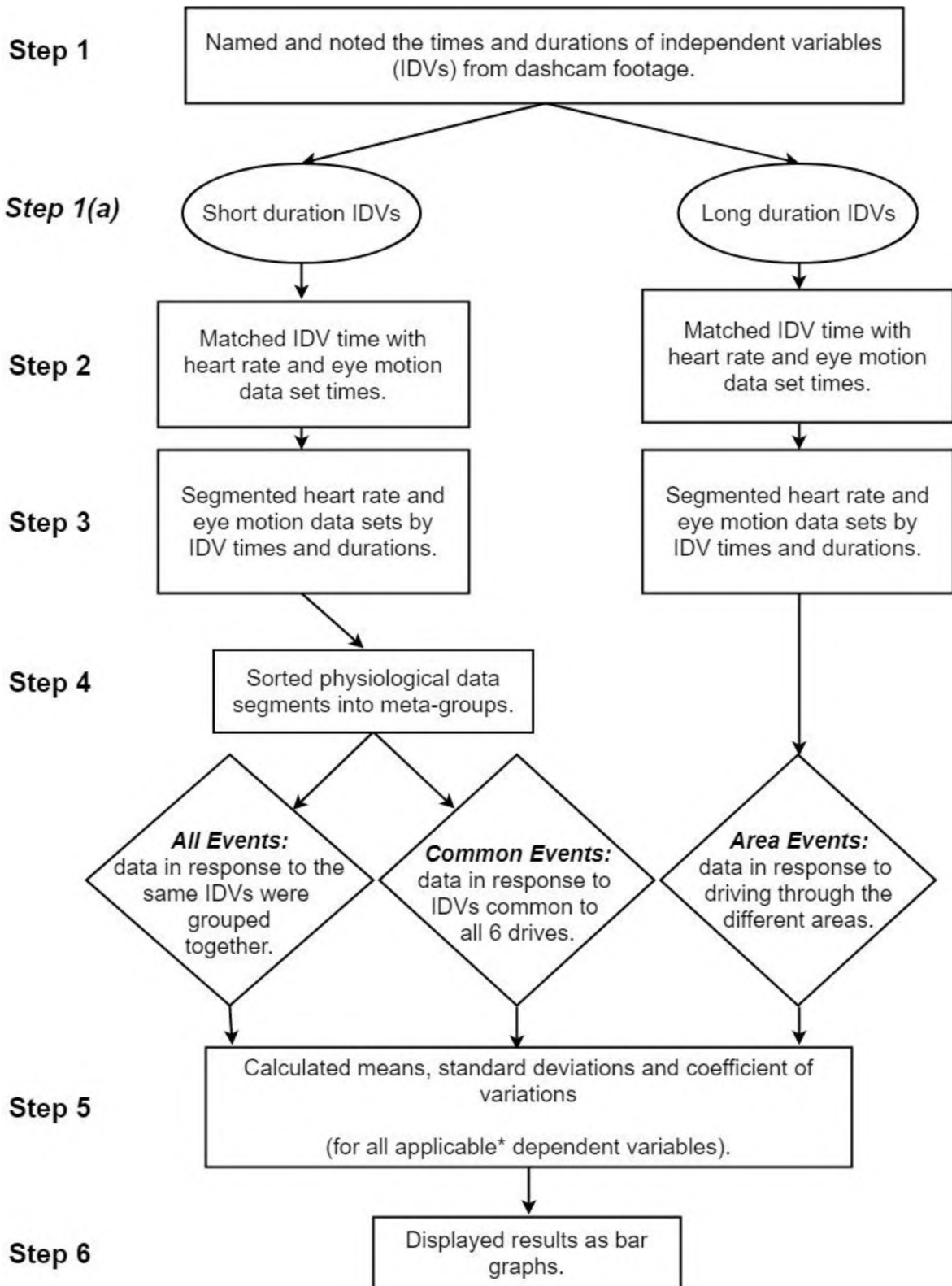


Figure 10: Flowchart schematic summarising the data analysis process undertaken.

Often, a scenario would be followed by a period where the driver was not required to make overt changes in speed or direction. In other words, there was an absence of an external prompt and subsequent driver action. These situations consisted of driving along a portion of road and were referred to as 'in-between events' In-between events were named according to the zoning district they occurred in, followed by a consecutive number (e.g. Industrial Main 16, abbreviated to IM16, IM17...etc).

Long duration driving scenarios were identified from the dashcam footage as follows. Landmarks were defined to demarcate each zoning district. The time when the landmark was reached was recorded and used to determine the duration of the drive through each area. The driving scenario was named according to the area.

### **3.11 Step 1(a): Division of Short and Long Duration Independent Variables**

The comparison between dependent variables (i.e. mental workload indicators) were constrained by differences in their sample duration requirements. For example, frequency domain analysis requires longer sample lengths and therefore was not appropriate to be used to assess the mental workload of short duration independent variables.

Dependent variables were classified into short and long duration mental workload indicators. Section 3.11.1 "Indicators with Shorter Duration Sample Limits" and Section 3.11.2 "Indicators with Longer Duration Sample Limits" below, discuss the basis for the classifications.

Based on this, driving scenarios were divided into short and long duration categories. Short duration scenarios were those that lasted between five seconds to five minutes with an average of 30 seconds.

Long duration scenarios were those lasting five to 30 minutes and consisted of driving through different zoning districts along the route. Long duration scenarios are also referred to as "Area Events" (see Step 4).

Short duration driving scenarios were identified from the dashcam footage as follows. Each driving scenario encountered was named by combining the description of the external prompt (e.g. 2-way stop street) and the driver action (e.g. turn left). The duration of each event was determined from the dashcam's running time stamp.

### 3.11.1 Indicators with Shorter Duration Sample Limits

Eye motion metrics are suitable as ultra-short measures in the order of seconds. Minimum sample durations were only a few seconds long, making eye motion responses suitable to assess mental workload of the shortest events (Van Orden *et al.*, 2000; Ahlstrom and Friedman-Berg, 2006; Marchitto *et al.*, 2016).

The non-pathological physiological average for the duration of one cardiac cycle is 0.8 seconds (Gersh, 2000). This makes heart rate frequency appropriate in the assessment of events lasting for several seconds.

Time domain analysis of heart rate variability (HRV) was set at a minimum sampling duration of 30 seconds. This was to have enough data points with which to measure inter-beat-interval variation.

Therefore, eye motion and heart rate frequency were used to assess the mental workload of events from five seconds and above. Time domain analysis was applied to events longer than 30 seconds. As the mean event duration was 30 seconds, time domain analysis could be used in the assessment of most events.

### 3.11.2 Indicators with Longer Duration Sample Requirements

In this study, longer durations refer to several minutes. Eye motion metrics and heart rate frequency are not computationally sensitive to sample length. Both indicators were used in assessing the MWL of events and areas with upper range sample durations. The range of sample durations that eye motion and heart rate frequency can measure - with regards to driving scenarios - makes them a versatile measure.

However, time domain HRV measures are computationally sensitive to sample duration. The Task Force of the European Society of Cardiology (1996) recommends that time domain HRV analysis be limited to five minutes to obtain stable results.

Area Events ranged between 5 and 30 minutes in duration. Time domain sample sizes were limited to the first five minutes of driving through each area.

Frequency analysis of HRV and Rating Scale of Mental Effort (RSME) are suitable as mental workload indicators for longer duration tasks. When using typical calculation technique, frequency analysis requires a sample duration of at least one minute for high frequency band components, and at least two minutes for the low frequency band. The reason is computational as the sample duration should be ten times the wavelength of the lower frequency limit defining the particular frequency band (Task Force of the European Society of Cardiology, 1996; Castaldo *et al.*, 2019). However, work has been reported on computing spectral analyses using intervals of less than two minutes. This was done using a different “moving window” technique where data were analysed using successive overlapping intervals (Stuiver *et al.*, 2012). The scope of the present research was however limited to typical calculation techniques.

As a few driving scenarios were two minutes or more long, HRV spectral analysis was reserved for assessing Area Events exclusively. Sampling durations of Area Events were limited to five minutes due to time domain constraints, making it an appropriate measure for the meta-grouping.

Being a subjective measure, RSME requires a task of several minutes for the operator to ascertain a conscious perception of mental effort (Marquart *et al.*, 2015). Furthermore, RSME was applied to longer samples so as not to interrupt excessively the driving task for administration of RSME. These measures were exclusively used to indicate mental workload of the longer interval duration of driving through each zoning district.

The NASA-TLX was used to indicate mental workload of the entire drive as it is best suited as a cumulative task measure (Brookhuis *et al.*, 2009; da Silva, 2014).

### **3.12 Step 2: Matching independent and dependent variables**

Recordings of the dashcam, heart rate sensor and eye tracker began at slightly different times. Time offsets were calculated to match the driving scenario times to that of the psychophysiological datasets.

### **3.13 Step 3: Processing of Psychophysiological Data**

#### 3.13.1 Heart Rate and Heart Rate Variability

Data from the Polar H7 heart rate sensor belt was retrieved from the Polar Flow website in .txt format. The .txt file was imported into the Data Reduction and Analysis Tool (V 3.4-21) developed by Prof. Matthias Göbel, updated in 2018, for the department of Human Kinetics and Ergonomics.

Data were then processed using the interval durations of driving scenarios in phase one. Heart rate data were filtered to exclude the following:

- Data points  $< 50 \text{ bt}\cdot\text{min}^{-1}$
- Data points  $> 150 \text{ bt}\cdot\text{min}^{-1}$
- Data points with a greater than 20% variation between beats.
- Extra and missing beats

For time domain analyses, intervals less than 30 seconds were excluded as they consisted of too few data points. Several data points of inter-beat-intervals are required to calculate variation for a meaningful result.

Most of the driving scenario intervals were too short for spectral analysis and this analysis was not performed for intervals of less than five minutes. Spectral analyses were calculated for the longer duration scenarios of driving through different areas. In this case, heart rate frequency and time domain analyses were also re-processed according to these longer area-based intervals.

### 3.13.2 Eye Motion Metrics

Raw data collected by the Dikablis Cable Eye Tracker were retrieved using the manufacturer's software. The .txt file was uploaded to the Data Reduction and Analysis Tool for processing according to driving scenario intervals.

As the eye tracker operated at 25 fps and eye motion measures occur in time frames of milliseconds (or more), the driving scenarios with intervals of five seconds could be processed. The limiting factor were instances where the pupil was not detected due to changes in illumination and fast and/or reaching lateral head movements.

The following parameters were used in the processing of raw data into various eye motion metrics:

- Saccade velocity defined as  $> 20^{\circ} \cdot s^{-1}$
- Fixations defined as velocities  $< 5^{\circ} \cdot s^{-1}$  (ideally  $0^{\circ} \cdot s^{-1}$  but with the inclusion of micro-saccades)
- Fixations between 100 – 1000 ms
- Eye blinks between 70 – 400 ms
- Eye blink frequency between 3 – 40 bl.min<sup>-1</sup> (excluding double blinks)

## 3.14 Step 4: Meta-grouping of Short Duration Driving Scenarios

Events from all participants were selected and grouped into three main categories termed All Events, Common Events and Area Events. The groupings were made to determine if there would be a discernible effect with respect to the overall event type on different mental workload (MWL) indicators.

### 3.14.1 All Events

All Events refers to the meta-grouping of responses by driving scenario. For example, all events where a single pothole was avoided were grouped together for statistical analysis. This included all pothole avoiding scenarios occurring within and amongst participants' drives along the set route.

The number of data points for each scenario varied between 3 and 427. Some events were encountered multiple times for all participants (e.g. driving without change in speed or direction) and some events (e.g. overtaking a moving vehicle) occurred once for only some of the participants.

The All Events meta-group included driving scenarios that were both anticipated and unanticipated by participants. Anticipated events included scenarios where the duration between the presentation of the external prompt and participant action was relatively longer (e.g. stopping at a stop street). These are also events that the researcher would announce to direct the participant along the route.

In contrast, unanticipated events had a relatively shorter duration between external prompt and the need to react (e.g. overtaking a parked car on a narrow road). These were events which could not be anticipated by the researcher, nor participant, in advance.

#### 3.14.2 Common Events

Common (or shared) Events were scenarios which reliably occurred once while driving the set route. These shared events were therefore named according to the external prompt, action and specific location.

For example, all participants turned left from Graham Street to the R350 provincial road after stopping at the T-junction. The sample size for Common Events is thus the same as the number of participants ( $n=6$ ).

The Common Events meta-group consisted only of anticipated events as participants were told about the external prompt and what action to be taken before approaching. As such, Common Events consists primarily of navigational actions. However, some scenarios consisted of looking for a space to pull-over into, or overtaking a large pothole that was barricaded, and thus easier to detect in advance.

### 3.14.3 Area Events

The set driving route spanned several different zoning districts of the town, including industrial, residential and provincial road areas. Data were categorized according to the area condition to see if mental workload indicators differed accordingly. The sample size was the same as the number of participants (n=6).

Unlike All Events and Common Events, the Area meta-grouping was longer in duration, ranging from five minutes to 30 minutes. The longer-duration area classification allowed for comparison between psychophysiological and subjective RSME mental workload indicators.

### **3.15 Steps 5 and 6: Statistical Analysis and Graphs**

Data were analysed descriptively rather than inferentially for two reasons. Firstly, the number of independent variables (i.e. events) far exceeded that of the dependent variables (i.e. MWL indicators) making inferential statistics unfeasible. Secondly, for many events, sample sizes were low with data from only six completed drives. This was due to eye tracker equipment failure mid-way through data collection.

Means were used as the measure of central tendency and standard deviation was used as the measure of variability. After data reduction, the coefficient of variation of mental workload indicators were calculated to compare variabilities. Microsoft Excel 2016 was used to calculate these statistics and generate graphs.

## **CHAPTER 4 – RESULTS**

This chapter describes the results of the present study and consists of four main topics. The first section, Section 4.1, describes how the mental workload responses of the different variables displayed as bar graphs in Appendix F was further analysed.

Secondly, Section 4.2 and Section 4.3 present the findings of the data reduction process. It is in these sections that the responsiveness of mental workload measures is quantified.

Thirdly, Section 4.4 contains the results of the driving scenarios (independent variables) which were found to have increased mental workload the most.

Lastly, Section 4.5 contains the results of the subjective measures themselves – without the additional step of identifying higher mental workload areas.

### **4.1 Identification of Events with Higher Mental Workload**

The identification process was used to summarise the large volume of results so that comparisons between the responsiveness of different mental workload measures could be made.

Despite a low sample size, the number of mental workload (MWL) indicators used, as well as the hour-long driving task, yielded a large volume of data. For most MWL indicators (excluding heart rate variability's spectral analysis and the subjective measures) there were 100 driving events displayed across three categories of graphs. The three categories (referred to as 'meta-groups') were the short-duration All Events and Common Events, and the long-duration Area Events. The outcome was a total of 35 bar graphs (Appendix F).

#### **4.1.1 Process of Threshold Selection**

This section begins with a summary of the threshold selection process and the steps taken afterwards. Following the summary is a detailed explanation of the

process, explained in four steps (from A to D). The threshold selection process of the Heart Rate Variability: SDNN results from the All Event meta-group will be used as an example.

(A) The graphs were used to identify the independent variables (referred to as 'events' and 'driving scenarios') which differed most from the average. (B) Out of these variables, the value of the event with the least difference from the average was chosen as a 'threshold'. Events falling beyond the threshold value were taken as indicative of increased mental workload.

(C) The identified higher mental workload events were then tallied up in frequency distribution tables (refer to Appendix G). (D) The absolute frequencies were relativised into a percentage. This method was applied to each to the bar graphs of each dependent variable across the All, Common and Area Event meta-groups.

The results of this process enabled the comparison between the measures' responsiveness in general, and also showed which kind of measures respond to which kind of events. Details of each step now follows using the All Event's SDNN example as previously mentioned:

### Step A

The values represented by the most visually outstanding bars were selected. In the case of the SDNN example, lower values are indicative of increased mental workload. Figure 11 shows the lowest identified events with an orange tick above each bar.

Other variables where an increase in mental workload is indicated by lower values are heart rate variability: rMSSD and high frequency power. Heart rate frequency and heart rate variability low frequency power are variables with increases in mental workload reflected by higher values. In the case of eye motion variables, responses on both the high and low ranges were used as a potential indication of increased mental workload. An explanation regarding this is given in the upcoming Section 4.1.2: 'Use of High and Low Thresholds for Eye Motion Metrics'.

With certain graphs, based on the values exceeding the threshold, as few as one event was identified. In other graphs, (representing a specific MWL measure), as many as 22 events were identified. Overall, a median of two events and a mode of one event was selected per graph.

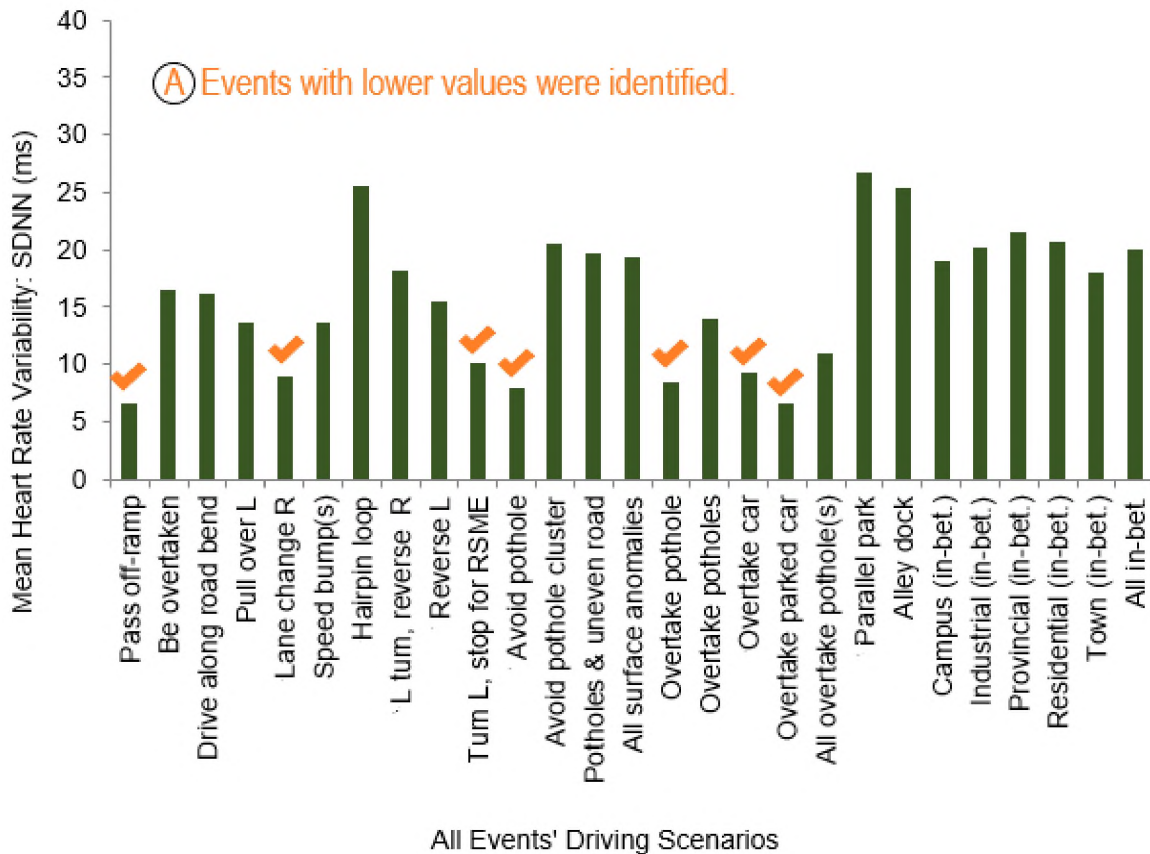


Figure 11: Step 'A' of selecting a threshold value for higher mental workload events was selecting events with lower SDNN values. The selected events are marked with an orange tick above the bar. Note that the second half of the graph was excluded as it did not contain events with particularly low SDNN values. The full graph can be found in Appendix F, Figure41.

## Step B

Of the events identified in Step A, a 'threshold' value was determined. The highest value of the identified events was chosen where the dependent variable had lower values associated with an increase in MWL. The All Events' SDNN example is an instance of this.

In the example, "Turn L, stop for RSME" was the event with the highest value of the lower values previously identified. This value was 10.14 ms and was rounded off to the nearest whole number, 10 ms, to be used as a threshold. A horizontal black line was drawn on the graph to indicate that events with values below it were considered to be indicative of higher mental workload (see Figure 12 below). With this graph, six values fell below the threshold line.

The lowest value was chosen in cases where the dependent variable had higher values associated with an increase in MWL (e.g. heart rate). A horizontal grey line was used to indicate that events exceeding the line were counted as a higher mental workload event.

For eye movement metrics, both high and low were chosen as thresholds (an explanation follows in the upcoming Section 4.1.2). Eye motion bar graphs have both grey and black threshold lines.

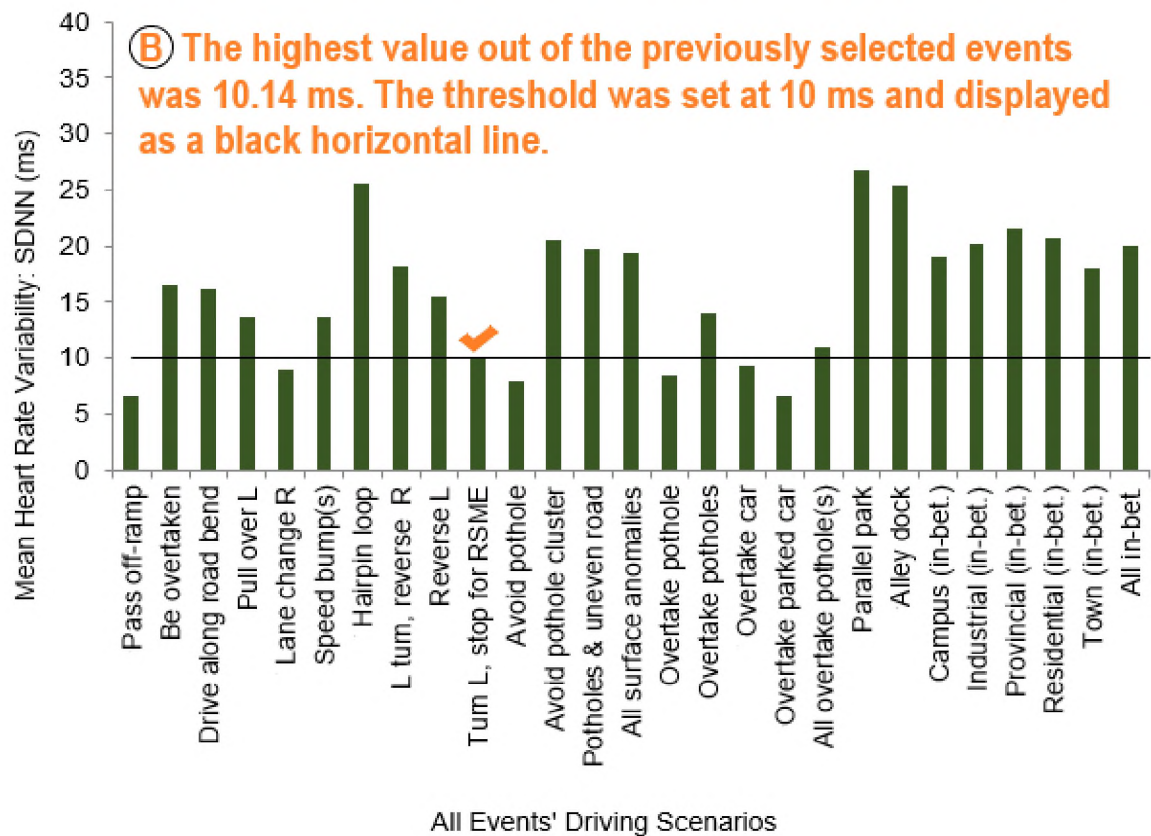


Figure 12: Step 'B' consisted of identifying the highest value out of those selected previously from step 'A'. This value was rounded off to the nearest whole number to be used as the threshold value. Note that the second half of the graph was excluded as it did not contain events with particularly low SDNN values. The full graph can be found in Appendix F, Figure 41.

### Step C

The six higher mental workload events that were identified in Step B were tabulated into the All Events' two-way frequency distribution table (Appendix G, Table X). There is one table for each meta-group. Figure 13 below illustrates the layout of the tables using the highlighted SDNN example. The figure shows four of the six higher mental workload events which fell below the threshold. Only part of the table is displayed to save space.

All Events	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Frequency Distribution of Events
Overtake moving car	1	1		1		1				1				1		1		7
Move around pothole		1			1			1				1		1		1		6
Pass confusing off-ramp		1	1		1						1					1		5
Overtake parked car	1	1	1		1							1						5
Straight at 2-way stop							1	1		1							1	4

Figure 13: Step C consisted of tabulating the higher mental workload events into the All Events' two-way frequency distribution table. A portion of the results from the SDNN example is highlighted with an orange rectangle. The full table can be found in Appendix G, Table X.

In this way, the number of values exceeding the grey line and/or falling below the black line were counted on each graph. The two-way tables included both the frequency distribution of mental workload indicators and higher mental workload events.

This is a binary approach as events were classified as either indicative of higher mental workload or not. This reduces the complexity of the measures in favour of simplicity for the sake of comparison.

#### Step D

Lastly, the absolute frequencies of the All and Common Events (short duration events) tables were relativized into a percentage. They were divided by the total number of occurring independent variables for each meta-group. For example, the frequency of six SDNN higher mental workload events were divided by 19 which was the total number of higher mental workload events for the All Event meta-

grouping. Refer to the upcoming Section 4.2 where these results are displayed as bar graphs and described further.

Long duration independent variables (Area Events) were kept as absolute frequencies. As the frequencies were either one or two out of a possible total of five, relativising the absolute frequencies was not necessary. Furthermore, the mental workload between short duration and long duration events were not subject to comparison, in which case percentages would be used. Refer to Section 4.3 where these findings are described further.

#### 4.1.2 Use of High and Low Thresholds for Eye Motion Metrics

Eye motion measures were split into thresholds of higher and lower values. There are mixed results in the literature regarding whether higher or lower values indicate an increase in MWL. The contradictory findings can be explained by the type of task, thus making eye motion MWL indicators highly task dependent.

For example, visual fatigue may decrease saccade duration whereas task complexity may increase it (Ahlstrom and Friedman-Berg, 2006; McGregor and Stern, 1996; Schmidt *et al.*, 1979).

Fixation duration was found to decrease with an increase in task demand and during a visual tracking task (Van Orden *et al.*, 2000; De Rivecourt *et al.*, 2008). However, fixation duration increased in tasks related to hazard perception (Marchitto *et al.*, 2016; Underwood *et al.*, 2011).

Similar contradictions were found with blink duration, blink frequency and pupil diameter measures as discussed in the Section 2.6 of the Review of Literature. Saccade amplitude and velocity are used less frequently as MWL indicators, so it is not known how they perform in response to different tasks.

It is unknown how to fully interpret eye motion responses given the lack of real-world driving and MWL studies. Furthermore, driving is multi-dimensional with visual and mental aspects closely related (Marquart *et al.*, 2015). Unlike simulator, vigilance and tracking tasks, real-world driving is more difficult to classify as a singular task type with an associated eye motion response. As such, both the

higher and lower responses were considered as an indication of higher mental workload.

## **4.2 Relative Frequency Distribution Graph: All Events and Common Events**

Figure 14 on the next page displays the relative frequency distributions of short duration mental workload (MWL) measures. The frequency refers to how often an MWL indicator response exceeded the range of values interpreted as 'normal MWL' in response to a particular driving scenario. Values beyond the defined normal MWL ranges were indicative of increased MWL. This method was undertaken to compare MWL responses to different kinds of driving scenarios (events).

Comparison between frequency distributions indicates the relative sensitivity of each MWL indicator in response to real-world driving scenarios. The sensitivity of a particular measure to a particular scenario is not an absolute indication of sensitivity. It is relative to its responses overall as well as the responses of other MWL indicators.

All Events includes the mental workload indicators of all short duration driving scenarios which lasted 90 seconds at most. These events included both predictable as well as unpredictable events.

Common Events identify mental workload indicators in short duration driving scenarios that were anticipated by drivers. The anticipation was due to the driving route being pre-set and containing specific driving scenarios common to all drivers.

Frequency responses of eye motion metrics were separated into two ranges. That is, the number of responses exceeding the upper threshold (labelled '[UPPER]') as well as number of responses falling below the lower threshold (labelled '[LOWER]').

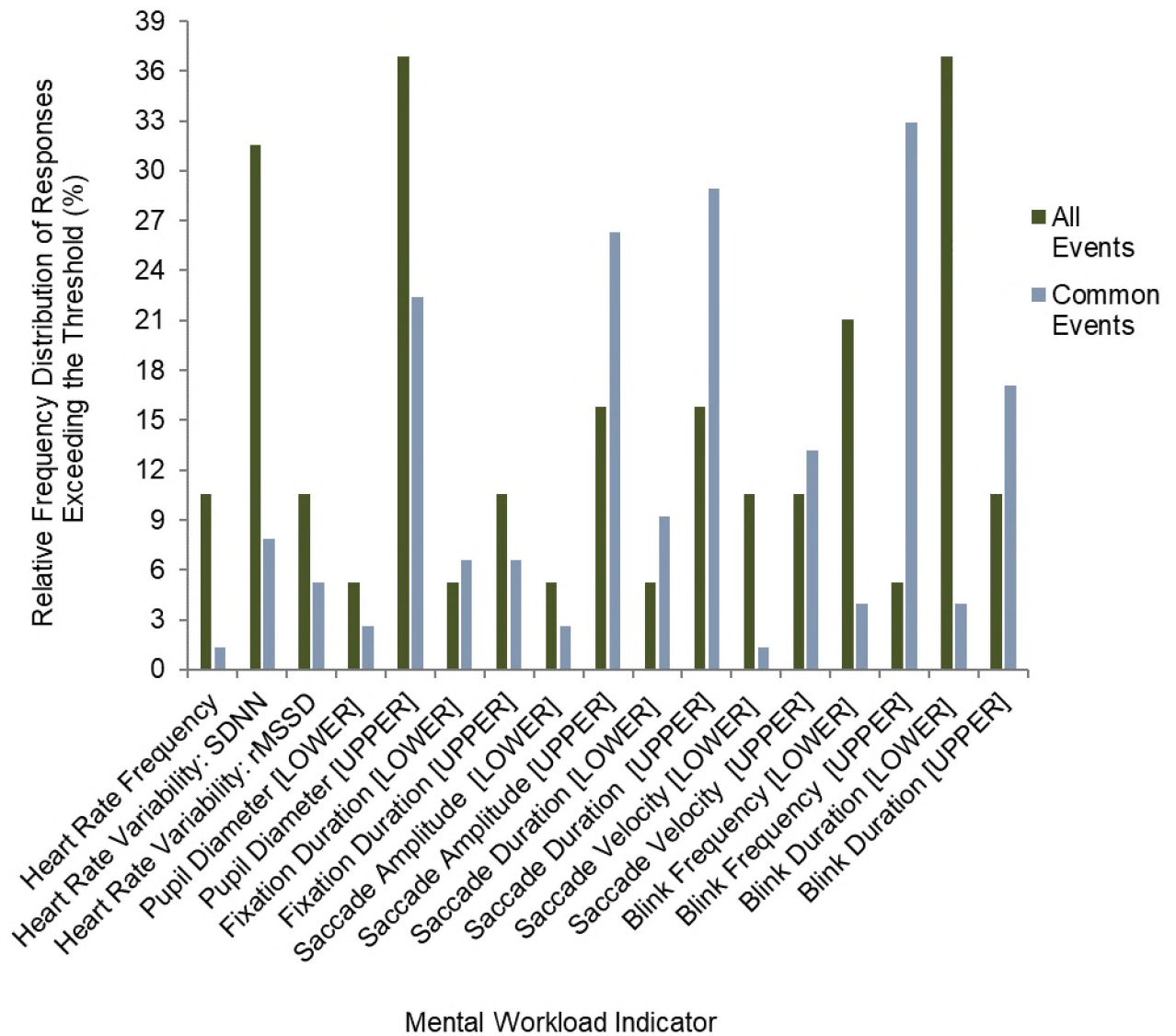


Figure 14: Frequency distribution of MWL indicators relativised by the total number of possible events for each meta-grouping. Eye motion measures have two bars depicting frequencies outside the upper and lower limits.

Eye blink metrics are affected both by mental workload and fatigue. Similarly, pupil size is highly dependent on changing ambient illumination. Details of this can be found in Section 2.6 of the Review of Literature.

The means, standard deviations and coefficients of variation of the All Events and Common Events results are tabulated in the upcoming Table I of Section 4.2.2. The most responsive MWL measures of All Events and Common Events are listed for comparison in Table II of Section 4.3.2.

#### 4.2.1 General Description of Frequency Distribution Results

In this section, an overview of the results of Figure 14 is given. That is, the mental workload measures with the most and least frequencies, will be described overall - regardless of meta-group.

Increased pupil diameter, and decreased blink duration had the highest relative frequencies of all measures at 36.8%.

Increased blink frequency identified a comparatively large amount of higher MWL events with a 32.9% relative frequency.

The SDNN measure of HRV had a relative frequency of 31.6%, indicating that it is a sensitive measure of MWL. Next, longer saccade duration was responsive to changes in MWL at a relative frequency of 28.9%.

In contrast, the measures with the lowest overall responsiveness was heart rate frequency and slower saccade velocity at a relative frequency of 1.3%. Furthermore, shorter pupil diameter, shorter saccade duration and shorter fixation duration were found to be relatively unresponsive measures.

#### 4.2.2 Measures of Central Tendency and Variance

Generally, the variance in responses of each MWL measure between All Event and Common Event meta-groups are comparable. Table I and Table II contain descriptive statistical measures of the All Events and Common Events groups respectively.

Measures of pupil diameter, fixation duration, saccade amplitude, saccade velocity and blink durations had a ~2% difference in the coefficient of variation (CV) between meta-groupings. This similarity in the variability of data supports the statistical comparisons between the results of both groups.

With differences of < 0.5% between meta-groupings, heart rate variability (HRV) measures had the most similar CVs. However, along with blink duration, HRV measures had the greatest variability of data overall measures with CVs slightly higher than 30%.

With a 6% difference, blink frequency had greater variance in responses for All Events compared to the 11.8% CV for Common Events.

Saccade duration had a 3.4% lower CV for All Events compared to that of the Common Events meta-group. Heart rate frequency showed a 1.5% lower CV for the All Events group compared to the Common Events group.

*Table 1: Mean, standard deviation and coefficients of variation for MWL indicators from the All Events driving scenarios.*

<b>Meta-group: All Events</b>			
<b>MWL Indicator</b>	<b>Mean</b>	<b>Standard Deviation</b>	<b>Coefficient of Variation (%)</b>
Heart rate frequency [bt.min <sup>-1</sup> ]	93.1	2.8	3.0
HRV: SDNN [ms]	17.0	5.2	30.5
HRV: rMSSD [ms]	21.3	6.5	30.5
Pupil Diameter [mm]	2.8	0.3	12.2
Blink Frequency [bl.min <sup>-1</sup> ]	23.9	4.2	17.8
Blink Duration [ms]	158.2	51.9	32.8
Saccade Amplitude [°]	9.9	2.0	20.6
Saccade Duration [ms]	79.1	7.3	9.3
Saccade Velocity [° .s <sup>-1</sup> ]	113.0	20.3	18.0
Fixation duration [ms]	93.5	8.7	9.3

Table II: MWL indicators' mean, standard deviation and coefficient of variations in response to Common Event driving scenarios.

<b>Meta-group: Common Events</b>			
<b>MWL Indicator</b>	<b>Mean</b>	<b>Standard Deviation</b>	<b>Coefficient of Variation (%)</b>
Heart rate frequency [bt.min <sup>-1</sup> ]	91.8	4.1	4.5
HRV: SDNN [ms]	18.6	5.6	30.1
HRV: rMSSD [ms]	23.5	7.2	30.4
Pupil Diameter [mm]	2.7	0.3	10.8
Blink Frequency [bl.min <sup>-1</sup> ]	26.5	3.1	11.8
Blink Duration [ms]	183.4	61.3	33.4
Saccade Amplitude [°]	10.7	2.4	22.6
Saccade Duration [ms]	81.5	10.4	12.8
Saccade Velocity [°.s <sup>-1</sup> ]	118.8	24.1	20.3
Fixation duration [ms]	92.1	9.8	10.7

#### 4.2.3 Comparison between short duration MWL measures

Table III lists the top frequency measures identified in Figure 14 between meta-groups for comparison. Longer pupil diameter responses were common to both All Events and Shared Events top relative frequency measures.

Both All Events and Common Events had blink duration and blink frequency as particularly responsive measures. However, the Common Events group had increased blink frequency as responsive in comparison to decreased blink frequency in the All Events group. Although blink frequency was identified as responsive under both meta-groupings, this measure had a higher CV of ~30%.

The only heart-beat related measure was HRV: SDNN of the All Events group. SDNN had a higher variance overall with a CV ~30% making this measure both responsive to All Events as well as variable across participants.

It is noteworthy that Common Events registered ocular measures with higher limits (i.e. increased blink frequency, longer saccade durations and increased saccade amplitude).

*Table III: Comparison of responsive MWL measures between the All Events and Common Events meta-groupings. Percentages have been rounded off to the nearest whole number.*

All Events		Common Events	
MWL Indicator	% Higher MWL Events Identified	MWL Indicator	% Higher MWL Events Identified
Longer pupil diameter	37%	Increased blink frequency	33%
Shorter blink duration	37%	Longer saccade duration	29%
Heart Rate Variability: SDNN	32%	Longer saccade amplitude	26%
Decreased blink frequency	21%	Longer pupil diameter	24%
-	-	Longer blink duration	17%

### 4.3 Area Events Overview

Long duration driving scenarios were termed Area Events. Comparing MWL measures of short and long durations is ideal but not viable. This is because time domain analysis results require similar sample durations for accurate comparison. Rating Scale of Mental Effort (RSME) scores and spectral analysis of Heart Rate Variability (HRV) were not employed in the short duration meta-group and thus cannot be compared. Eye motion metric comparisons between long and short

durations would be tentative at best. This is because eye motion as an MWL indicator is best suited to short duration samples.

Area Events allowed for the comparison between MWL measures suitable for analysis of long duration samples (5 minutes). Heart rate variability spectral analysis was used in this category, as well as the subjective measure of RSME.

The frequency distribution results of Area Events were not relativised like the short duration frequency distribution results were.

Compared to the numerous short duration events, Area Events consisted of only five events. Therefore, the frequency at which each measure identified an event above (or below) the set threshold was either once or twice.

As with the short duration driving events, eye motion measures were separated into upper and lower ranges.

#### 4.3.1 Area Events Results

MWL indicators which exceeded the threshold in two areas:

- Increased Heart Rate Frequency
- HRV: high frequency power [LOWER]
- Pupil Size [LOWER]
- Saccade Amplitude [UPPER]
- Saccade Amplitude [LOWER]
- Saccade Duration [LOWER]
- Saccade Velocity [LOWER]
- Eye Blink Frequency [UPPER]
- RSME

MWL indicators which only exceeded the threshold in one area:

- Heart Rate Variability: SDNN

- Heart Rate Variability: rMSSD
- HRV: low frequency power
- HRV: LF power relative to (LF + HF)
- Pupil Size [UPPER]
- Fixation Duration [LOWER]
- Fixation Duration [UPPER]
- Saccade Duration [UPPER]
- Saccade Velocity [UPPER]
- Eye Blink Frequency [LOWER]
- Eye Blink Duration [LOWER]
- Eye Blink Duration [UPPER]

The three saccadic measures of amplitude, duration and velocity registered as responsive mental workload indicators with an absolute frequency of two. An increase in saccade amplitude was found to be responsive. In contrast, shorter saccade duration and slower saccade velocity were found to be responsive.

The HRV: High frequency band registered twice as many Area Events than the Low frequency power band did.

The subjective RSME measure identified two Area Events of higher MWL.

#### 4.3.2 Coefficient of Variation

Measures of central tendency and variance are listed in Table IV below. The higher CV measures were above 17% and included four measures, namely:

- HRV: Low-Frequency power
- HRV: High-Frequency power
- RSME
- Blink duration

The High-Frequency power band and RSME measures were found to be responsive measures. These measures also had a relatively higher variation in responses than most other MWL measures.

*Table IV: MWL indicators' descriptive statistic information in response to the long duration Area Events group.*

<b>Meta-group: Area Events</b>			
<b>MWL Indicator</b>	<b>Mean</b>	<b>Standard Deviation</b>	<b>Coefficient of Variation (%)</b>
Heart rate frequency [bt.min <sup>-1</sup> ]	93.0	1.7	1.8
HRV: SDNN [ms]	24.1	3.1	13.0
HRV: rMSSD [ms]	30.8	4.3	13.8
HRV: high frequency power [ms <sup>2</sup> ]	143.2	24.7	17.2
HRV: low frequency power [ms <sup>2</sup> ]	635.4	174.8	27.5
HRV: LF power relative to (LF + HF) [%]	81.9	3.3	4.1
Pupil Diameter [mm]	2.6	0.3	10.9
Blink Frequency [bl.min <sup>-1</sup> ]	26.7	1.8	6.6
Blink Duration [ms]	188.5	33.1	17.6
Saccade Amplitude [°]	10.6	0.6	6.0
Saccade Duration [ms]	80.1	6.2	7.8
Saccade Velocity [°.s <sup>-1</sup> ]	119.9	11.0	9.2
Fixation duration [ms]	94.2	3.9	4.1
RSME	35.2	7.6	21.6

#### **4.4 Overview of Driving Scenario Results**

The primary research aim was to compare the responsiveness of commonly used MWL measures. A secondary research aim was to explore the kind of situations different MWL measures respond to. However, an unanticipated finding was that certain driving scenarios from each meta-category were repeatedly classified as higher MWL events by several measures. That is, the frequency distribution tables (Appendix G) took both MWL indicators and event frequencies into account.

The repeated encounters of certain independent variables while driving allowed for a measuring frequency. The relative frequencies of higher MWL events for each meta-grouping was relativised according to the number of possible MWL measures. Given that these events are independent variables (of different categories) there are no measures of central tendency or variance.

The results of the All Events group is displayed in

Figure 15 and the Common Events group in

Figure 16 below. Only driving scenarios which exceeded MWL thresholds most frequently were included. As there were only five Area Events in total, all five area frequencies were included in the graph of Figure 17.

#### 4.4.1 All and Common Events (short duration)

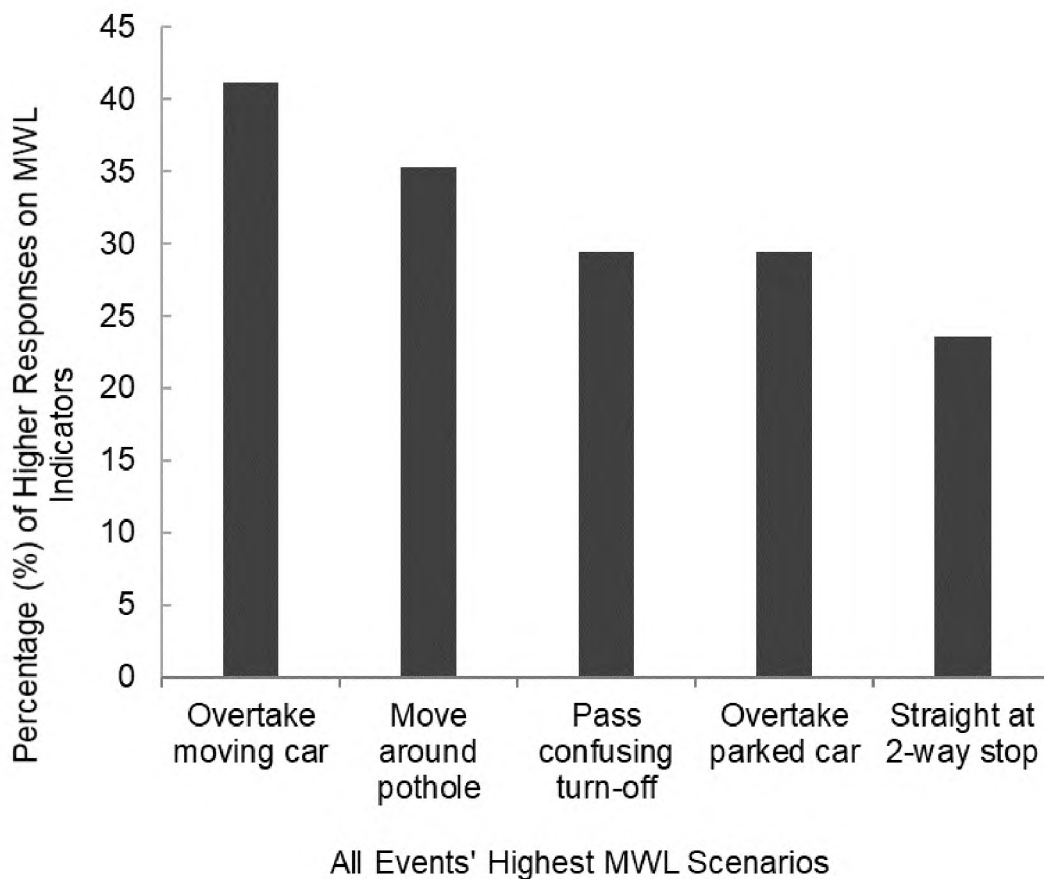


Figure 15: Relative frequency distribution of higher MWL driving scenarios of the All Events meta-grouping.

Out of All Events, overtaking a moving vehicle was found to elicit greater responses from MWL indicators than other events - at a relative frequency of 41.2%. This was followed by moving around a pothole (without overtaking it by driving on the adjacent road lane) which was detected as a at a frequency of 35.3%.

Following this, three other events were identified by several variables (refer to Appendix G, All Events Table X) as potentially increasing MWL. Passing by the

confusing turn-off and overtaking a parked car on a narrow road had a relative frequency of 29.4%. Driving straight after stopping at a 2-way stop street had a relative frequency of 23.5%.

Photographs and details accounting for the complexity of these locations are included in Section 6.3.1 of the Conclusion Chapter.

#### 4.4.2 Area Events (long duration)

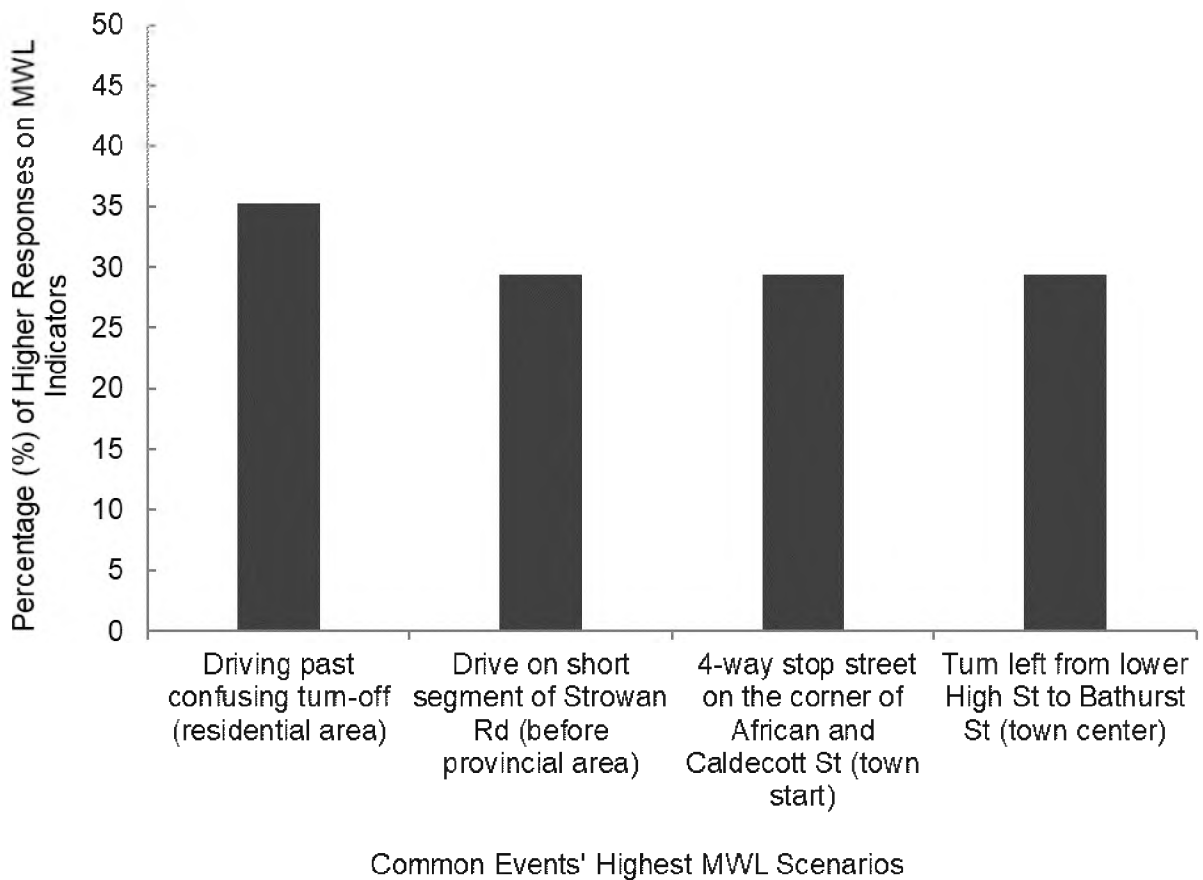


Figure 16: Relative frequency distribution of higher MWL events of the Common Events meta-grouping.

The higher mental workload events for Common Events are specific to locations within Makhanda (formerly Grahamstown). Photographs and details accounting for the complexity of these locations are included in Section 6.3.2 of the Conclusion Chapter.

Driving past the confusing turn-off was identified at 35.3% times as eliciting a marked response of MWL indicators in the Common Events group. This event was also identified in the All Events group at a frequency of 29.4%.

Driving on the short stretch of road before turning onto the Provincial Road was found to result in increased MWL results for 29.4% variables.

Also, at a frequency of 29.4%, was navigating the 4-way stop street at the corner of African and Caldecott Street of the beginning of the town area. Participants were instructed to drive straight ahead after stopping at this intersection.

Furthermore, turning left from High Street onto Bathurst street caused 29.4% of mental workload measures to register it as a higher mental workload event. This location was within the busy centre of town.

#### 4.4.2 Area (long duration events)

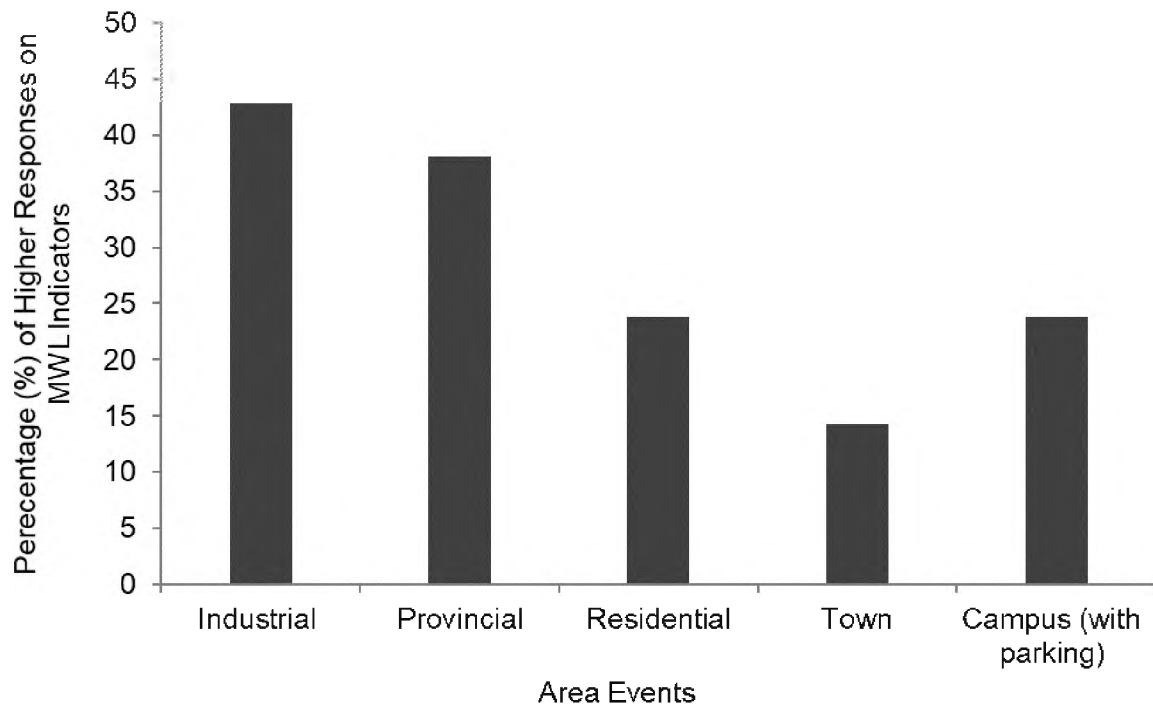


Figure 17: Relative frequency distribution of higher MWL Area Events.

The industrial area was identified as the most MWL intensive area along the route at a frequency of 43%. This was followed by the Provincial Road at a frequency of 38%. Comparatively, at a lower frequency of 23.8%, the residential and campus areas (with parking) were highlighted as areas contributing to increasing MWL. Driving through the main town area (Central Business District) only registered as a higher MWL event in 14.3% of cases.

It is worth noting that the Area Events category included the subjective measure of RSME in addition to psychophysiological measures.

Details accounting for the mental workload results of these areas are included in Section 6.3.3 of the Conclusion Chapter.

#### **4.5 Overview of Subjective Measures' Results**

Subjective MWL measure results are presented in this section. Unlike the psychophysiological measures, the subjective measures' results are included in the Results Chapter as opposed to the Appendix.

This is because these results were less extensive and required minimal (RSME) or no (Raw TLX) data reduction. While there were numerous psychophysiological variables used, there were only two subjective MWL tools. Furthermore, the comparison between subjective MWL indicators to psychophysical ones fits the broad theme of the research question of comparing MWL measures.

##### **4.5.1 RSME Results**

While the RSME was used alongside other Area Event (long duration) measures as a means of identifying higher MWL scenarios, results obtained from the RSME merit consideration in their own right.

The subjective RSME scores of each Area Event's MWL will be compared to that of the psychophysiological results. Figure 18 below displays RSME results. The frequency at which each area was flagged by a psychophysiological measure as contributing to a higher MWL follows in Figure 19.

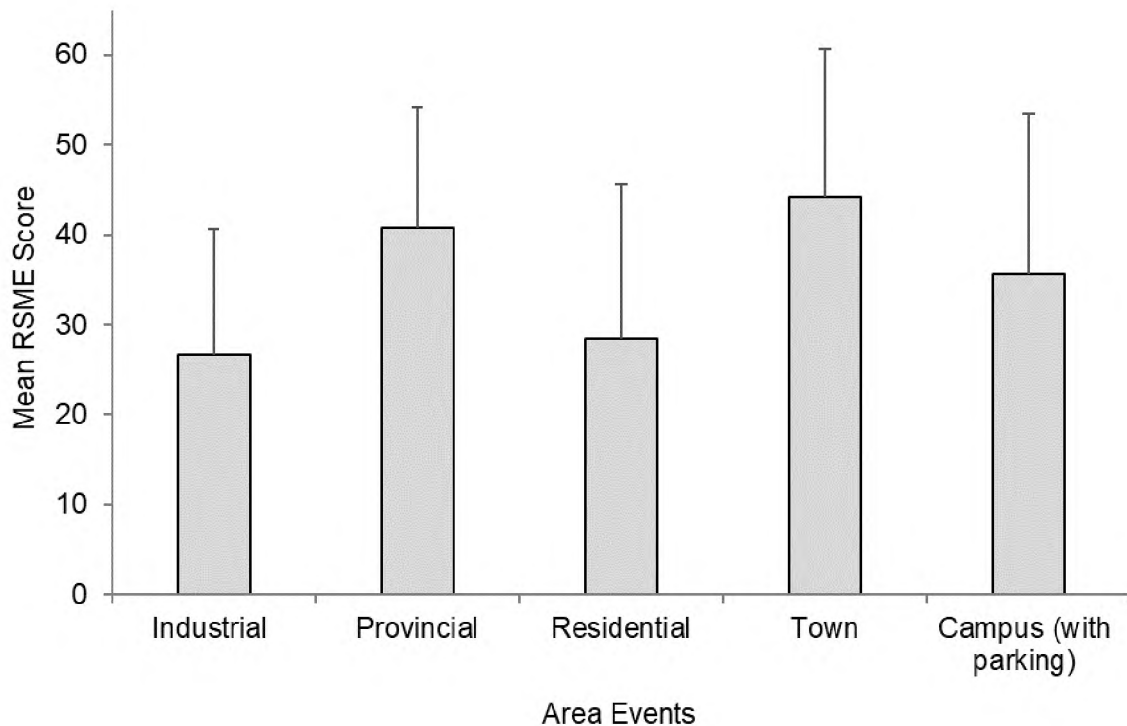


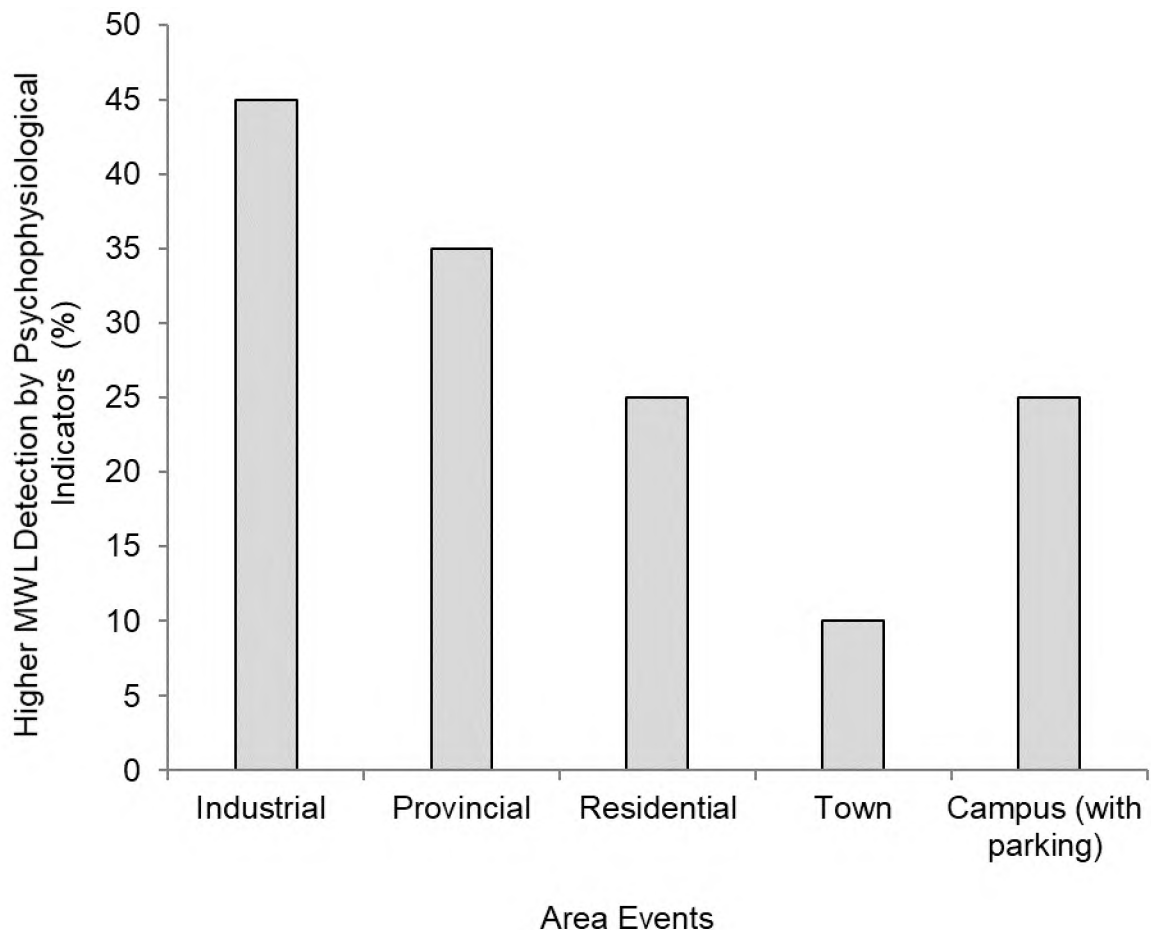
Figure 18: Mean RSME scores of driving through each area. Error bars represent the standard deviation of the mean.

The average rating of all areas was 35.2 ( $\pm 7.6$ ). Driving through the busy town area was perceived as requiring the most mental effort at a mean of 44.2 ( $\pm 16.6$ ). This while this rating, however, differed the most amongst participants and had the largest standard deviation, average responses ranged between 26.7 and 44.2 on the RSME scale of zero to 150 Thus the ratings overall were not diverse.

Driving along the provincial main road was rated as the second most effortful area to drive through with a rating of 40.1 ( $\pm 13.3$ ). Given the lower standard deviation, this rating was more agreed upon than that of the town drive.

Driving through part of the campus and performing the parking tasks was scored with a mean of 35.7 ( $\pm 17.8$ ). This average was almost identical to the overall average rating of 35.2.

The residential and industrial areas were rated as requiring the least mental effort of all areas. The residential area mean score was 28.5 ( $\pm 17.2$ ) and the industrial area was rated at a mean of 26.7 ( $\pm 14$ ).



*Figure 19: Relative frequency of higher MWL-inducing events as identified by psychophysiological indicators only.*

Figure 19 follows the same pattern found in Figure 17: ‘Relative frequency distribution of higher MWL area events’. The industrial area is followed by the provincial, residential, campus and town areas as ordered by the frequency each area was flagged for increasing MWL.

#### 4.5.2 NASA-TLX (Raw TLX)

A modified version of the NASA-TLX was used named the Raw TLX (RTLX). This version omits the weighting subscales in favour of the ‘raw’ ratings.

This multi-dimensional measure was used to assess the MWL of two tasks upon completion. The first was a baseline condition where participants performed a two-minute tracking task on a computer. The second task was the real-world drive. The results of these ratings are displayed in Figure 20 below:

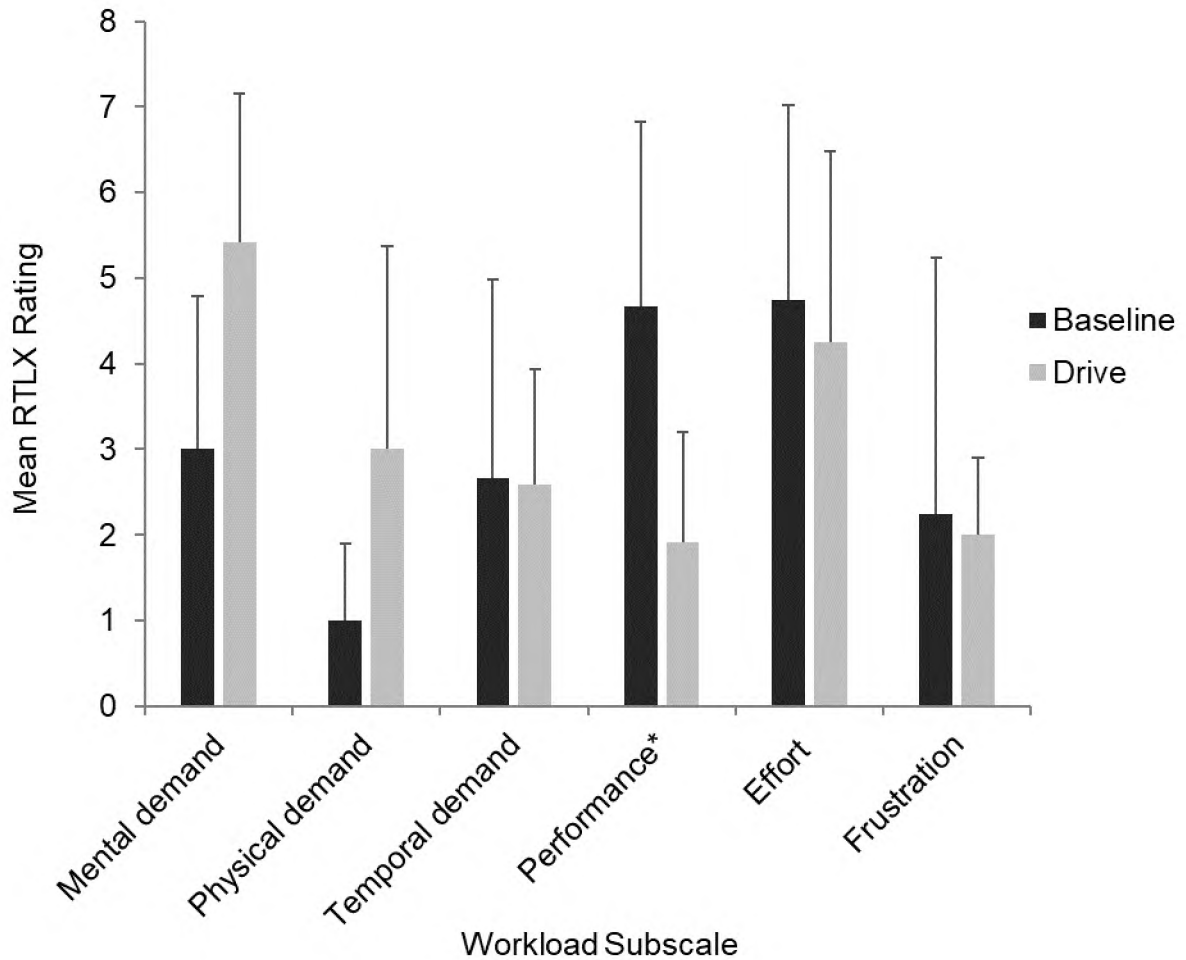


Figure 20: Comparison between Raw TLX scores of the drive and baseline conditions. \*The performance subscale defines lower ratings as “perfect” and higher ratings as “failure”. The other subscales qualify lower values as “very low” and higher values as “very high”. Error bars represent the standard deviation of the mean.

Mean performance, mental demand and physical demand ratings differed the most between the baseline and driving tasks. The driving task had a better performance rating at 1.9 ( $\pm 1.3$ ) in comparison to the 4.7 ( $\pm 2.2$ ) rating of the baseline task. The variance in the baseline task performance rating was greater than that of the drives.

The mental demand of the drive was rated 5.4 ( $\pm 1.7$ ) whereas the mental demand perception of the tracking task was 3 ( $\pm 1.7$ ).

The perceived physical demand of the baseline task was less than the drive by a difference of 2. However, physical demand ratings differed more amongst participants for the drive ( $\pm 2.4$ ). Ratings of the tracking task's physical demand were less varied ( $\pm 0.9$ ).

Participants rated the baseline task as more effortful than the driving task. The baseline effort rating was 4.8 ( $\pm 2.2$ ) whereas for the drive it was 4.3 ( $\pm 2.2$ ).

MWL scores of temporal demand and frustration had similar responses for both tasks. Temporal demand of the drive was rated only 0.1 lower than the 2.7 mean of the baseline task. However, the variance in responses for the baseline task was higher by  $\pm 0.9$  than the drive.

Perceived frustration was greater for the baseline task with a mean rating of 2.3 ( $\pm 3$ ). There was a notable variation in participant responses. Comparatively, frustration experienced during the drive was less, at a rating of 2 ( $\pm 0.9$ ), and had more unanimous responses than the other subscales.

## **CHAPTER 5 - DISCUSSION**

The first half of this chapter discusses the main result findings as they relate to the research aims. Namely, which mental workload indicators were the most responsive overall, and to which categories (or types) of real-world driving scenarios.

The second half of this chapter is a reflection on the research methodology and its limitations.

### **5.1 Short Duration Mental Workload Responses**

The following two sections are based on the findings of Section 4.2.3: Table III of the Results Chapter, which lists the most responsive mental workload (MWL) indicators of the All Events and Common Events meta-groupings (i.e. short duration driving scenarios).

Short duration events were divided into the All Events and Common Events groupings. The MWL of the participant drivers can be inferred from the kind of MWL indicators that were most responsive. A commonality was found between the measures' direction of effect on MWL of each group. Specifically, measures of the All Events group tended towards values indicating an increase in MWL. On the other hand, measures of MWL indicated decreasing MWL in the Common Events group.

In addition to these commonalities, an argument is made for driver MWL based on which MWL indicators were unique to each group. The following discussion details how these inferences were made based on the research results.

#### **5.1.1 All Events**

The All Events group consisted of MWL responses to all driving scenarios encountered throughout all six drives. Therefore, this grouping included driving scenarios that were both anticipated (e.g. preparing several seconds in advance to stop at an upcoming stop street), as well as unanticipated. 'Unanticipated

events' refers to driving scenarios with a shorter time between the presentation of an external prompt, and the necessary action taken in response. For example, a pothole becomes apparent mere seconds before the driver must decide and execute the action of overtaking it.

What now follows is a discussion about the most responsive dependent variables and MWL.

At a relative frequency of 37%, longer pupil diameter and shorter blink duration were the most responsive variables in the All Events meta-grouping.

An increase in pupil diameter is associated with an increase in visual processing demands (Van Orden *et al.*, 2000; Iqbal *et al.*, 2005). However, a confounding factor is that pupil diameter is highly responsive to changes in ambient illumination (Benedetto *et al.*, 2011). The high responsiveness of increasing pupil diameter may also be accounted for by the frequency at which illumination levels changed throughout the drives.

Task-evoked pupillary response (TEPR) are smaller changes (< 0.5mm) in pupil diameter which are indicative of increased cognitive processing (Marquart *et al.*, 2015). However, the processing technique required in separating smaller and larger changes in pupil size is beyond the scope of this research.

Shorter blink duration indicates a processing of more visual information (Recarte *et al.*, 2008; Faure *et al.*, 2016).

At a relative frequency of 32%, lower SDNN (Heart Rate Variability) was the second most responsive MWL indicator.

A decrease in SDNN is indicative of an increase in MWL (Brookhuis and de Waard, 2010; Tjolleng *et al.*, 2017; Charles and Nixon, 2019). This suggests that the time domain measure is relatively sensitive to MWL increases during both anticipated and less-anticipated driving events. Furthermore, a lower SDNN is a reliable indication of an increase in MWL even though it is not as computationally robust as the rMSSD calculation (Mehler *et al.*, 2011; Shakouri *et al.*, 2018).

The third most responsive measure was reduced blink frequency with a relative frequency of 21%. A reduction in blink frequency relates to an increase in visual information processing and sustained attention (Ahlstrom and Friedman-Berg, 2006; Faure *et al.*, 2016). This is comparable to the shorter blink duration responses.

The unanticipated events of this study include hazard perception which accounts for the increase in fixation duration. Longer fixation durations occurred in response to an increase in hazard perception during a simulator study (Underwood *et al.*, 2011). However, fixation metrics are dependent on the task itself. The gaze of the driver is determined to a large extent by the driving environment (e.g. traffic, pedestrian movements, checking if it is safe to turn or change lanes, etc.).

The eye movement metrics in this case support a tendency of the eyes being open in order to gather and process more visual information or reduce the risk of missing important visual information (Faure *et al.*, 2016). In the context of Wickens' 4D resource model of MWL, the discussed eye motion measures would support that visual-spatial cognitive resources were used (Wickens, 2008).

Overall, the types of variables that frequently responded to All Events suggest increased driver alertness and visual processing. The decrease in SDNN, blink frequency and blink duration, and increase in fixation duration indicate an increase in workload.

These findings are attributed to the nature of the All Events driving scenarios. Unanticipated driving scenarios necessitate alertness to respond timeously and appropriately. The type of anticipated events would have tended towards inducing a level of arousal. In this case, anticipating these events did not serve to lower arousal.

The main limitation of the All Events analysis was that the number of data points for each driving scenario differed. Section 5.6.2 of the limitation section discusses this further.

### 5.1.2 Common Events

MWL responses to Common Events are interpreted as MWL responses to anticipated driving scenarios.

The Common Events meta-group consisted of MWL responses to specific driving scenarios shared by all six drives. In other words, the physical location of the external prompt and the driver's response were the same. For example, all drivers stopped at the 2-way stop street on Graham Street before turning left onto the R350 provincial road (see Appendix E1: Directions through the light Industrial Area, Figure 33, point 1d on the map).

As such, Common Events excluded events which were unique to a driver (e.g. overtaking a vehicle on Constitution Street). Unique driving scenarios were unanticipated by the driver. In contrast, Common Events were those that were anticipated. They typically included scenarios such as navigating intersections, maintaining speed and direction, or avoiding a distinct or large (and thus anticipated) hazard.

Increased blink rate was the most responsive MWL measure of the Common Events grouping. A 33% relative frequency of higher MWL responses was observed. In two driving simulator studies, an increase in blink rate was observed in response to increased task demands by the addition of a secondary task (Faure *et al.*, 2016). It was also found to increase in response to time-on-task which is a response of fatigue (Benedetto *et al.*, 2011).

Attributing increases in blink rate to mental workload – as opposed to drowsiness – is thus difficult. Fatigue (a low activation state) and increases in visual task processing (a higher activation state) both increase blink rate (Recarte *et al.*, 2008).

The present research limited the total driving time to below the recommended time before a break is required to limit fatigue caused by the drive. However, the possibility of fatigue due to other factors cannot be excluded.

It is worth consideration that a *decrease* in blink rate was a frequent response to All Events' driving scenarios as well. In contrast, an *increase* in blink rate was the

most frequently responsive (or “sensitive”) MWL measure in the Common Events category. The increase in blink rate in response to anticipated events imply that lower activation is the cause of the frequent increase in blink rate.

At a frequency of 29%, longer saccade durations were the second most responsive MWL measure for Common Events. Saccade duration is uncommonly used as MWL indicator. During an air-traffic control simulation, saccade duration increased with time on task (McGregor and Stern, 1996). This is supported by the understanding that little-to-no visual information is processed during saccades (Goldberg and Kotval, 1999; Marquart *et al.*, 2015). Although, drowsiness-level fatigue was not a factor in the present study, these findings suggest less arousal occurred during the anticipated Common Events.

The third most responsive measure was increased saccade amplitude with a relative frequency of 26%. Saccadic movements bring the eyes to different fixation points, which together allow for the visually scanning of the environment (Goldberg and Kotval, 1999; Marquart *et al.*, 2015).

The frequent increase of saccade amplitude coupled with saccade duration means that participants visually scanned further reaches of the environment. This eye movement is in accordance with real-world driving which requires that the driver makes observations of a wide reach of the immediate environment.

Furthermore, the increased saccade duration matches the increased amplitude which means that saccade velocity was unchanged. Saccade velocity did not register as a responsive mental workload measure either, which supports this deduction. Given the above, the increased frequency of longer saccade amplitude is better attributed to driving itself, rather than an indication of mental workload. If gaze patterns were accounted for, the effect (if any) of cognitive load on saccade amplitude would be more apparent. For example, it may be the case that saccade amplitude and duration increases due to the driver looking to the far left for cross-traffic – rather than due to mental workload.

An increase in pupil diameter at a frequency of 24% was the fourth most responsive MWL indicator. As previously discussed, it is difficult to interpret

whether the increased pupil size were TEPRs or the effect of changing illumination levels – or a combination of both.

A high-fidelity driving simulation study found an increase in pupil diameter to be more sensitive to increases in MWL than faster blink rate (Niezgoda *et al.*, 2015). The present study had opposite findings. The difference can be attributed to differences in simulation and real-world applications decreasing the transferability of physiological results (Charles and Nixon, 2019).

Longer blink duration was the fifth most responsive mental workload measure at a relative frequency of 17%. Longer blink durations occur in response to fatigue (Ahlstrom and Friedman-Berg, 2006; Faure *et al.*, 2016). The longer blink durations support the findings of the increase in blink rate and saccade duration responses. Anticipated driving scenarios elicit a less focused and alert or aroused state than unanticipated and anticipated events combined.

Given the increased blink frequency and duration, it can be inferred that the task demands of anticipated driving events were less than that of the All Events meta-group. That is, the anticipated driving scenarios of the Common Events group resulted in lower MWL in comparison to that of the All Events group.

The interpretation of MWL in terms of arousal lends itself to the cognitive energetic theory of MWL (U.S. Army Research Laboratory, 2000; da Silva, 2014). The arousal levels in response to Common Events would be less than that of All Events. However, it would not be low enough to result in substantial underperformance.

## **5.2 Comparison of Responses Between All Events and Common Events**

This section compares the most responsive MWL indicators of the All Events (anticipated and unanticipated events) and Common Events (anticipated events) meta-groups. The sensitivity and suitability of these MWL indicators to real-world driving are the criteria used for the comparison.

Blink frequency and duration were responsive MWL indicators for both All Events and Common Events. In addition to being responsive, these indicators showed

some potential to differentiate between higher and lower levels of MWL. However, caution should be applied when interpreting blink measurements. Blink rate increases in response to increased visual demand, but also fatigue (Recarte *et al.*, 2008). Similarly, an increase in blink duration is associated to drowsiness and fatigue in literature – more so than increases due to task demands (Ahlstrom and Friedman-Berg, 2006; Faure *et al.*, 2016).

Fatigue and drowsiness were observed in response to long duration simulation tasks. It is uncertain to what extent responses may differ in simulator studies compared with real-world results. Some researchers argue that real-world driving is more visually complex and creates a different degree of hazard perception in comparison to even high-fidelity simulations (Owsley and McGwin, 2010; Underwood *et al.*, 2011).

However, the lack of real-world driving studies which follow similar protocols to that of laboratory studies makes comparison tentative and uncertain. In summary, blink frequency and duration are not pure indicators of MWL, though their responsiveness to real-world driving conditions shows promise.

Pupil diameter was responsive to both meta-groups as well. However, illumination could not be controlled for and analysis of TEPRs is beyond the scope of the study. Further research is needed to determine the validity of pupil diameter changes as a mental workload indicator during real-world conditions of changing illumination.

The heart rate variability measure of SDNN was only responsive to the All Events meta-group. Interestingly, it was the only responsive short duration measure that was not an eye movement. SDNN may be a good indicator of MWL increases for real-world driving situations that are unanticipated. Such events include overtaking, being overtaken, avoiding potholes and navigating roads with uneven surfaces.

Heart rate variability has been shown to be a valid MWL indicator (Fallahi *et al.*, 2016; Luque-Casado *et al.*, 2016; Charles and Nixon, 2019). However, time domain calculations are affected by recording duration (Task Force of the

European Society of Cardiology, 1996; Charles and Nixon, 2019). A limitation of the current research is that sampling durations differed in an order of seconds.

Saccade amplitude and saccade duration were responsive to Common Events. Using these measures to assess mental workload levels requires accounting for the gaze of the drivers. Without accounting for where drivers were looking, changes in saccade amplitude and duration could not be used as a mental workload indicator. Thus, it is not known whether these changes were due to the driving task itself, or endogenously made due to changes in the driver's mental workload.

However, when considering that All Events did not have saccade duration or amplitude as a particularly responsive measure, an inference can be made.

Frequent saccade amplitude and duration changes suggest that visual scanning of the environment was pronounced when driving scenarios were anticipated and less strain-inducing (i.e. Common Events). This is opposed to the combination of the unanticipated driving scenarios and the anticipated scenarios (albeit strain-inducing) of the All Events meta-grouping. Looking at the context of the type of events inducing the responsive saccadic measures, a tentative link can be drawn between scanning the environment more when driving scenarios are less arousing.

The following list consists of measures that were not found to be responsive to changes in MWL for short duration events:

- Heart rate frequency
- rMSSD calculation of heart rate variability
- Shorter pupil diameter
- Shorter fixation duration
- Shorter saccade duration
- An increase or decrease in saccade amplitude
- An increase or decrease in saccade velocity

### 5.3 Long Duration Mental Workload Measures

Unlike the short duration MWL measures, it is difficult to draw conclusions about the MWL levels of drivers for Area Events as a category. Hence, the most responsive MWL indicators will be appraised, rather than compared in the manner done for the short duration events.

There were 9 out of 21 (42%) “sensitive” or frequently responsive MWL indicators for long duration, Area Events (e.g. driving through town, residential areas, etc.). These measures were as follows:

- Increased Heart Rate (HR)
- HRV: decrease in high frequency power
- Shorter pupil diameter
- Longer saccade amplitude
- Shorter saccade amplitude
- Shorter saccade duration
- Slower saccade velocity
- Increased blink frequency
- Rating Scale of Mental Effort (RSME) results

Some of the measures listed above point to an increase in MWL, namely increased HR and decreased HRV: high-frequency power. A decrease in HRV's high-frequency power is indicative of increased MWL, as well as parasympathetic nervous system activity (Acharya *et al.*, 2006; Hoover *et al.*, 2012). HR increased with the addition of an incentivised memory recall task during a real-world, high-way driving study (Mehler *et al.*, 2011).

In contrast, the shorter pupil diameter and increased blink frequency may indicate a decrease in cognitive load, although ascertaining whether these measures indicate lower MWL is contentious. Regarding pupil size, as previously discussed, it is difficult to distinguish the effects of illumination from that of MWL.

With the increased blink rate, it is unclear whether the cause was due to increased MWL or to fatigue (high or low activation respectively). The increased blink rate of Common Events was attributed to low activation because of the context of other measures. That is, most of the other responsive measures were indicative of low activation (arousal). Area Events, however, do not have enough of a majority of either low or high arousal results with which to make a similar inference.

The saccade metrics do not provide much in the way of MWL interpretation either. The inclusion of both the upper and lower limits of saccade amplitude is likely due to the driving task requirements, rather than MWL itself.

The RSME differs from the other measures in three ways. Firstly, it does not have a direction qualifier (i.e. upper or lower values) in the same way. Second and thirdly, the RSME differs in that it is a discrete and a subjective MWL measure. Therefore, the RSME results will be evaluated in more detail in the following section.

### 5.3.1 Appraisal of Responsive Long Duration Mental Workload Measures

Although it is unclear whether there was an overall increase or decrease in MWL in response to Area Events, the research aim can still be addressed. That is, the measures were found to be sensitive when driving through the different areas. The MWL measures will be evaluated in terms of its overall suitability as an MWL measure in the context of real-world driving.

It then remains that the most responsive MWL measures were the four saccadic measures, HR, HRV: high-frequency power and blink frequency.

However, out of these measures, HR, HRV: high-frequency power and blink frequency are the most appropriate (of all the responsive) physiological MWL indicators.

Pupil size was excluded as an MWL indicator due to the confounding effect of illumination. The saccadic measures were excluded as they seem more indicative of being reflexive to the task rather than indicating MWL due to task demands.

As previously mentioned, the inclusion of both the upper and lower ranges of saccade amplitude show that there was an abundance of gaze activity. This is to be expected as driving necessitates that the eyes frequently scan the environment for visual information. Furthermore, the number of saccade metrics on the list (and the absence of upper or lower ranges of fixation duration) point to high gaze activity. Eye motion measures, in general, are subject to the influence of confounding factors (Kramer, 1990; Marquart *et al.*, 2015; Charles and Nixon, 2019).

In summary so far, the most responsive short duration measures were blink duration and frequency, SDNN, and increased fixation and saccades – whereas long duration responsive measures were HR, HRV: high-frequency power and blink frequency.

### 5.3.2 Comparison Between RSME and Psychophysiological Responses

The Rating Scale of Mental Effort (RSME) scores was found to be a responsive (sensitive) MWL measure for the All Events category. However, the responsiveness of these measures is not the same as being meaningful MWL indicators in a larger context.

This section compares the subjective RSME results of Figure 18, with the frequency distribution of physiological measures Figure 19. (Both figures are in section 4.5.1.) In doing so, the suitability of the RSME as an MWL indicator of short duration, real-world driving events will be evaluated.

The Industrial Area had the highest relative frequency with regards to physiological indicators. For driving through the Industrial Area, 45% of physiological measures exceeded their average MWL threshold values. Driving through the Town Area was flagged as exceeding average MWL ranges the least, with a relative frequency of 10%.

RSME scores contradicted the above results. Driving through the town was perceived as requiring the most mental effort and received a mean score of 44.2. The industrial area was rated as requiring the least amount of mental effort for all areas with an average score of 26.7.

The disparity can be accounted for by comparing the variety of driving scenarios encountered by the driver for each area. The industrial area had the least variety of driving scenarios. In other words, it had the most repetitive driving scenarios. The high frequency at which physiological measures exceeded their average thresholds was due to one or two driving scenarios being frequently repeated. Those scenarios were driving along road bends and turning at yield signs. In this way there was more opportunity for these events to register a particularly high (or low) value.

This line of reasoning also supports the need to appraise the list of most response MWL indicators. There appears to be a disjoint between the long duration measures' sensitivity and its suitability as an MWL indicator in comparison to the short duration indicators.

In the case of RSME responses, the repetitive driving scenarios felt less mentally effortful to the drivers *because* they were repetitive. Thus, the RSME score was low for the Industrial Area. Driving through the town had a greater variety of driving scenarios; increasing task demand and perceived mental effort.

Furthermore, the physiological measures of HRV: time domain analyses, blink rate and pupil diameter are best suited for short duration measures (Charles and Nixon, 2019). Subjective measures rely on the short-term memory of the driver making it a cumulative measure and thus appropriate for measuring MWL over longer durations (Marinescu *et al.*, 2016).

Therefore, RSME is a suitable MWL indicator for long duration driving events. There is an association between increased driving scenario variety, increased task demand and increased perception of mental effort. Also, as a subjective measure, the RSME is a cumulative MWL indicator making it appropriate in the assessment of longer duration scenarios. Therefore, the RSME fulfils the criteria of being firstly responsive and secondly a valid measure for long duration Area Events.

## 5.4 Raw-TLX

### 5.4.1 Discussion of Results

In this section the RTLX results of perceived MWL for the driving and baseline tasks will be discussed. Following this discussion, an assessment of the RTLX in the context of the other measures will be addressed (i.e. the research aim answered).

The baseline task was a two-minute computer tracking task which was included to help interpret the driving task results by way of comparison. This relational method of interpretation has often been used in other MWL studies (Bustamante and Spain, 2008).

Figure 20 in 4.5.2 of the Results Section displays the mean ratings of the RTLX mental workload subscales for the baseline and driving tasks. The mental and physical demand of driving was given a higher rating than the baseline task. The mental demand of driving was rated at 5.4, and the baseline task was rated as 3. This is with 21 being the maximum for all subscales, except for performance where 0 was the maximum and defined as “perfect” performance. This means that driving was perceived as low in mental demand, and the baseline task was even less mentally demanding. The differences in task duration and complexity easily accounts for this difference.

In the same way, the physical demand of driving was rated low with a mean of three and the baseline task very low with a mean of one. Again, this difference is easily accounted for as the baseline task required the operation of a mouse, and the driving task required operation of the gears, pedals and steering wheel as well as movements of the head. Still, the experienced drivers did not perceive the manually operating the vehicle to be physically demanding.

With a difference of only 0.1, temporal demand was effectively rated the same for both tasks at ~2.6. The very low rating is easily accounted for as neither task was designed with a time pressure aspect.

On the other hand, participants' perception of their performance, effort required and frustration favoured driving over the baseline task. The biggest difference was the performance rating. Participants rated their baseline task performance 2.8 gradations lower than their overall driving performance. Performance responses of the baseline task varied more than that of the drive.

Overall, participants perceived their driving performance to be close to "perfect", and their baseline performance to be good. Likewise, participants found the baseline task to be slightly (0.5 gradations) more effortful than driving. At ratings between 4.3 and 4.8, both tasks were perceived as requiring little effort. A similar pattern was found with ratings of frustration. The baseline task received a mean rating of 2.3 and the driving task a mean of 2.0. The rating of performance, effort and frustration was due to the baseline task being unfamiliar. In comparison, participants were regular drivers of manual cars.

#### 5.4.2 Raw-TLX as Contextual Information

Comparing the sensitivity or responsiveness of the RTLX to the RSME and physiological measures cannot be done directly. For example, the RTLX was administered once after the drive as a cumulative MWL measure. Physiological measures on the other hand were continuous and, even amongst themselves, could not be compared due to differences in scale, unit and type.

However, the RTLX can be used in a theoretical way with the other measures' results. The RTLX can provide a sense of the range of MWL experienced cumulatively.

In the discussion of MWL for All Events and Common Events, MWL for both short duration meta-groups were reasoned to be within a fairly optimal range wherein performance, and hence safety, was not compromised.

The MWL measures responsive to Common Events (anticipated events) indicated that driver MWL was low. However, MWL was not too low as to be fatiguing. On the other hand, the MWL measures found be sensitive to All Events (where unanticipated events were impactful) was indicative of higher MWL.

There is a vagueness when comparing MWL of tasks requiring the use of qualifiers like 'high' and 'low' as opposed to using an absolute value or description. MWL is a theoretical construct that cannot be directly measured (Brünken *et al.*, 2003). The use of these qualifiers can create misinterpretation when comparing MWL of multiple tasks. This is especially the case when there is no fast reference point or range to work from. Unless explicated further, describing MWL as being 'higher' suggests overload, and describing it as 'lower' implies drowsiness.

Results from the RTLX provided a reference point of overall MWL experienced. Mental demand was fairly low, and participants felt they performed well. Furthermore, the task required some effort but not to the point of outright frustration. Using this information as context, the higher mental workload experienced in response to All Events is indicative of increased alertness rather than overload.

The underlying conceptual framework used in this instance is the cognitive energetic theory. The consideration of fatigue and high arousal at opposite ends of the MWL spectrum with an optimal level of arousal in-between, fits in with the inverted-U model (Brookhuis and de Waard, 1993; U.S. Army Research Laboratory, 2000).

Using this model, driving performance can be inferred from the Y-axis. The RTLX finding indicated optimal levels of workload, but slightly skewed towards lower arousal. The implication is that performance was still ideal. In the context of driving, this means that the risk of accident due to the driver's MWL status is minimal.

This level of MWL is optimal, as is corroborated by the experimental design which sought to avoid states of fatigue or overload. Driving on freeways and for durations above 90 minutes was excluded to keep risk – and MWL – within safe, optimal levels. Hence, although the sensitivity of the RTLX compared to other measures could not be determined, the RTLX was found to be an accurate measure of MWL. It shows potential to inform a range of MWL with which other measures can be contextualized.

## 5.5 Discussion of Procedures and Limitations

This section is a discussion of the insights gained in conducting the research project. Firstly, the challenge of using saccade duration and amplitude as mental workload indicators is discussed. The rest of this section discusses the observations and limitations encountered during conducting this research on real-world driving and mental workload.

Saccade duration and amplitude were found to be responsive measures to less-arousing, anticipated driving scenarios. However, changes in mental workload levels cannot be deduced from changes in saccadic eye movements alone. Gaze behaviour (where participants looked) during real-world driving would need to be accounted for. However, separating the influence of task-dependent gaze during real-world driving, where there are no stable fixation points, from that of mental workload is experimentally difficult. Therefore, saccadic measures are not suitable mental workload indicators during real-world driving.

What follows now are the observations made about real-world driving and mental workload research in a broader sense. The scarcity of mental workload and real-world driving studies was expected. The risk of collision associated with inducing sub-optimal workload during real-world driving situations is unethical. Steps can be taken to maintain optimal levels of mental workload during research as was employed in the present study. However, this comes at the expense of gaining further insight into the indications and conditions of sub-optimal mental workload during real-world driving.

Another challenge of real-world driving research is the experimental effort required. Many driving scenarios have the potential of occurring during each drive that is carried out. The potential scenarios need to be anticipated in advance as was done in the Independent Variables section of the Methodology chapter (section 3.1).

While scenarios related to intersections can be predicted to an extent by route-planning, other events occur randomly and cannot be predicted. On the other hand, many scenarios (e.g. being pulled over by a traffic cop, having to perform an

emergency stop, etc.) did not occur. The consideration of multiple potential scenarios, with only a handful occurring, amounts to experimental effort which does not filter down to the results. However, the experimental effort was necessary for the integrity of the research. It made data analysis manageable when it came to naming and organising the driving scenarios which did occur.

Another consequence is that obtaining an extensive number of data points per driving scenario requires many drives to take place. This requires experimental effort as well as resources. Moreover, a large amount of data is then collected – especially if dependent variable measures are continuous. Processing and analysing the data take time. This equates to considerable experimental time and resources needed to collect enough data and to analyse the data using inferential statistics.

The uncontrolled nature of real-world driving meant that the same driving scenario differs in duration each time. The difficulty with this is that time domain measures require sampling durations of the same length. Once again, a solution can be achieved by executing numerous repeated drives to increase the potential to gain driving scenarios with the same durations.

However, this present study's investment in effort and resources is valuable. Determining which measures best indicate mental workload during real world driving has implications for reducing experimental effort for future studies.

## **5.6 Specific Limitations**

The following section lists and discusses issues influencing the validity of the results.

### **5.6.1 Low Sample Size due to Eye Tracker Failure**

The sample size was initially planned to be 12 and within a range of 10 – 15 drives. However, after collecting six data sets the eye tracker equipment failed and, despite multiple efforts, it was unable to be repaired locally. Unfortunately, the effect was an overall reduction in the possible number of data points across all

independent variables. The Common Event meta-group had only six data points for each independent variable. The All Events grouping had some independent variables with only three data points. The halving of the original sample size reduced the certainty of the findings and calls for a further study of the same design.

#### 5.6.2 Large range of samples for All Events

The All Event driving scenarios had between three and 427 samples for all dependent variables per each driving scenario. A refers to the dependent variable data collected in response to driving scenarios that were encountered for example, overtaking a moving vehicle was an infrequently occurring scenario. The amount of dependent variable response data (or 'samples') for overtaking (the 'event') was less than that for turning right.

The events with a very low number of samples collected ( $< 10$ ) reduce the validity of the findings for those less common driving events. Furthermore, the differences in the number of samples across the different driving scenarios makes their comparison tentative.

The reason for the large range is due, in part, to the real-world, largely uncontrolled nature of the study. Other than some navigational-related events (e.g. the type and location of an intersection and the route), events occurred randomly or not at all. Even though the nature of the study determined the outcome of an unequal number of samples, the study design initially aimed to avoid very low samples. However, the eye tracker equipment failure prevented this.

#### 5.6.3 Subjective method of establishing thresholds of higher MWL

The first step of the data reduction method was visually identifying the highest (or lowest) set of bars for each bar graph. Then the highest or lowest value of those identified was defined as a threshold value. Values out of range were then considered to be indicative of increased MWL.

The limitation of this method is that the identification of higher mental workload values (and thus events) is essentially based on picking out what appears to be outlying values. No mathematical or statistical method was used to check if these values could irrefutably be considered outliers from the average. The consequence is that some results marked as indicative of increased MWL may not be that different from the average and therefore not truly an indication of increased MWL. However, as different MWL indicators have different units and scaling the use of a standard difference from mean calculation to identify outliers could not have been applied.

#### 5.6.4 Different Sampling Durations for All Events' Time Domain Analysis

As time domain analyses are influenced by sample length, it is advised to standardize interval durations (Task Force of the European Society of Cardiology, 1996; Charles and Nixon, 2019). For the All Events meta-group, sample durations differed between several seconds up to a minute in a few instances per data set. The different sampling durations were due to the differing durations of the independent variables. For example, the action of turning left after a yield sign took slightly different times to execute on different occasions.

The result is that the validity of time domain results for All Events is compromised to some extent.

#### 5.6.5 Changing illumination levels confounded pupil size results

Illumination levels could not be controlled given the real-world nature of the study. Attempts to distinguish the effect of illumination from mental workload (visual attention) were not made given the great time cost of doing so.

#### 5.6.6 The unknown influence of the equipment and researcher

The researcher provided directions to the participants throughout the drive. It is unknown what effect this may have had on the mental workload results. In addition, the effect of wearing the eye tracker, heart rate belt and stopping to give RSME ratings had an unknown effect on the driver's MWL. A habituation session

was held to minimize this effect. However, the drive still deviated from being naturalistic.

#### 5.6.7 Standard-sized parking bays were unable to be reserved

Tight regulations regarding parking on campus as well as changing campus security staff meant that parking bays were not able to be reserved. Parallel parking was performed in a make-shift bay that was larger than average. The unrealistic set-up made executing the parking less demanding than would be expected.

#### 5.6.8 Participants drove different vehicles

University-owned vehicles were used for insurance and liability purposes. The vehicle booking system, and demand for vehicles throughout the university, meant that the same vehicle could not be reserved for all participants. Participants were assigned either a 7-seater Toyota Avanza or Toyota Hilux (single-cabin pickup truck). It is unknown what effect that driving the different vehicles had on MWL.

#### 5.6.9 Participants drove at different times of the day

While peak traffic times were avoided, some participants drove during the morning and others in the afternoon. The effect of time of day is unknown and was unable to be determined due to the small sample size.

#### 5.6.10 The use of frequency as an MWL indicator for Area Events

Events with numerous dependent variables indicating an increase in MWL were interpreted as being more mentally demanding. However, the number of times that a measure responds is also dependent on the sensitivity of the measure to a particular type of scenario and the frequency with which that scenario occurs.

#### 5.6.11 The exclusion of performance measures

By excluding performance indicators mental effort or exertion was unable to be determined. Instead, mental workload in general was assessed without

consideration of mental exertion. Thus, the study was limited in that it excluded an important approach used in the assessment of mental workload.

#### 5.6.12 Baseline data was not used to normalise physiological readings

Data collected in response to a reference task (i.e. baseline data) was not used to normalise the responses from the main driving task. The consequence is that the scaling of results is not consistent. Differences between responses to driving scenarios might have been distorted in that some differences could have been magnified or downsized. Furthermore, physiological responses between individuals, in general, are variable and even recordings of responses for one individual can be idiosyncratic. Normalizing data would have served to reduce these differences and represent the results more accurately.

## **CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS**

### **6.1 Chapter Overview**

The chapter begins with the conclusion to the research project in Section 6.2.

Next, in Section 6.3, the practical findings are presented. These are details of the specific driving scenarios and locations that were found to increase mental workload are presented. As this was an additional finding, it is given after the conclusion.

Suggestions for further research regarding the assessment of mental workload during real-world driving are made in Section 6.4.

The chapter ends with Section 6.5. with a summary of the main research findings followed by a summary of the practical findings.

### **6.2 Conclusion**

The primary research aim was to compare the responsiveness of different MWL indicators for different classes of independent variables. Mental workload theories were used as the conceptual framework underlying the findings.

With respect to both anticipated (Common Events) and unanticipated (All Events) short duration events (less than five minutes), blink frequency and blink duration were sensitive measures. In addition, the use of upper and lower ranges of values allowed for the distinction between higher and lower MWL making it a suitable measure overall.

An increase in pupil diameter was responsive to both classes of short duration measures. However, illumination was a confounding factor bringing the suitability of the measure into question and indicating an area of future research.

The SDNN time domain analysis was found to be a responsive measure to unanticipated events. However, SDNN calculations had varying sample durations

(between several seconds to a minute) which may have impacted the validity of this result.

Fixation duration was responsive to the unanticipated event group. Saccade duration and saccade amplitude was found to be responsive to the anticipated event group. This outcome suggests that visual processing was emphasised during unanticipated scenarios, and that visual scanning predominated during anticipated scenarios.

For long duration (five minute and more) events, heart rate frequency, high-frequency power HRV, blink frequency and RSME were responsive and suitable MWL indicators. However, blink frequency may be better suited to short duration events. RSME scores were determined to be based on the variety of driving scenarios that were encountered. More event variety resulted in increased perception of mental effort.

Blink frequency was responsive to long duration events and both categories of short duration events.

The RTLX results were used to determine the overall range of MWL experienced during the drive. Knowing the range of workload contextualises other MWL results. A result suggesting 'higher' MWL can then be interpreted as to whether this means MWL is approaching overload – or if it indicates an increase in arousal.

As discussed in Section 5.4: 'Raw-TLX Discussion', the cognitive energetic theory of MWL proved useful in this regard (Brookhuis and de Waard, 1993; U.S. Army Research Laboratory, 2000). The model offered a framework in which to place different MWL results for comparison. This is important as there is no direct measure of MWL for performing such comparisons, so it needs to be done conceptually. The theory is a simple way to compare MWL and consider possible effects on performance, which has safety implications in the context of driving.

The RTLX findings indicated that participants did not find the driving to be demanding, or too easy. The energetic theory framework was applied to reason that there was no risk of overload or underload during this drive. Hence performance was optimal and the risk to safety was low. The experiment was designed to limit risk, which corroborates this reasoning.

Eye-motion measures were overall the most responsive measure. As discussed in Section 5.1.1: 'All Events', Wickens' multiple resource theory of MWL was used to describe the weight of visual-spatial cognitive resources during driving (Wickens, 2008). However, this theory is better suited for driver distraction research as it conceptualises cognitive resources and competition.

The secondary aim of the research was to identify promising research areas. This is because of the research gap of studies using common MWL indicators for real-world driving. The section "Indicated Areas for Future Research" addresses this aim below.

An additional finding was that overtaking moving and parked vehicles, potholes, navigational confusion and unpredictable movements of road users at intersections result in greater mental workload. These situations were from the short duration event groupings. The findings have practical relevance in that interventions and further assessments are recommended below, with the intention of being able to reduce driving mental workload in the future.

### **6.3 Practical Relevance of the Research**

The driving scenarios that follow were identified as resulting in higher mental workload. These events were marked by a relatively greater number of dependent variables as mentally demanding driving situations.

The findings do not answer the research question and they are included as an additional finding. Also, this study included determining if plausible causes for the increased mental workload could be found. In identifying these causes, possibilities for improving the driving scenarios were made.

#### **6.3.1 All Events**

The following discussion uses values represented in the relative frequency distribution bar graph of Figure 15 in Section 4.4.1 of the Results Chapter.

### Overtaking

In the All Events category, overtaking moving vehicles was identified as the most cognitively demanding at a frequency of 41.2%. Overtaking on highways is a mentally demanding manoeuvre with a high accident risk (Bar-Gera and Shinar, 2005; Vlahogianni and Golias, 2012). The present study found overtaking to be flagged by almost half of all MWL indicators as cognitively demanding. Given that no highway driving was performed, the high-demand status of overtaking is emphasized.

### Potholes

Second to overtaking was navigating around potholes with a frequency of 35.3%. This is unsurprising as, in recent years, potholes have become a feature of Makhanda's (formerly known as Grahamstown) roads. The following two images are stills taken with the dashcam while participants drove along the set route. The images were taken from different areas in Makhanda to illustrate the prevalence of potholes throughout the city.

Residents complain about damage to vehicles and the dangers of suddenly swerving or reducing speed to avoid potholes (SABC Digital News, 2018). However, potholes are difficult to avoid, even with careful driving as they sometimes span the width of a driving lane. Figure 21 below shows an example of road surface anomalies spanning the width of the driving lane.



*Figure 21: Image of New Street in the Town Area showing road degradation on the left, and a deep pothole with a fallen barricade near the middle of the road. Image taken on 19 September 2018.*

Attempts at repairing the potholes have been made by community members. However, these attempts often create uneven road surfaces. With repeated attempts the road surface is further weakened over time resulting in more potholes and road surface anomalies. Figure 22 below shows an area where several repair attempts have been made.



*Figure 22: The potholes on upper Milner Street have been filled in several times which has created an uneven road surface. Image taken 17 September 2018.*

In addition to vehicle damage, there is evidence that road surface anomalies pose a great risk to road users (Koorey *et al.*, 2003; Rosolino *et al.*, 2014).

There is no literature regarding the effect that potholes of this degree have on driver mental workload. The evidence is based on naturalistic driving studies which look at the frequency at which road surface anomalies cause accidents.

Road surface anomalies is an issue that urgently needs to be addressed. Allocation of funds from government for materials and equipment is needed. However, proper training and skill development is also needed to fix and maintain roads for the long term. Project management and communication between sectors, workers and the public will facilitate the process and serve to raise awareness.

### Navigational Uncertainty

Three events were marked by 29.4% of MWL measures as increasing MWL. The action of driving past a particularly confusing turn-off increased MWL as drivers became uncertain about the direction to take. The road geometry made drivers inclined to turn left as the road was wider, however the route required driving straight ahead on the narrower road. Figure 23 below shows the fork in the road which led to uncertainty in participants.



*Figure 23: The red arrow shows the turn-off into Short Street where participants thought they should turn left onto. The green arrow shows the continuation of Constitution Street which was the planned route. Image taken 19 September 2018 from the Residential Area.*

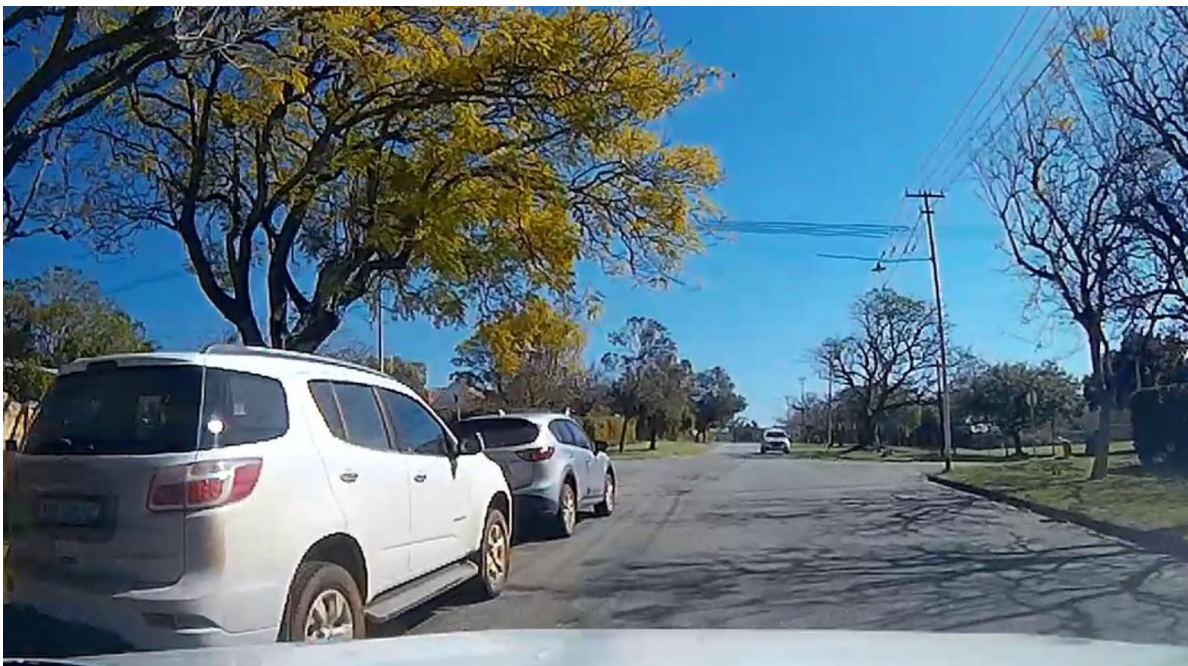
In Janssen's (1979, as cited in de Waard, 1996) driving classification, the top-level tasks are strategic and pertain to route planning and navigation while driving. They are more demanding than responding to local situations (intermediate level) and operating the vehicle (low level). Uncertainty about whether to drive straight or make the off-turn increased task demand.

In this case, adding clear signage naming the roadways, as well as clearer road markings, would serve to reduce confusion. Signs with road names and which

areas they lead to would add clarity. The roadway on the right leads to a main road (lower Milner Street) close to the Town Area. On the left, is an area with private residences.

### Overtaking Parked Cars

Overtaking parked cars on narrow roads with two-way traffic also had a 29.4% frequency. In doing so the driver has to make sure there is no oncoming traffic which increases workload. Refer to Figure below of one such instance. Prohibiting parking on narrow, two-way roads will reduce mental workload and the risk of collision.



*Figure 24: An instance where overtaking parked cars required briefly driving onto the lane with on-coming traffic. The parked cars on the left were overtaken on the narrow Graham Street road. Image taken on 30 August 2018.*

### 2-way Stop Streets

Driving straight at a 2-way stop street was determined to increase mental workload by 23.5% of mental workload measures. In a naturalistic driving study, stop street intersections were identified as a high cause of accident or near-crashes (Precht *et al.*, 2017). However, traffic light intersections contributed the greatest number of incidents whereas the current study did not identify any of the traffic light intersections as a higher MWL event.

### 6.3.2 Common Events

The values mentioned in the following discussion are those also displayed in the bar graph of Figure 16 from Section 4.4.1 of the Results Chapter. With the exception of navigational uncertainty being identified as a higher mental workload event by 35.3% of measures, the other three events were identified by 29.4% of measures.

#### Navigational Uncertainty (Residential Area)

Driving past the navigationally confusing Short Street turn-off (see Figure 23 above) had the highest frequency of identification at 35.3%. The same turn-off was found to be a higher mental workload inducing event in the All Events meta-grouping. This places emphasis on the need for additional signage at the junction to reduce uncertainty and thus mental workload.

#### Stowan Road Segment (Industrial Area)

At a relative frequency of 29.4%, driving along the short portion of Stowan Road was identified as cognitively demanding. It may be that the short road meant less available time to process the navigational instructions, where making a right turn was shortly followed by making a left turn onto the Provincial Road. Another factor influencing MWL maybe the anticipation of transitioning from the Industrial Area to the Provincial Road. Figure 25 below is an annotated image of the direction travelled by participants on the Stowan Road segment.



*Figure 25: The short segment of Strowan Road at the end of the Industrial Area. After turning right onto the road, there was a stop street at which participants turned left onto the R350. Image taken on 30 August 2018.*

#### 4-way Stop at African Street and Caldecott Street (Town Area)

Driving straight ahead after stopping at the 4-way stop street was identified as a high mental workload event at a frequency of 29.4%. The intersection is pictured in Figure 26 below.



*Figure 26: The African Street and Caldecott Street 4-way stop. On the right side of the image the slope of African Street is visible. Image taken on 20 September 2018.*

The centre of the intersection is on the apex of a hill and the intersection is large. This means that vehicles cannot readily be seen approaching the stop and are only visible once stopping at the top of the street. This is especially the case with the African Street stop on the right (see Figure 27 below). Drivers need to exercise caution even when the intersection looks clear of traffic, and the driver has right-of-way because of this. In addition, at the time of the study it was not uncommon for drivers to slow down instead of stopping at intersections. The need for caution in this regard accounts for this intersection increasing cognitive load of drivers.



*Figure 27: From the position of the research vehicle, vehicles approaching the intersection from the right was visible once stopped at the top part of the slope. Image taken 5 June 2019.*

The addition of traffic lights would reduce mental workload in this case. It would create certainty about when to move on again without having to search for other vehicles stopping at the intersection.

#### Turning Left onto Bathurst Street (Town Area)

Also, at 29.4% frequency, turning left from lower High Street onto Bathurst Street was found to be a higher mental workload event. The driver has the right-of-way at the turn (see Figure 28 below). However, the area is busy and the movement of jaywalking pedestrians and other vehicles at that end of Bathurst Street can be unpredictable. This is largely in part to the bus stop located on the right-hand side of the street end, a few meters away from the left turn. Creating a bus-only lane and including traffic lights at this intersection would help to streamline traffic and pedestrian movements. The predictable movements of traffic and pedestrians would reduce mental workload of road users.



*Figure 28: The left turn onto Bathurst Street in the Town Area. Pedestrians often cross Bathurst Street at this intersection. Image taken on 20 September 2018.*

Furthermore, the line dividing Bathurst Street into two lanes (both with traffic flow in the same direction) is very faint (see Figure 29 below). Thus, drivers have to use their discretion about where on the road they should drive. This uncertainty increases mental workload and risk of collision or near-crashes. Painting clear demarcation lines would reduce mental workload in this regard.



*Figure 29: Driving down Bathurst Street after turning left. To the right of the image is the bus stop, which is demarcated with a yellow rectangle painted on the road with the letter "B" next to it. No clear road lanes are demarcated. Image taken on 20 September 2018.*

### 6.3.3 Area Events

These findings are displayed from Figure 17 in Section 4.4.2 of the Results Chapter. The Industrial Area was flagged by 42.9% of mental workload indicators for increasing workload. Driving within the Industrial Area was found to increase mental workload the most out of all Area Events. In contrast, the Town Area was flagged by only 14.3% of mental workload indicators.

These results are not congruent with what was found for the short duration meta-groups above. Navigational uncertainty was identified as a higher mental workload cause in both the All Events and Common Events meta-groupings. This event happened in the Residential Area, which is not corroborated by the Area Events result of 23.8% of mental workload indicators flagged for the Residential Area (and for the Campus Area). Only the Town Area had a lower percentage than the Residential Area

Most incongruent, however, is that for Common Events, two driving scenarios from the Town Area were identified as higher mental workload events. Namely, the 4-way intersection at the corner of African and Caldecott Street and turning left into Bathurst Street. It would be expected then, that the Town or Residential Area would have been identified by the greatest number of mental workload indicators as the highest mental workload area.

In addition, the Industrial Area was found to be the most demanding by the physiological measures. The Industrial area had few potholes, little traffic and was navigationally straightforward. The town, on the other hand, had all of these features but was found to be the least demanding.

The explanation regarding the discrepancies found between RSME and physiological measures apply in this case. That is, the industrial area had one or two repetitive driving scenarios which were repetitively flagged by certain MWL measures. Conversely, areas with less repetitive driving scenarios (like town with more variation) meant less chance of an event being flagged. See Section 5.3.2 named 'Comparison Between RSME and Psychophysiological Responses' in the Discussion Chapter.

## **6.4 Indicated Areas for Further Research**

The exploratory nature of this study has resulted in numerous indicated areas of further research.

### **6.4.1 Blink frequency**

Blink frequency was found to be a highly responsive mental workload measure during real-world driving. All categories of events studied had blink rate as a frequent measure. It was found to be responsive to both short duration (anticipated and unanticipated) driving scenarios and long duration events.

The primary recommendation is for more research using blink frequency as a mental workload indicator in the application of real-world driving. To gain maximum benefit from such research, further research is also required to determine when changes in blink rate are due to fatigue or to smaller mental

workload changes. Research into when blink frequencies are due to mental workload or fatigue during real-world driving is needed.

#### 6.4.2 Other Short Duration MWL Indicators

Pupil diameter was found to be a responsive MWL measure which makes it a promising measure in real-world driving applications. However, further research is needed to determine if - and how - changing illumination levels can be separated as an extraneous factor.

SDNN shows promise as a responsive and selective mental workload indicator in response to unanticipated driving events. However, a challenge with real-world applications is that the same driving scenario differs in duration each time. Further research would include determining the effect of different recording durations (in the order of seconds) on results.

#### 6.4.3 Long Duration MWL Indicators

Heart rate was a responsive mental workload indicator during real-world driving. HR is used as a physical workload indicator which makes the crossover interesting. It is recommended that HR be researched as a mental workload indicator when driving through different districts. It could be used to assess the strain taken by drivers in different areas, especially those designed to reduce traffic (and mental demand) through different interventions.

The RSME was concluded to be both a responsive and valid mental workload measure. Unlike the physiological measures, its results had fewer confounding factors. Further studies comparing RSME (or a similar unidimensional scale) with psychophysiological mental workload measures is therefore recommended.

#### 6.4.4 Raw-TLX

The RTLX was found to corroborate the low-to-mid mental demand of the driving task as determined by the task protocol. However, more research is needed to determine if this would be the case when more extreme levels of mental workload are induced. The question is whether the RTLX would be useful for contextualizing

MWL ranges in drives where mental underload or overload is experienced. However, care must be taken to avoid risky situations and ensure that the research remains ethical. Finding participants who routinely do risky driving, like long-distance drivers, may be used to manage the risk.

#### 6.4.5 Heart Rate Variability: frequency domain analysis

In this study, frequency analysis was not performed for mental workload responses with durations less than two minutes. Consequently, comparing the responsiveness of frequency domain analysis outcomes to those of other very short mental workload indicators was excluded in this study. It is therefore recommended that future research implement a moving window technique to analyse responses to events under two minutes. This technique calculates power by overlapping time segments of 30 second intervals to link heart rate variability responses to driving scenarios.

### **6.5 Summary of Main Research Findings and Practical Findings**

In this chapter, the research aims provided the framework for the conclusion to the research. The research sought to determine which commonly used mental workload indicators are the most 'sensitive' or responsive to different real-world driving scenarios. Typically, mental workload indicators are used to assess mental workload during simulator driving. It is therefore unknown how the same measures would respond in real-world situations.

Blink frequency was found to be the most responsive measure to all three groupings of real-world driving scenarios. Blink frequency was responsive to scenarios that were anticipated (and alertness-inducing or arousing) and anticipated and non-arousing. It was also responsive to driving scenarios unanticipated by drivers and therefore arousing. Blink frequency was also responsive to longer driving events of thirty minutes, such as driving through different zoning districts.

Given that this was a novel and exploratory study, and that the study had several limitations, further research was recommended. There were two limitations in

particular which systematically influenced the research results. The first was the low sample size due to the failure of the eye tracker. The other was the fundamentally subjective manner used to qualify thresholds of high mental workload for each dependent variable. Other notable limitations included the use of frequency as an indicator of the responsiveness of dependent variables, the large range of data points used in the grouping of non-arousing anticipated driving scenarios with unanticipated scenarios, and the difference of sampling durations used for the heart rate variability time domain analyses.

Further research was recommended to determine the limits of blink frequency as a mental workload measure. Blink frequency is influenced by fatigue and drowsiness. Research into when blink frequencies are due to mental workload or fatigue during real-world driving is needed.

With regards to subjective mental workload indices, the modified NASA-TLX known as the Raw-TLX showed promise as a contextualising measure. The Raw-TLX does not make use of weighed scales in the analysis of mental workload. Yet the findings corroborated the expected mental workload of drivers, given the constraints of the methodology. That is, the methodology aimed to avoid sub-optimal levels of mental workload, and drivers indicated an overall moderate experience of cognitive load.

Furthermore, the indices of heart rate variability: SDNN and pupil diameter were found to be responsive to driving scenarios that were either unanticipated by drivers, or anticipated events that were still arousing. However, further research is needed to explore how best to separate mental workloads' task-evoked pupillary responses from that of illumination. In the case of SDNN, the challenge is that it is influenced by different sampling durations. Further research is needed to determine the extent of the influence during real-world driving so that it can be accounted for. This is important because real-world driving scenarios will differ in length each time they occur.

With regards to less-arousing anticipated driving scenarios, heart rate frequency and the subjective RSME mental workload indices were found to be a particularly responsive mental workload indicator. Further research was recommended to

determine if driving through different areas would reliably lead to changes in heart rate frequency. The comparison of RSME results to physiological results during real-world driving warrants further research to see to what extent they could be used interchangeably.

In addition to the findings which address the research aims, some practical findings regarding the driving environment in Makhanda (formerly Grahamstown) were made. These were findings of specific driving scenarios and areas which were found to increase mental workload. They were included in the study to determine the plausible causes for the increased mental workload and were used to indicate what solutions could be implemented to reduce driver mental workload in these areas and situations.

These situations included navigating around potholes, navigational uncertainty where street signage was unclear or absent. Governmental funding and training to fix potholes and maintain roads and the addition of street signs will ultimately serve to reduce mental workload in these situations. Painting road demarcations to divide the road into two lanes on wide roads will reduce mental workload by increasing the predictability of traffic flow streams.

Furthermore, the increased collision-risk and mental workload experienced by drivers when overtaking parked cars on narrow streets, can be reduced by prohibiting cars to park on narrow roads. Intersections which are busy and chaotic may be improved by introducing traffic lights and improving predictability of vehicles and pedestrians.

While driving is an essential and everyday activity, it is also risky. Road accidents cause property damage, injury, disability and, in some cases, loss of life. While the factors leading up to and causing road accidents are numerous and complex, sub-optimal driver workload is one of the key factors. By working to determine the mental workload of drivers during real-world scenarios, instances of sup-optimal mental workload can be identified. In some cases, a clear cause for instances of sub-optimal workload may be apparent. Practical steps could then be undertaken which would ultimately reduce risk to road users.

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## APPENDICES

### Appendix A: NASA-TLX Questionnaire

#### ***NASA Task Load Index***

*Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.*

---

Name	Task	Date

**Mental Demand**      How mentally demanding was the task?

Very Low      Very High

**Physical Demand**      How physically demanding was the task?

Very Low      Very High

**Temporal Demand**      How hurried or rushed was the pace of the task?

Very Low      Very High

**Performance**      How successful were you in accomplishing what you were asked to do?

Perfect      Failure

**Effort**      How hard did you have to work to accomplish your level of performance?

Very Low      Very High

**Frustration**      How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low      Very High

---

Figure 30: The NASA-TLX questionnaire that was used in the research.

## Appendix B: Ethical Clearance Letter

Tel: +27 (0)46 6038468  
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19 July 2018

Nadia Schmidtke – [g11S1348@campus.ru.ac.za](mailto:g11S1348@campus.ru.ac.za)

Swantje Zschemack – [s.zschemack@ru.ac.za](mailto:s.zschemack@ru.ac.za)

Dear Nadia and Swantje,

### **Final Ethical Clearance – Application HKE-2018-09**

Your application for ethical clearance for the study titled “The impact of naturalistic driving scenarios on selected physiological and subjective indicators of mental workload” (reference number HKE-2018-09) has received final approval by the HKE Ethics Committee. This clearance is valid for a period of 1 year from the date of this letter.

Please note however that any significant changes made to the study and procedures need to be communicated to the HKE Ethics Committee (this includes changes in investigators), and another full review may be requested.

Upon completion of your study, please submit a short report indicating when and whether the research was conducted successfully, if any aspects could not be completed, or if any problems arose that the HKE Ethics committee should be aware of.

Sincerely,



M.C. Mattison  
2018 HKE Ethics Chairperson  
Department of Human Kinetics and Ergonomics  
Rhodes University; Grahamstown  
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## **Appendix C: Information to Participants**

*\*Please note that what follows is exactly the letter seen by participants at the time. The name of the research has since changed. In addition, the figure captions were added afterwards for convenience of this thesis.*

Dear Participant,

Your interest in contributing to this study is much appreciated.

This document serves to further inform your decision to participate in this ergonomics research entitled:

**“The impact of naturalistic driving scenarios on selected physiological and subjective indicators of mental workload”\***

### **Research purpose**

The focus of the research is to measure mental workload while driving. Driving is a complex task where safety is a major concern. Successful and safe driving requires the driver to pay attention to the road while making decisions. Doing so results in a certain amount of mental work being done by the driver.

Measuring this mental workload is an important step to finding out the role it plays in both safe and hazardous driving. Mental workload is, however, difficult to measure directly. There are several ways to assess mental workload, and this study will examine which one(s) are most sensitive.

This study uses measurements of eye-motion, and heart rate and variability, as well as questionnaires about your experience of mental workload.

### **Participant requirements**

All criteria must be fulfilled in order to participate in the research.

- Current student or staff member at Rhodes University.
- Between 18 – 60 years old.
- A *valid* South African license for driving light motor vehicles with a *manual transmission* (code B).
- Driving experience: two years and/or at least 5000km.

- Drive fairly regularly: at least weekly.
- Does not wear glasses (contact lenses are permitted).
- No major health issues (e.g. epilepsy, stroke, and heart conditions).
- No major cognitive impairments.
- Does not take medication for chronic pain management, sedative medications, or treatments causing drowsiness and/or impaired motor control.
- Agreement to obey speed limits and traffic regulations.

### **Task requirements**

Participants will be requested to do the following tasks. Please note that while it is preferable that all tasks be completed, you may withdraw from the study at any point.

- Sign a consent form.
- Fill out an application form to drive a Rhodes-owned vehicle.
- Take a short Rhodes University administered driving test (on a Tuesday at 14h00).
- 45 minutes to an hour of your time to get accustomed to driving the vehicle and wearing the heart rate belt and eye-motion tracker.
- Two hours of your time for the main testing session. This entails a 2-minute computer 'game' followed by a 70 minute drive, a three-point turn, parallel parking and alley docking.

### **Experimental procedure**

There are three parts to this study to be carried out in the order presented below. Each part will be scheduled for a different day, unless an alternative arrangement is requested. Please ensure that you have a good night's rest and refrain from consuming alcohol before participating in each part.

### Part 1: Rhodes University driving test

You will be driving a Rhodes University vehicle that is likely to be a 7-seater Toyota Avanza. This ensures that you, the participant, do not incur any fuel and/or vehicle maintenance costs. If the vehicle is damaged as part of the study the costs will be covered by Rhodes' insurance company.

In order to drive a Rhodes vehicle you'll first need to be approved by Rhodes' Traffic Department. This entails filling out an application form and passing the Rhodes driving test. The test is relatively basic and takes about ten minutes to complete.

The researcher will submit the application form and book the test for the earliest Tuesday afternoon (14h00) that you are available.

### Part 2: Habituation

The aim of the habituation session is to familiarize you with driving the vehicle itself, and then driving while wearing the equipment.

Firstly, you will be asked to drive the vehicle to acquaint yourself with the controls and general 'feel' of it. The drive will start on campus with the researcher in the passenger seat. You'll be asked to drive around off campus for ten minutes. There is no set route driving route for this part, though you'll be required to drive back to campus and park outside the department of Human Kinetics and Ergonomics (HKE).

In the department you will be fitted with a heart rate monitor band. Fitting it will require you to lift your shirt up. The band will sit securely around your chest around the level of the heart. You will then return to the vehicle and sit in the driver's seat.

Next, the eye-motion tracker will be fitted to your head. The sensation of wearing it is similar to that of eye-glasses. The tracker consists of a camera unit supported on a nose bridge. The nose bridge is placed on your nose and the unit is then secured by a band around the head. The researcher will ask you to look at certain points ahead and make any necessary adjustments.

At this point you will leave the parking area to drive while wearing the heart rate monitor and eye-tracker. Again, the researcher will be in the passenger seat. It will be requested that you first drive around a quiet residential area. You must drive for at least ten minutes but may drive for longer if you feel it necessary.

The habituation session will end with you driving back to the HKE department where the equipment will be removed.

### Part 3: Main driving session

This session is expected to take two hours in total. It will be scheduled on a weekday between 9h00 – 12h30 and 14h30 to 17h00. You will be required to drive along a set route. Please *do not* memorize the route in advance. The route is depicted in Figure 1 and 2 (*since re-named to Figure 31 and 32 for the purposes of this report*) below for your understanding; however, the researcher will sit in the passenger seat and direct you.

1. To start the session, you will be fitted with the heart rate monitor and eye tracker as outlined in the habituation session above in the HKE department.
2. You will be asked to do a two minute long tracking task on a laptop. The task requires you to move the cursor to match a moving line on the screen.
3. Next, the eye tracker will be removed and the heart rate monitor will be paused.
4. You will give a quick rating of your perceived mental effort in completing the task.
5. You will be asked to answer a longer six-question form regarding your mental workload.
6. You will then proceed from the department to a vehicle parked outside. The eye tracker will be re-fitted to your head while you are in the driver's seat. Dashcam recording will be started and the heart rate monitor will be set to record again.
7. You will be instructed to drive from the Rhodes Gym parking lot to the Makana Meadery (from the point labeled 1a to point 2 in Figure 1).
8. Do a three-point turn outside the Makana Meadery entrance to turn the vehicle 180°.

9. Stop to give a quick rating of your mental effort.
10. Drive to the unnamed road (3) along the R350 towards Cradock.
11. Turn around at point 3 and drive back into Grahamstown to Howick Street (4a).
12. On Howick Street you will be asked to pull over to give a quick rating of your mental effort.
13. You'll be instructed to drive from Howick Street (4a) to Park Road (just before point 5a).
14. Pull over to give a quick rating of mental effort.
15. Continue driving to 1 African Street (5a) and back to Prince Alfred Street (5l) on campus.
16. Pull over to provide a rating of mental effort.
17. Perform a parallel parking on Prince Alfred Street (5l).
18. Drive to the Rhodes Gym parking lot and alley dock into the reserved parking spot.
19. Answer the six questions on the longer questionnaire once again.
20. The driving session will then be over. The eye tracker and heart rate monitor will be removed.

### **Compensation, confidentiality and feedback**

Please note that no payment will be issued for participation.

Personal information and recorded data will remain confidential. Your information will be coded for anonymity and analyzed for research purposes.

You will receive feedback on the main findings of the research upon completion. This is expected to take 8 to 12 months from the time of participation.

### **Risks and benefits**

While driving in itself constitutes a risky activity, driving in the context of this study does not place experienced drivers in undue danger. This is because the risk involved in participating is little greater than the risk the participant would ordinarily incur with day-to-day driving.

Steps have been taken to reduce risks that may result from the equipment and experiment itself. It is generally recommended that drivers take a rest break every 120 minutes; driving time for this study is safely limited to 90 minutes. The habituation serves to reduce risk by ensuring familiarity with wearing the eye tracker and heart rate sensor. Use of cell phones, GPS devices, and radios will not be permitted, in order to reduce distraction. Peak traffic times and highway driving are excluded. Emergency contacts will be ready in case of incident. Risks can be further managed by obeying traffic regulations.

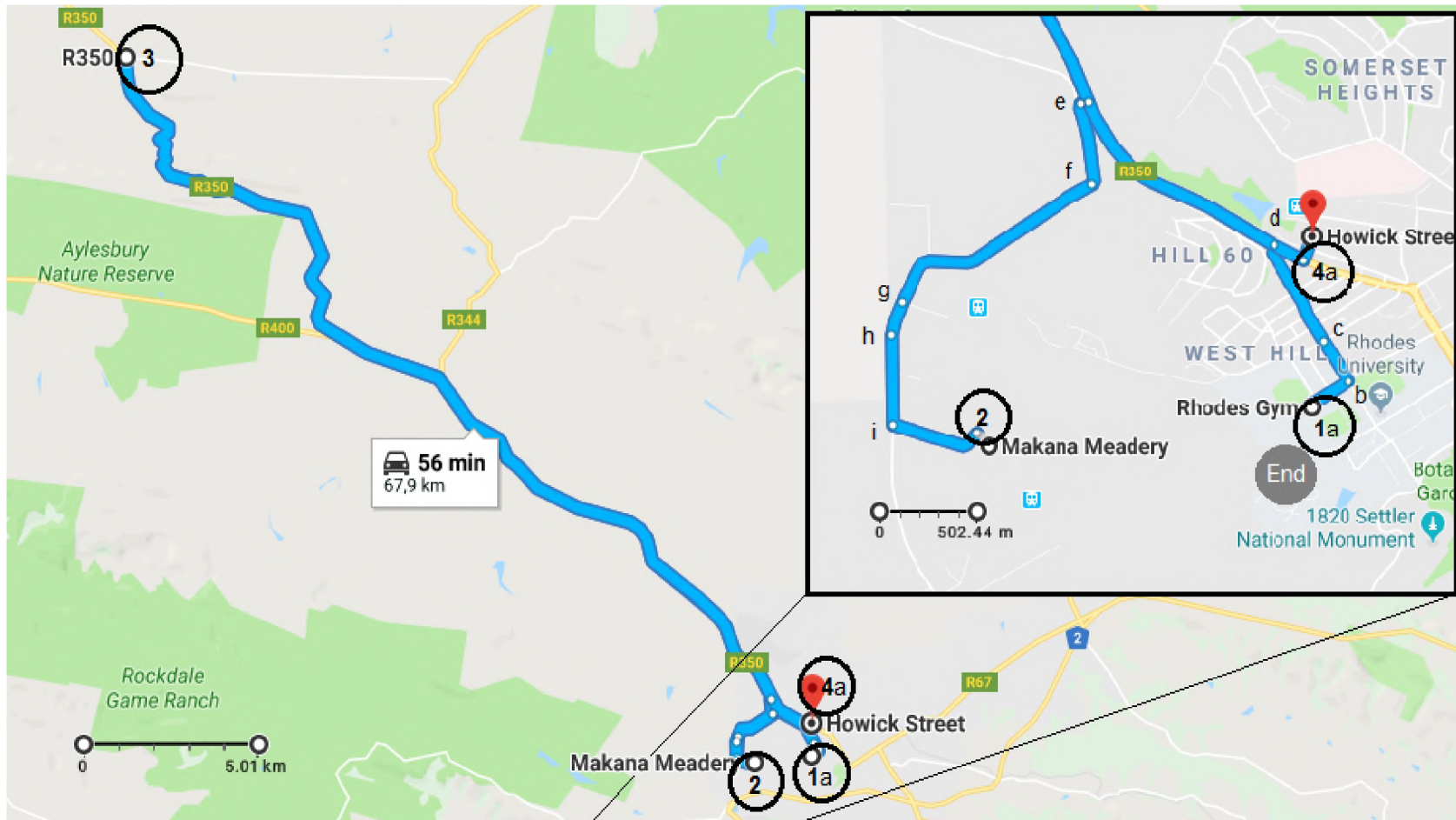


Figure 31\*: First half of the driving route from Rhodes University (1a) to Howick Street (4a). Scale 1:5km. Google. (n.d.-e).

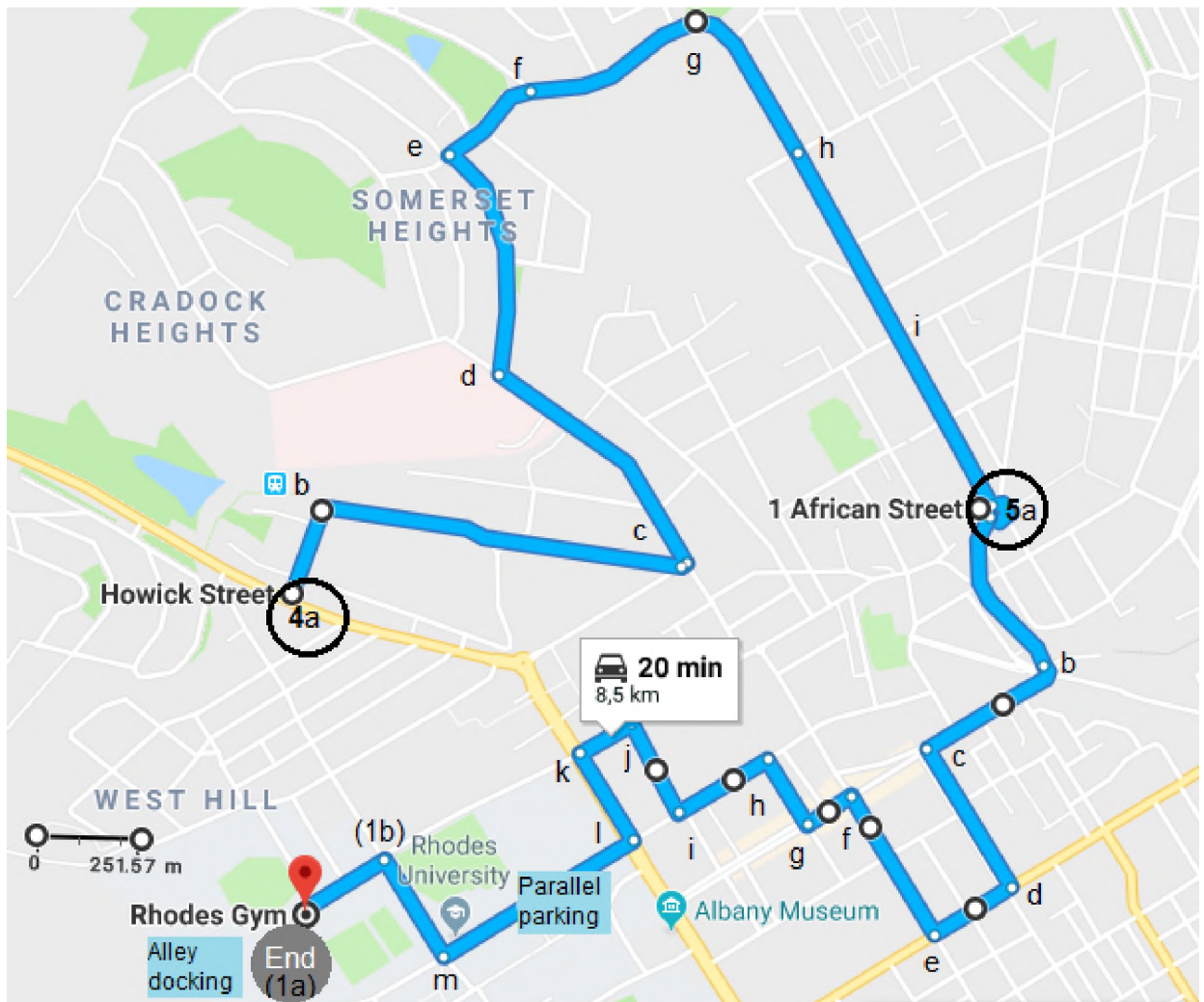


Figure 32\*: Second half of the driving route from Howick Street (4a) to Rhodes Gym (1a). Scale 1:252m. Google. (n.d.-f).

By participating in this study, you will contribute much needed information on what factors affect mental workload during real-world driving. You may also find that the study brings you awareness of how driving impacts your feelings of mental workload.

### Final remarks

Please be aware that you are free to withdraw from the study at any point without any penalty. Should you have any questions, concerns, or complaints regarding

the study, please feel free to communicate to the researcher, or research supervisor (Head of the HKE Department).

Supervisor & HoD: Dr Swantje Zschemack [s.zschemack@ru.ac.za](mailto:s.zschemack@ru.ac.za) (046 603 8472)

Thank you for participating in this study. Your contribution is invaluable and greatly appreciated!

Yours sincerely,

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Nadia Schmidtke  
MSc student, HKE  
073 295 4079  
[g11s1348@campus.ru.ac.za](mailto:g11s1348@campus.ru.ac.za)

## Appendix D: Participant Consent Form

I, \_\_\_\_\_ (*full name*), consent to participate in the study entitled:

**“The impact of naturalistic driving scenarios on selected physiological and subjective Indicators of mental workload.”**

I have been informed verbally and in writing of the following aspects:

- The purpose of the study.
- Time commitment of the study and the expectations of my availability and my consequent availability.
- The tasks I will be required to participate in.
- The risks and benefits of partaking in the study.
- The voluntary nature of the study.
- That my anonymity will be protected at all times.
- That information collected in the study may be used and potentially published for scientific purposes.

I am aware that I will be driving a Rhodes University owned vehicle and will not have to contribute to fuel or vehicle maintenance costs. I am aware that in the case of incident, I will not be required to pay for property damages.

I am aware that as the driver of the vehicle I am bound by South African law to obey all traffic rules and regulations. I understand that as the driver I will be liable for legal charges made against me in the event that I violate any traffic laws and regulations.

I am aware that by voluntarily consenting to participate in this study, I waive any legal recourse in the event of injury against the researcher, the Human Kinetics and Ergonomics Department or Rhodes University.

I will inform the researcher immediately if I experience any abnormality or distress. Furthermore, I am aware that I can withdraw from participation in the study at any time and am under no obligation to continue with the testing against my will.

I have had the opportunity to consider the information and ask questions, and I have had these questions answered satisfactorily.

**Signed in Grahamstown, on** \_\_\_\_\_ *(Date)*.

**Participant:** \_\_\_\_\_ *(Name)*  
and \_\_\_\_\_ *(Signature)*.

**Researcher:** \_\_\_\_\_ *(Full name)*  
and \_\_\_\_\_ *(Signature)*.

**Witness:** \_\_\_\_\_ *(Full name)*  
and \_\_\_\_\_ *(Signature)*.

## Appendix E: Driving Route Details

### E1 Directions through the light Industrial Area

Participants were asked to drive the vehicle along the route outlined in blue in Figure 33. The route was 5.1km long and was estimated by Google Maps (2018) to take nine minutes to complete when adhering to speed limits and with minimal expected traffic. Detailed directions and distances are listed in Table V.

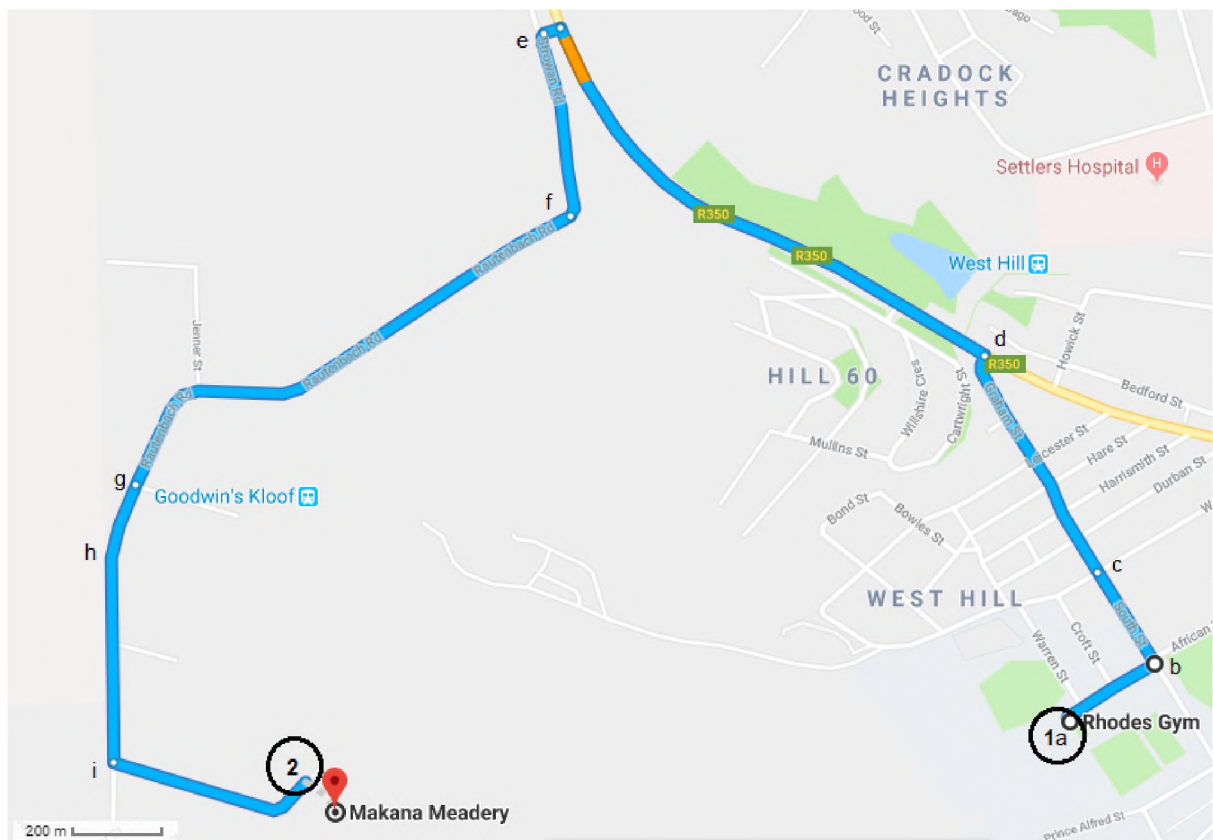


Figure 33: Driving route through the light industrial area from the Rhodes University gym (1a) to the Makana Meadery (2). Scale 1:200m. Map data: Google (n.d.-a).

Table V: Detailed directions from the Rhodes University Gym (1a) to Makana Meadery (2). Information via Google Maps (2018).

From Point:	Instruction	Continue ahead for distance:
1a	Depart from the Rhodes University Gym onto African Street. Head northeast.	230m
b	Turn left into South Street.	240m
c	Continue straight on as South Street becomes Graham Street.	550m
d	Turn left into Cradock Road/R350	1.2km
e	Turn left into Strowan Road.	39m
e	Turn left to remain on Strowan Road.	450m
f	Continue on as Strowan Road curves to the right and becomes Rautenbach Road.	1.2km
g	Continue on as Rautenbach Road becomes Stirk Road, passing point h.	650m
i	Turn left into Reynolds Street to the Makana Meadery entrance (point 2).	500m
2	Perform three-point turn to orientate the vehicle 180° away from the Makana Meadery. RSME rating to be taken before pulling off again.	N/A

After completing the three-point turn at the Makana Meadery, while the vehicle was stationary, the participant was asked to give verbally an RSME rating of the mental effort they expended while they were driving through the industrial area.

## E2 Directions through the Provincial Road

Participants were then instructed to drive to the R350 Provincial freeway (1e). Figure 34 depicts this drive to the Provincial freeway as well as the returning route to Grahamstown. On arrival at point 3, participants turned the vehicle around and drove back down the R350 to Howick Street in Grahamstown (4a).

This segment was 62.5km and was estimated by Google Maps (2018) to take 47 minutes to complete in typical conditions of low traffic volumes. Table lists the distances and directions that were taken to complete this segment of the testing route.

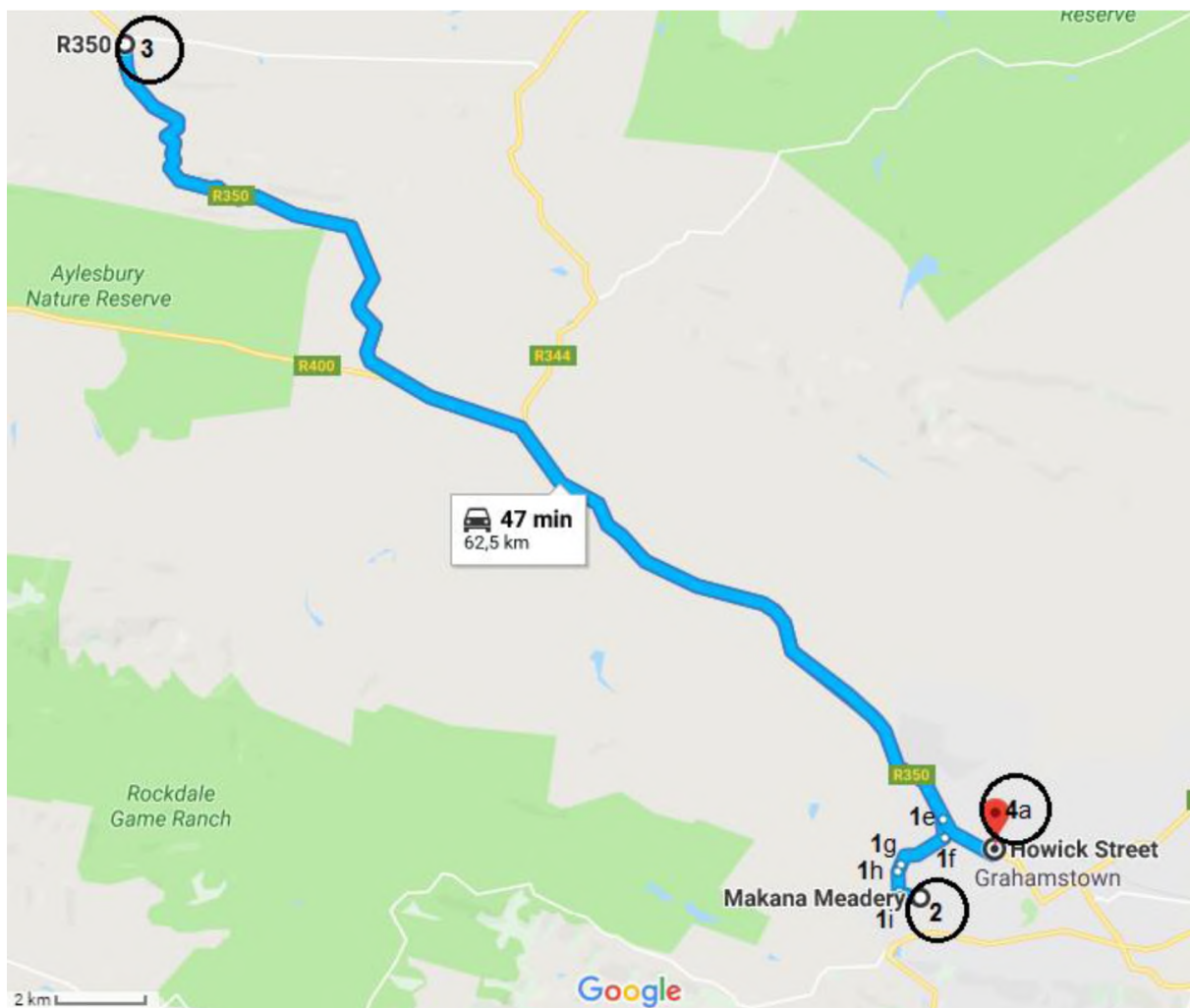


Figure 34: The provincial road route from Makana Meadery (2) to Howick Street (4a). Scale 1:2km. Map data: Google (n.d.-b).

Table VI: Detailed directions from the Makana Meadery (2) to the unmarked road (3) and then Howick Street, Grahamstown (4a). Information via Google Maps (2018).

From Point:	Instruction	Continue ahead for distance:
2	From Reynolds Street, head southwest.	500m
1i	Turn right onto Stirk Road.	450m
1h	Continue on as Stirk Road curves to the right.	170m
1g	Continue ahead as Stirk Road becomes Rautenbach Road.	1.2km
1f	Continue as the road curves to the left and becomes Strowan Road.	450m
1e	Turn right to remain on Strowan road.	39m
1e	Turn left onto the R350 Provincial road.	29,1km
3	Turn the vehicle 180° using most suitable manoeuvre (at the first intersecting dirt road).	N/A
3	Head South on the R350 back towards Grahamstown.	29km
1e	Drive ahead, keep to the left.	1.3km
4a	Turn left into Howick Street. Pull over when it is safe to do so to take RSME rating.	200m

The participant was asked to pull over when it was safe to do so on Howick Street. They were then asked to give verbally an RSME rating of their perceived mental effort required to drive on the Provincial road.

### E3 Directions through the Residential Area

From Howick Street (4a), participants were instructed to drive along the route outlined in Figure 35 and described in Table VII. This route segment was exclusively within a residential area and was 4.5km long. Google Maps (2018) estimated that this drive would take approximately eight minutes in low volume traffic conditions.

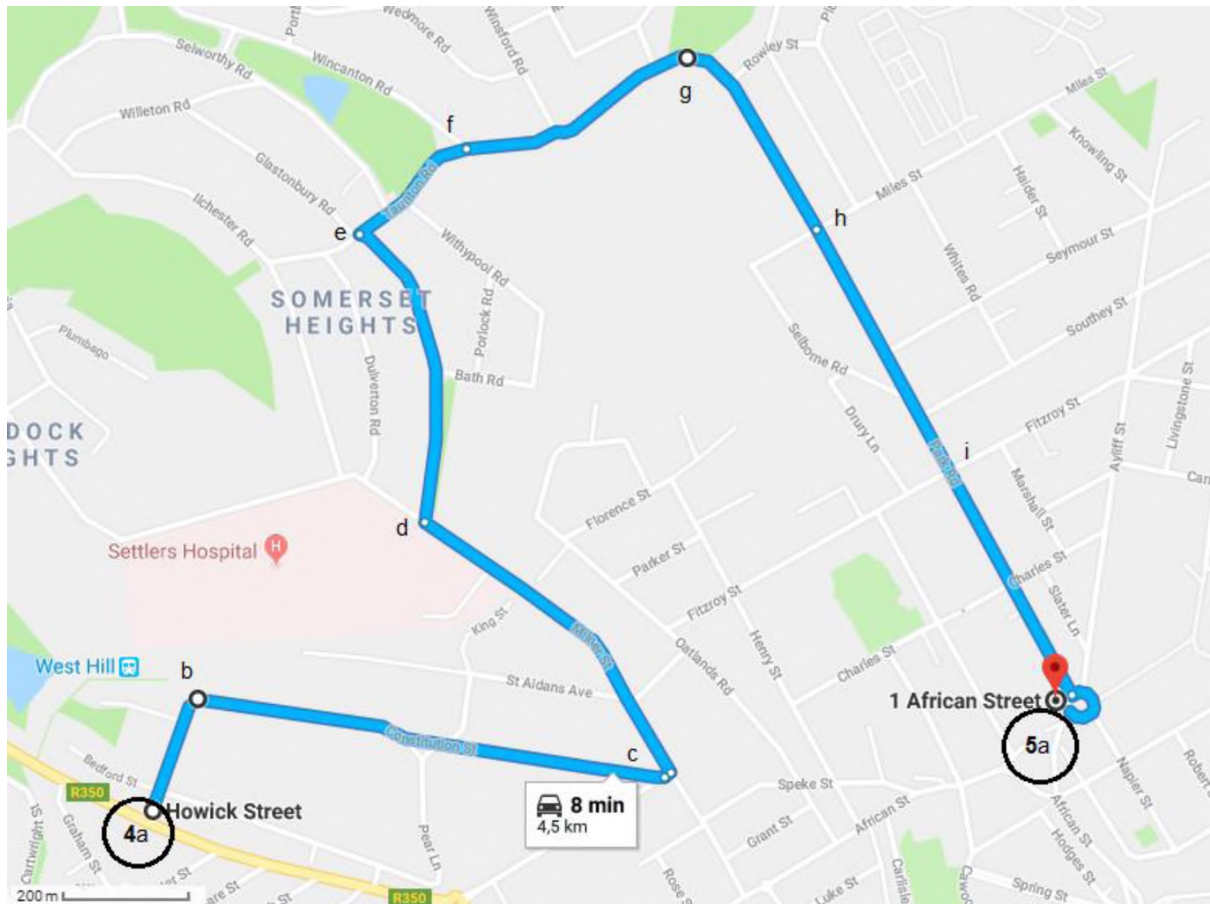


Figure 35: The residential route from Howick Street (4a) to 1 African Street (5a). Scale: 1:200m. Map data: Google (n.d.-c).

*Table VII: Detailed directions from Howick Street (4a) to 1 African Street (5a). Information via Google Maps (2018).*

From Point:	Instruction	Continue ahead for distance:
4a	Drive North along Howick Street.	220m
b	Turn right to follow Howick Street as it becomes Constitution Street.	850m
c	Keep left as Constitution Street leads onto Worcester Street.	14m
c	Turn left into Milner Street.	650m
d	Turn right onto Glastonbury Road.	550m
e	Turn right onto Tauton Road.	260m
f	Continue on as Tauton becomes Templeton Drive.	450m
g	Follow Templeton Drive as it curves to the right.	400m
h	Continue on as Templeton Drive becomes Park Road.	500m
i	Drive across Fitzroy Street, continuing down Park Road. Pull over when safe to do so for RSME rating.	500m
5a	Keep left to enter the traffic circle.	110m

When it was safe to do so, the participant was asked to pull over on Park Road before the traffic circle. They were then asked to provide a rating verbally of mental effort they experienced while driving through the residential area using the RSME scale.

#### E4 Directions through the Town Area

The route through the town started from the traffic circle (4a) and ended at the Rhodes University Gym (1a). This 4km segment of the route is shown in Figure 36 below. Google Maps (2018) estimated the drive to take 14 minutes. However, this excluded time taken to perform the parallel parking and alley docking manoeuvres. Table VIII lists directions along this route as well as the two parking locations.

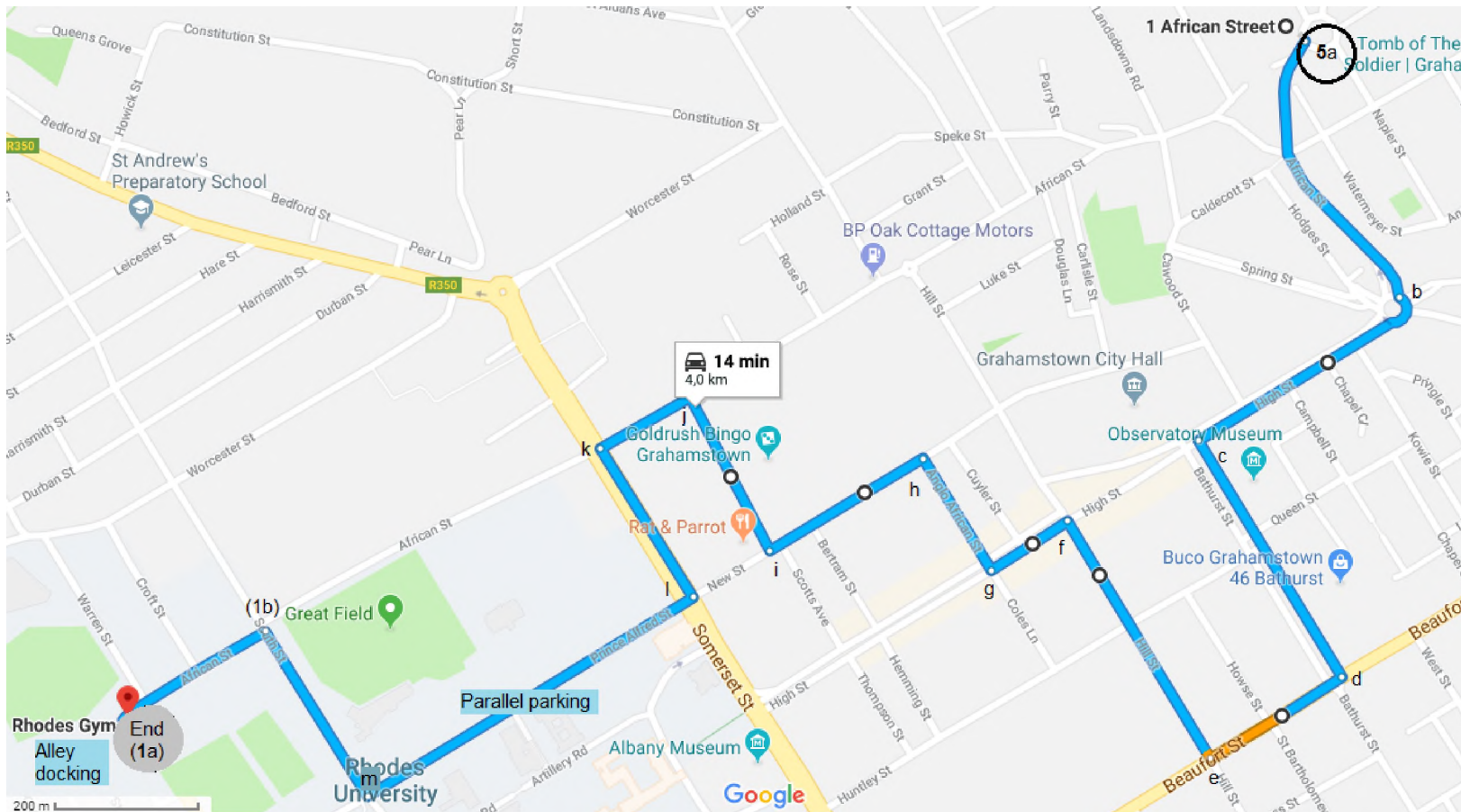


Figure 36: Route and parking locations along the planned route through the town.

From 1 African Street (5a) to the Rhodes University gym (1a). Scale 1:200m. Map data: Google (n.d.-d).

*Table VIII: Detailed directions of the planned route from 1 African Street (5a) to the Rhodes University Gym (1a). Information via Google Maps (2018).*

From Point:	Instruction	Continue ahead for distance:
5a	Exit the traffic circle onto African Street.	400m
b	Exit the next traffic circle onto High Street by taking the third exit.	350m
c	Turn left into Bathurst Street.	400m
d	Turn right onto Beaufort Street.	220m
e	Turn right onto Hill Street.	400m
f	Turn left onto High Street.	130m
g	Turn right onto Anglo African Street.	180m
h	Turn left onto New Street.	250m
i	Turn right onto Allen Street.	240m
j	Turn left onto African Street.	140m
k	Turn left onto Somerset Street.	240m
l	Turn right onto Prince Alfred Street. The participant was asked to provide a RSME rating and instructed to parallel park into the reserved parking spot before continuing to point m.	550m
m	Turn right onto South Street.	270m
1b	Turn left onto African Street.	230m
1a	On arrival at the Rhodes' Gym parking lot, the participant was asked to alley dock into a reserved parking bay.	N/A

The participant was asked to alley dock before providing their final RSME rating for driving through the campus area. The participant was asked to fill in the NASA-TLX questionnaire at the end of the testing session (1a on Figure 36). The researcher then proceeded to remove the eye tracker from the participant and both the participant and researcher disembarked the vehicle. Finally, the heart rate sensor belt was removed in the HKE department.

## **Appendix F: Dependent Variable Responses**

### **Structural Organisation of Results**

The structure of the data analysis and subsequently the bar graph results were based on two considerations. The first considers the difference in what constitutes an adequate sample length between measures of mental workload. The second concerns the 'meta-grouping' of driving scenarios into All Events, Common Events and Area Events. The result was the matrix in Table IX which shows the overall structure of results with a tick representing each bar graph.

Table IX: Matrix of mental workload measures and event meta-categories.

<b>Mental workload measure</b>	<b>All events</b>	<b>Shared Events</b>	<b>Area</b>
HR Frequency	✓	✓	✓
HRV: SDNN	✓	✓	✓
HRV: rMSSD	✓	✓	✓
HRV: high frequency power	N/A	N/A	✓
HRV: low frequency power	N/A	N/A	✓
HRV: LF power relative to (LF + HF)	N/A	N/A	✓
Pupil Diameter	✓	✓	✓
Blink Frequency	✓	✓	✓
Blink Duration	✓	✓	✓
Saccade Amplitude	✓	✓	✓
Saccade Duration	✓	✓	✓
Saccade Velocity	✓	✓	✓
Fixation Duration	✓	✓	✓
RSME	N/A	N/A	✓
NASA-TLX	Cumulative measure of the entire driving task.		

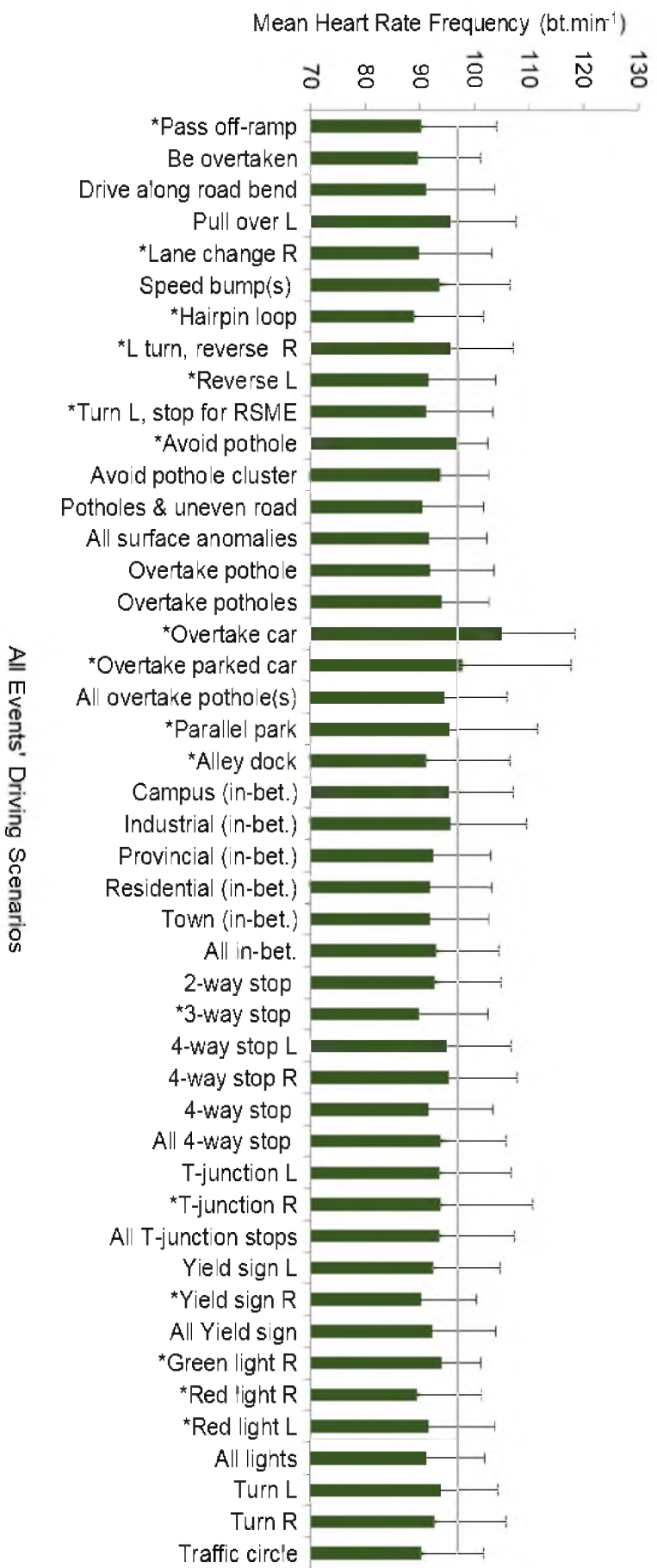


Figure 37: Mean heart rate frequency responses to the All Events' driving scenarios. The grey line is the threshold value of 97 bt.min<sup>-1</sup>. Events with means that were equal to or above the line were considered to be higher mental workload inducing. Error bars display standard deviation. \*Scenarios with < 10 data points.

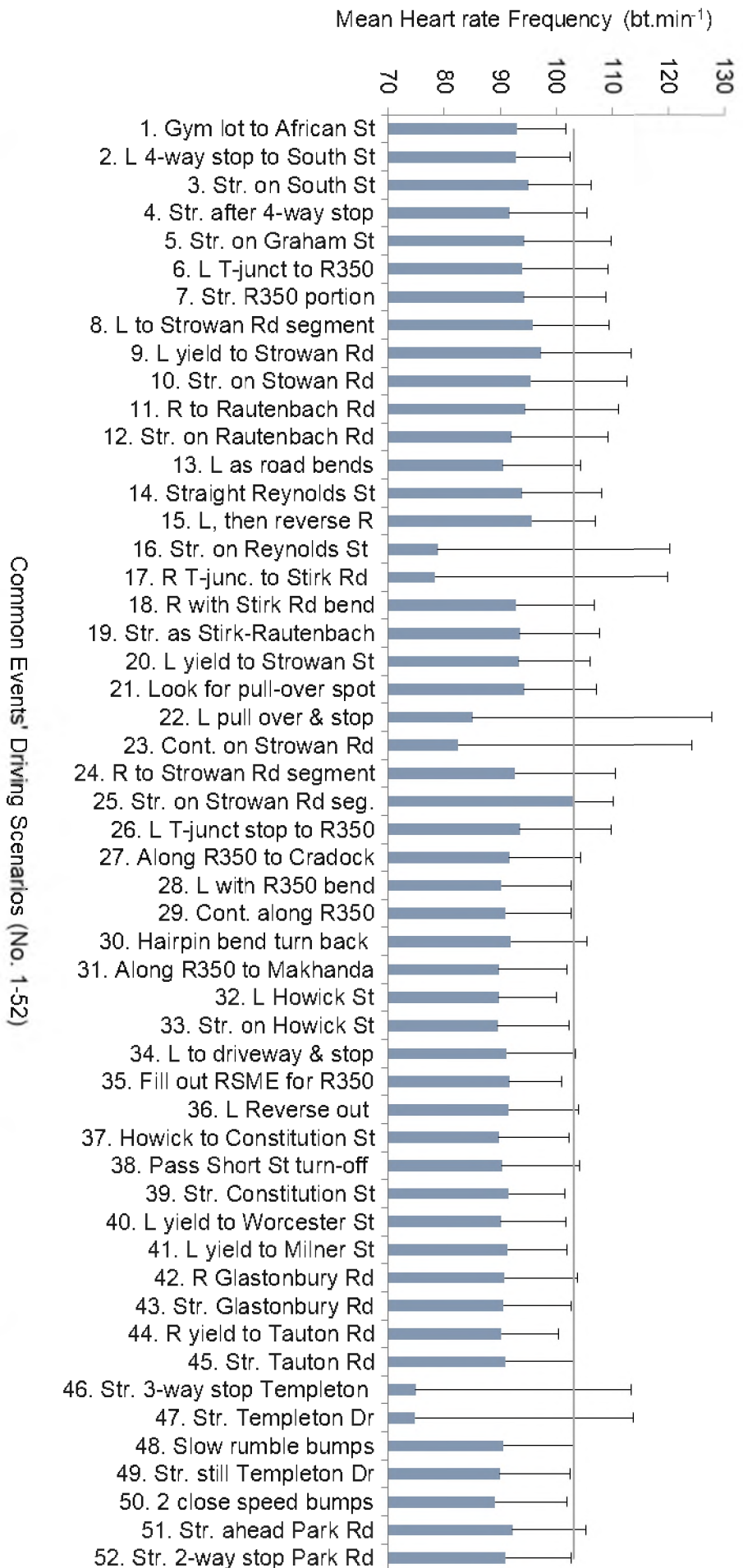


Figure 38: Mean heart rate frequencies in response to the Common Events' driving scenarios 1 to 52. Events with means equal to or above the grey line (103 bt.min<sup>-1</sup>) were considered to be higher mental workload inducing. Error bars depict standard deviation. Each event comprised six data points.

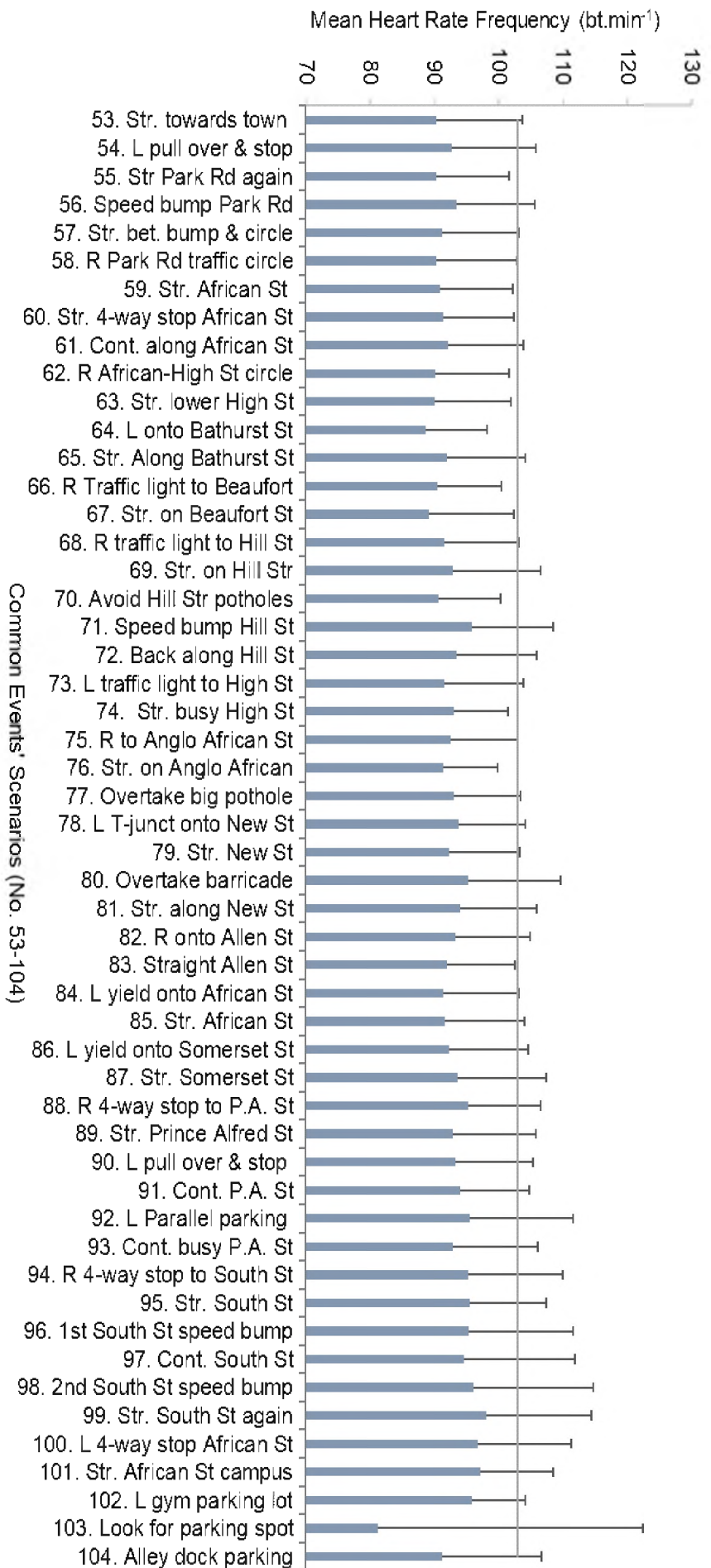


Figure 39. Mean heart rate frequencies in response to Common Events' driving scenarios 53 to 104. Events with means equal to or above the grey line (at 103 bt.min<sup>-1</sup>) were considered to be higher mental workload inducing. Error bars depict standard deviation. Each event comprised six data points.

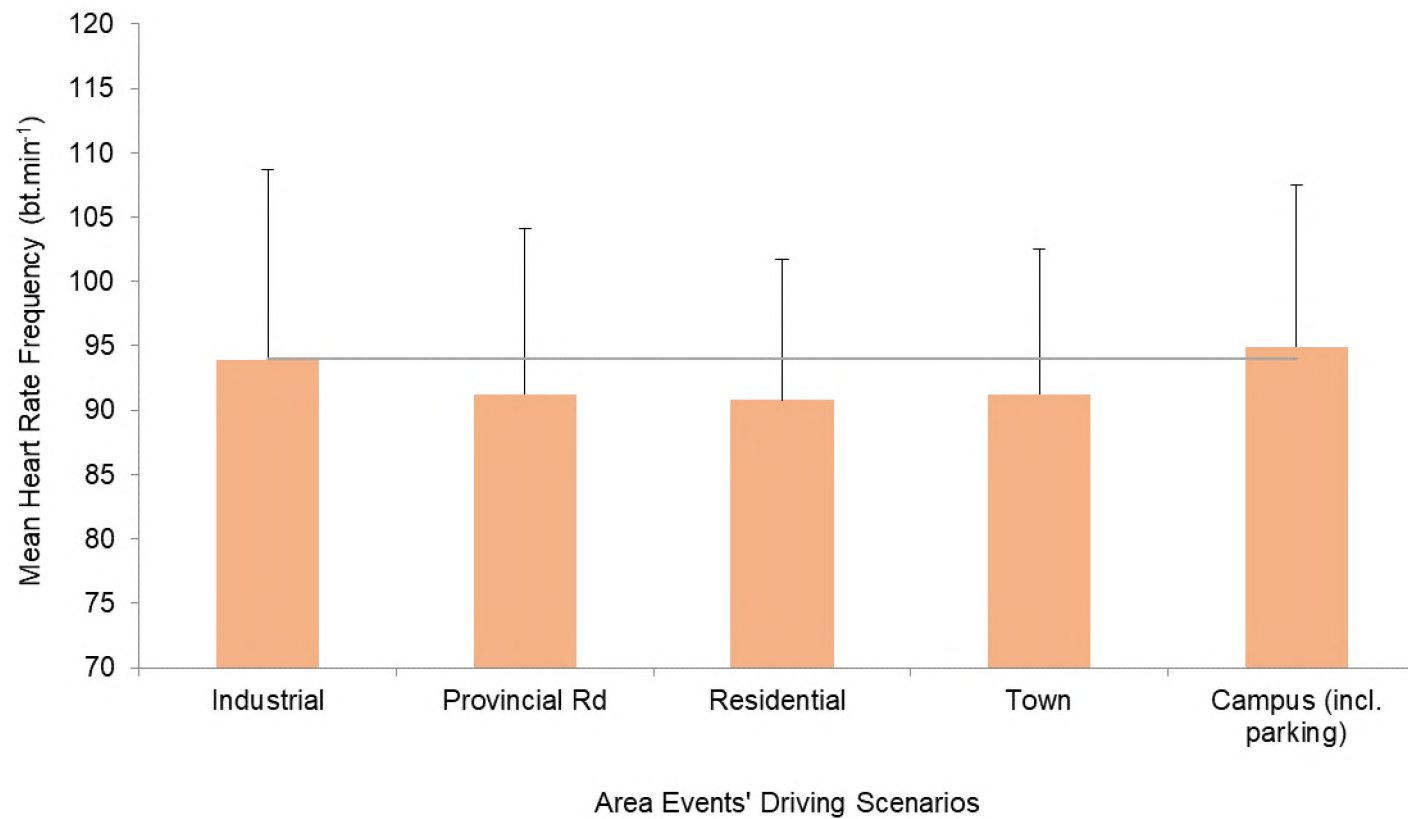


Figure 40: Mean heart rate frequency responses to driving within different areas. Events with means equal to and above the grey line (94 bt.min<sup>-1</sup>) were considered to be higher mental workload inducing. Error bars depict standard deviation. Each event had six data points.

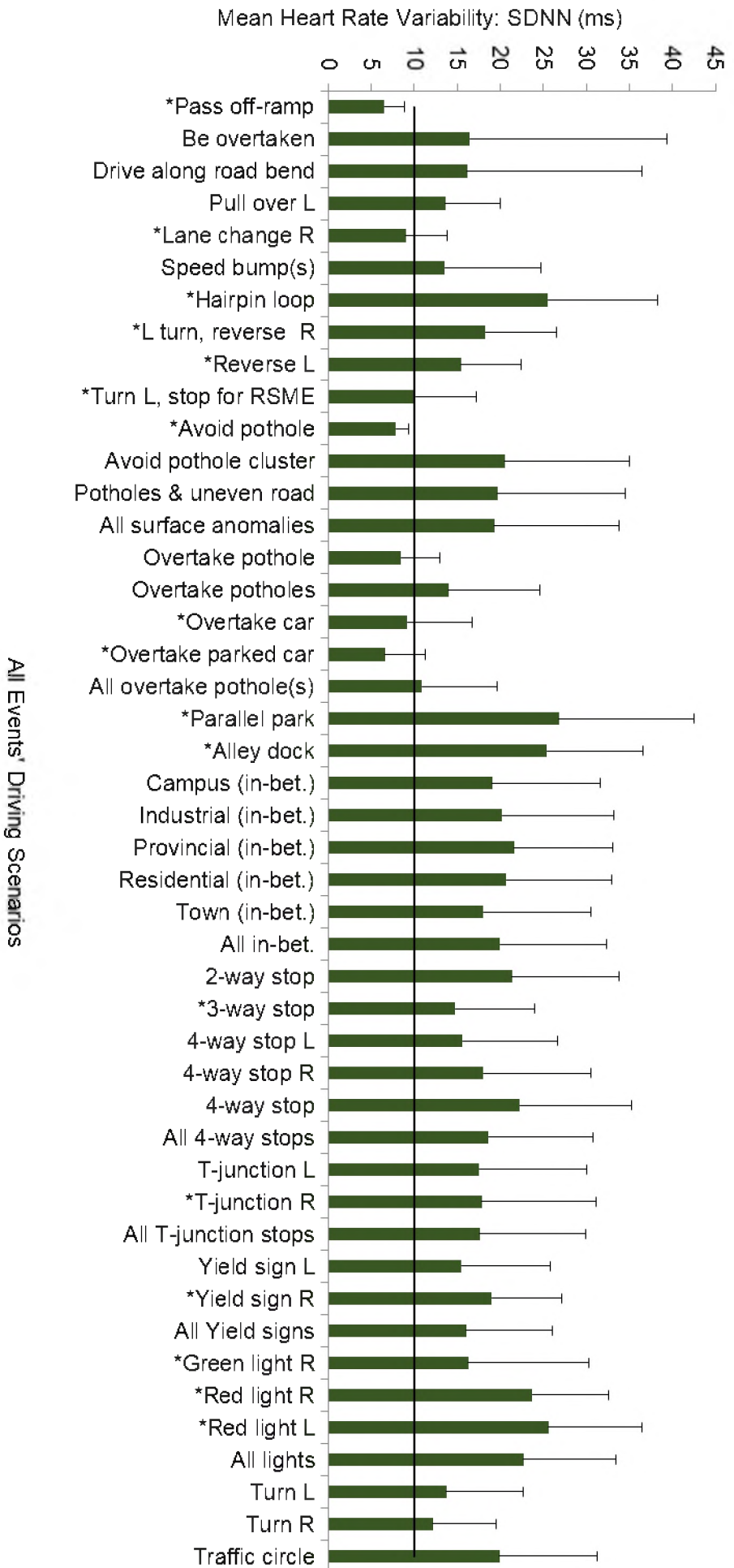


Figure 41: Mean SDNN responses to the All Events driving scenarios. Events with means below the black line (10 ms) were considered to be higher mental workload inducing. Error bars depict standard deviation. \* Scenarios with < 10 data points.

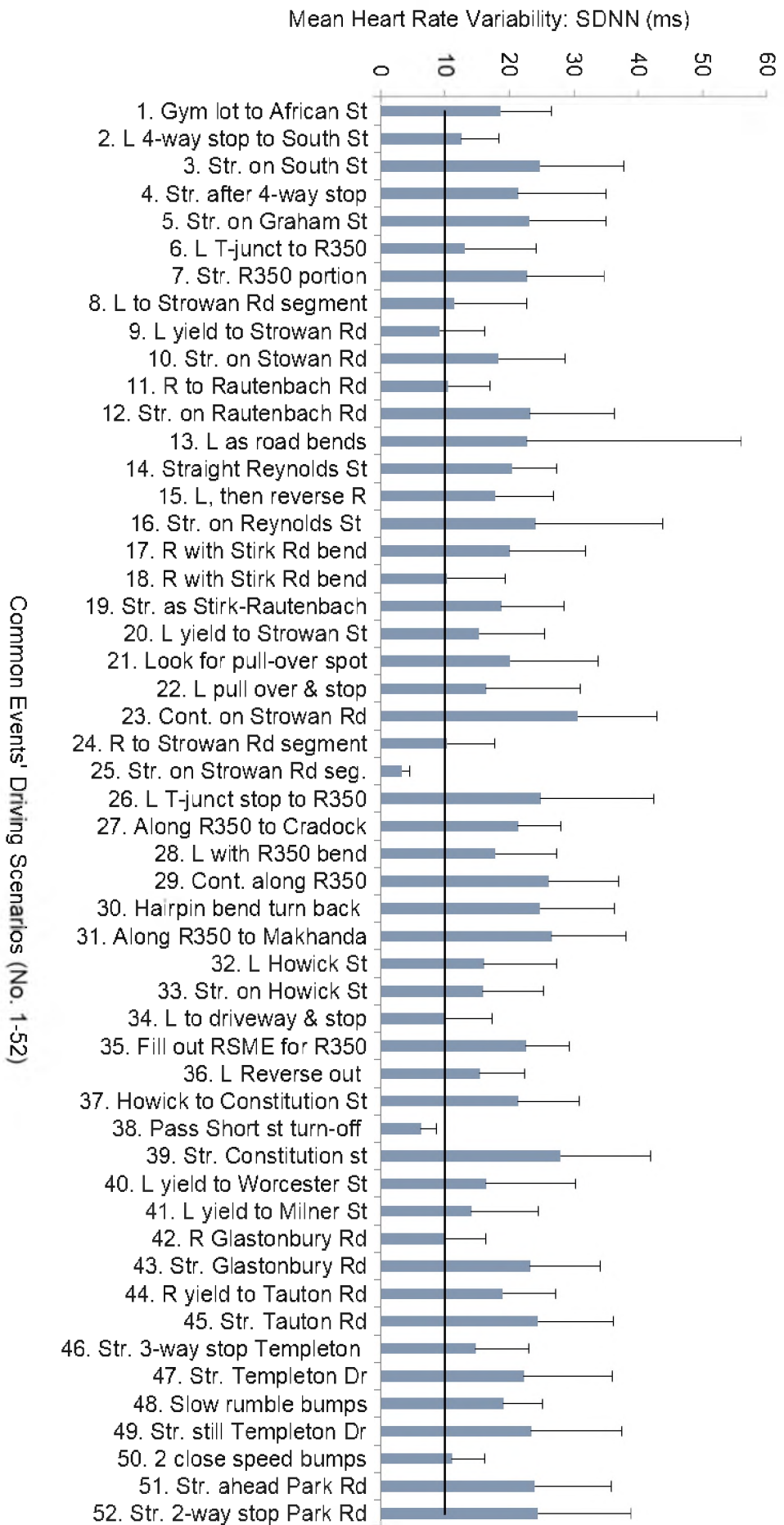


Figure 42: Mean SDNN responses to Common Events' driving scenarios 1 to 52. Events with means below 10 ms as depicted by the black line were considered to be higher mental workload inducing. Error bars depict standard deviation. All events had six data points.

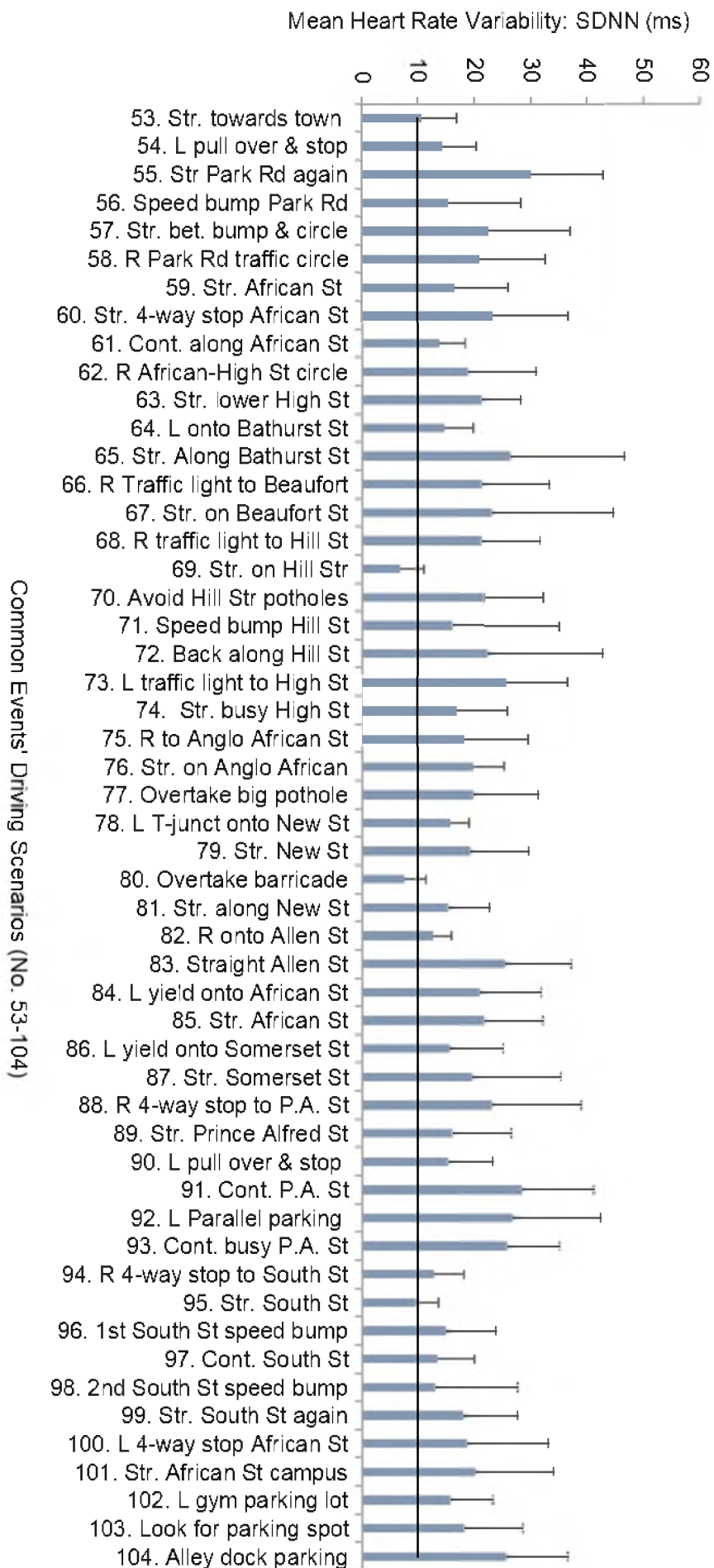


Figure 43: Mean SDNN responses to Common Events' driving scenarios 53 to 104. Events with means below the black line at 10 ms were considered to be higher mental workload inducing. Error bars depict standard deviation. Each event had six data points.

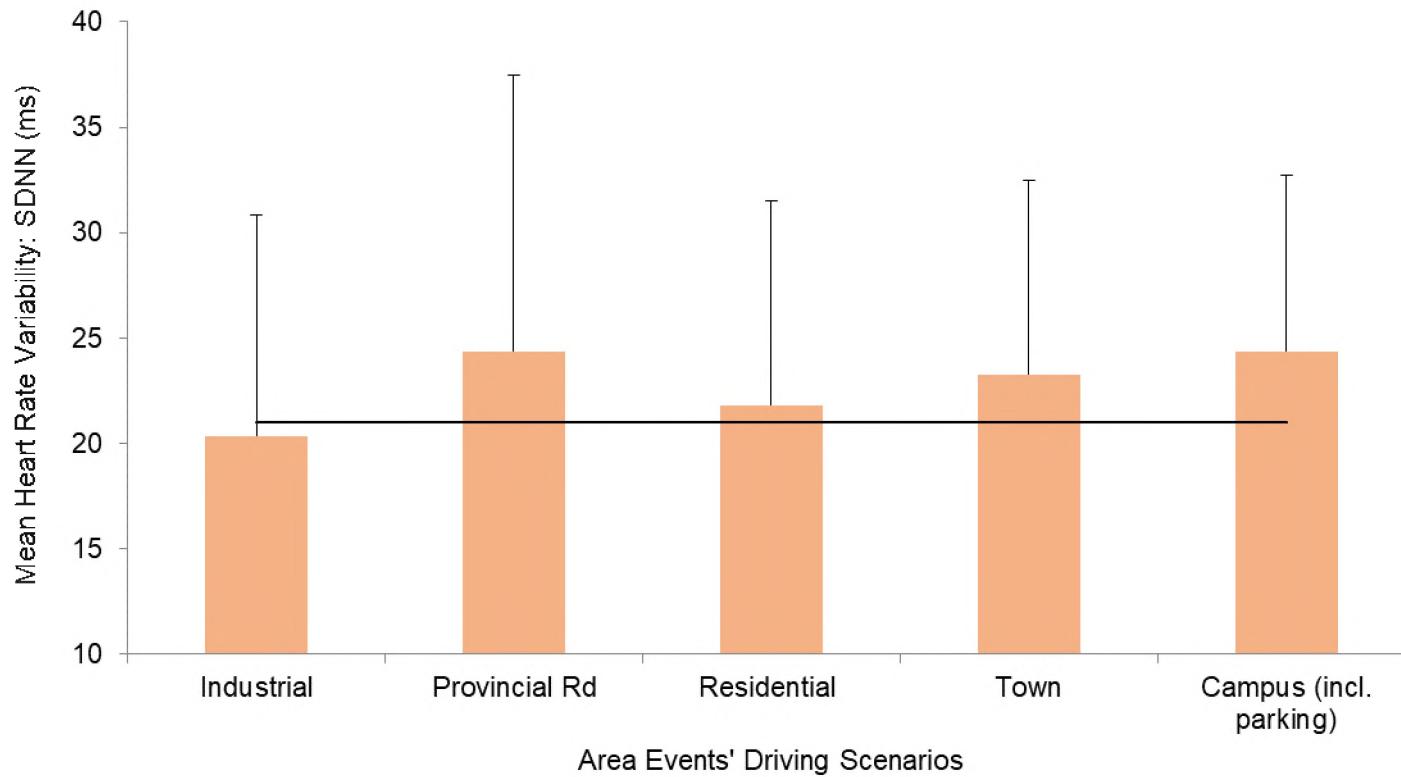


Figure 44: Mean SDNN responses to driving through the different areas. Events with means below the black line at 21 ms were considered to be higher mental workload inducing. Error bars depict standard deviation. Each area had six data points.

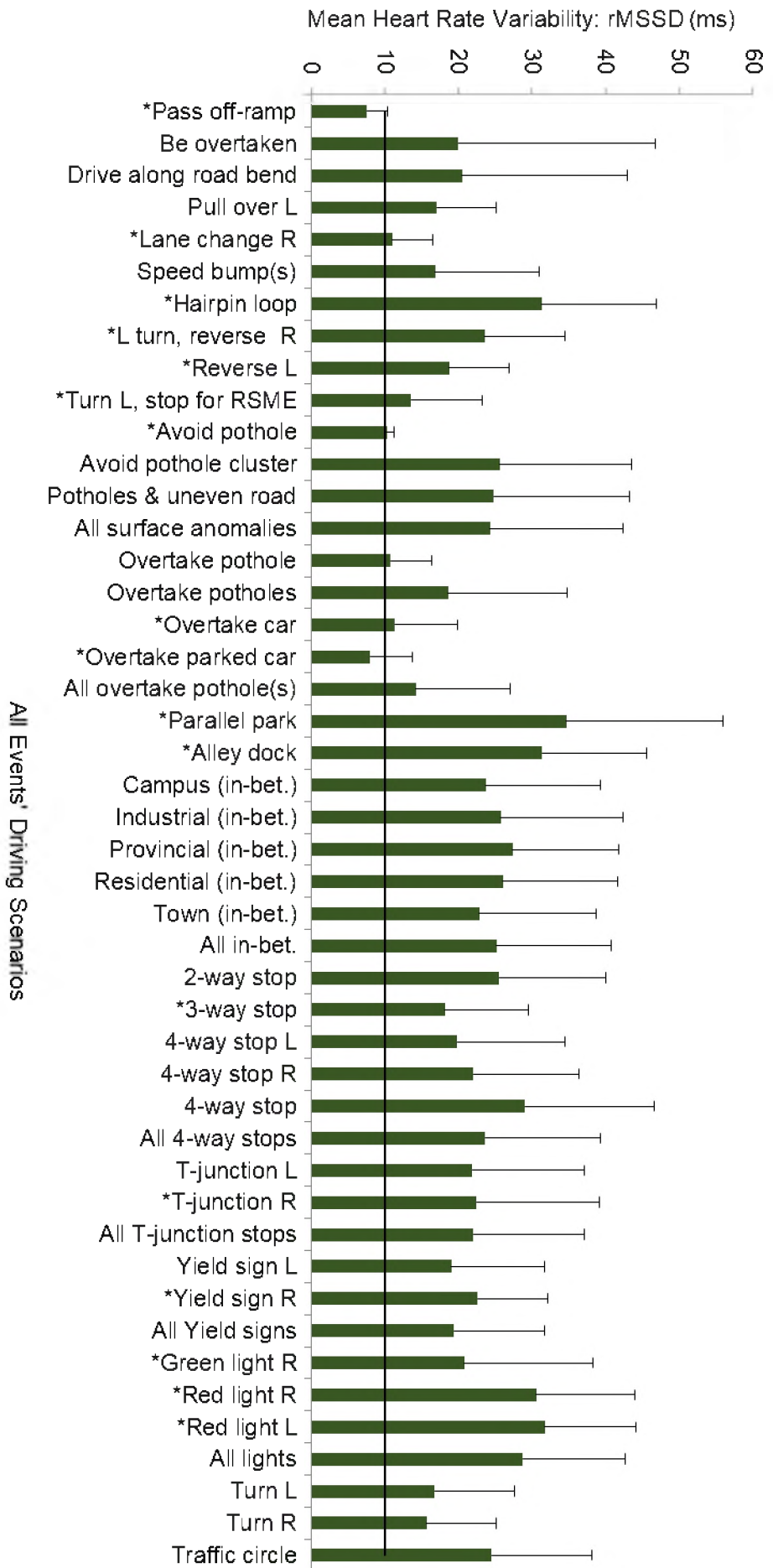


Figure 45: Mean rMSSD responses to the All Events' driving scenarios. Events with means below the black lines at 10 ms were considered to be higher mental workload inducing. Error bars depict standard deviation. \*Scenarios with < 10 data points.

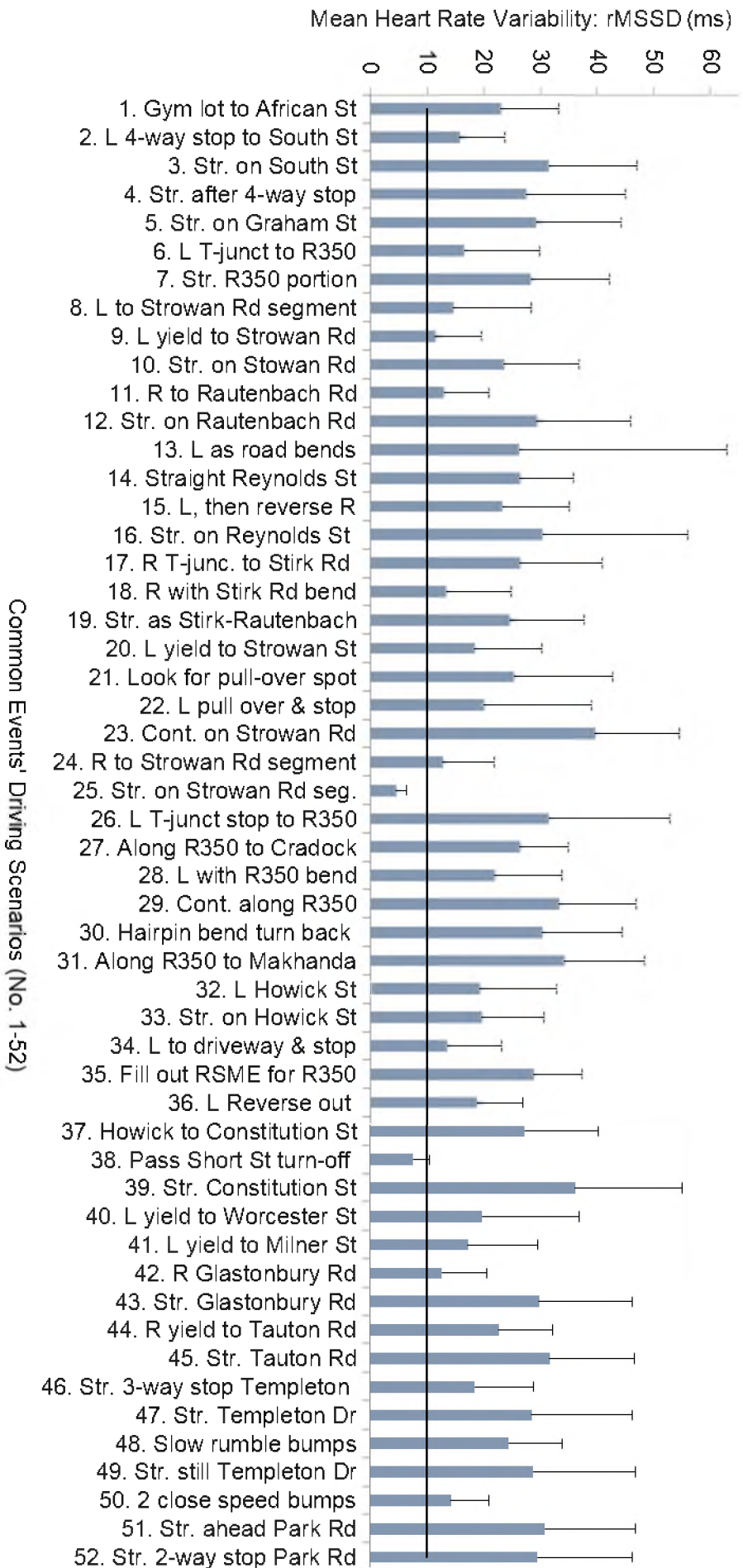


Figure 46: Mean rMSSD responses to Common Events' driving scenarios No. 1 to 52. Evens with means below the black line at 10 ms were considered to be higher mental workload inducing. Error bars depict standard deviation. Scenarios each had six data points.

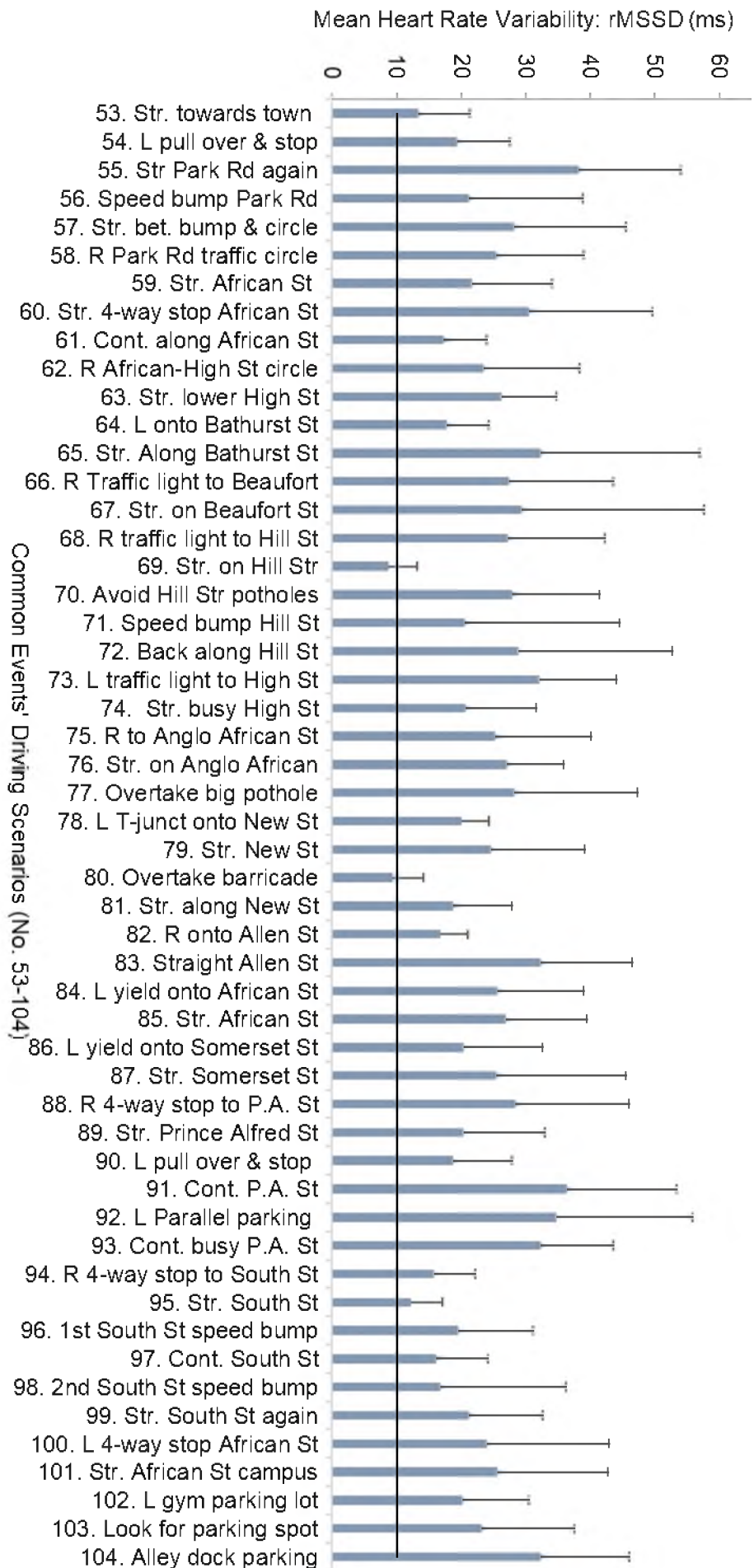


Figure 47: Mean rMSSD responses to Common Events' driving scenarios No. 53 to 104. Events with means below 10 ms as depicted by the black line were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points.

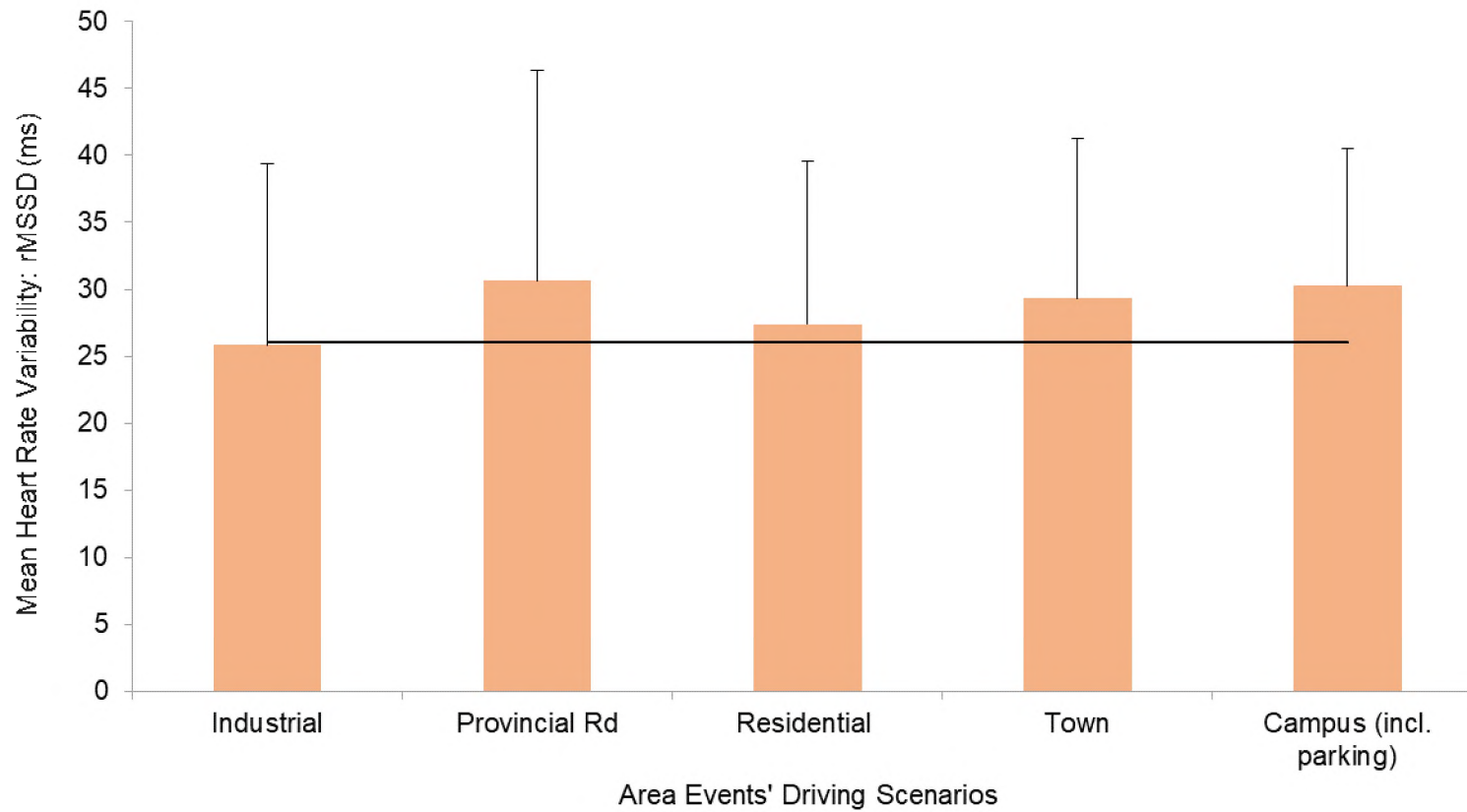


Figure 48: Mean rMSSD responses to Area Events' driving scenarios. Events with means below the black line at 26 ms were considered to be higher mental workload inducing. Error bars depict standard deviation. Scenarios each had six data points.

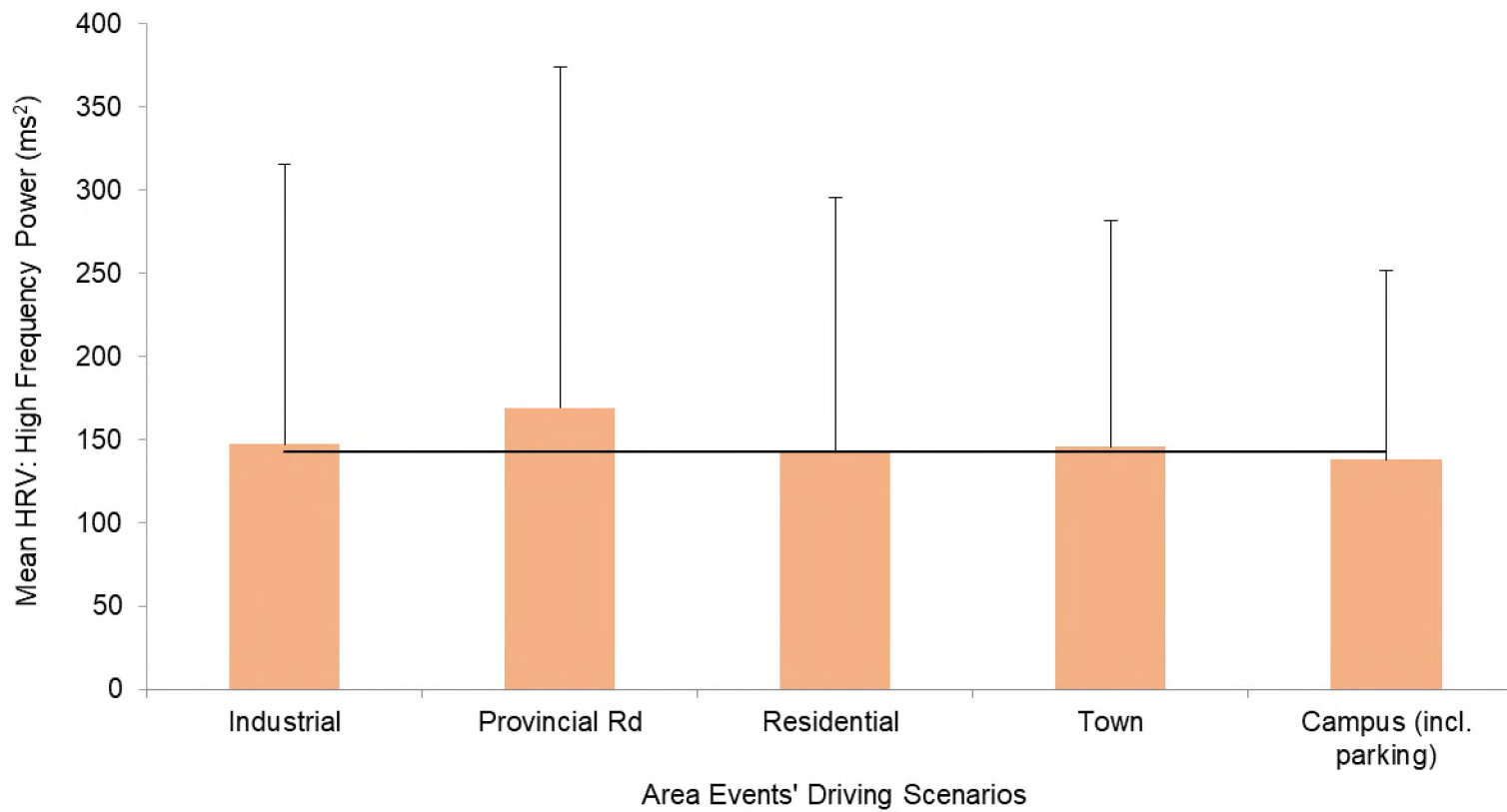


Figure 49: Mean high-frequency power responses to driving through different areas. Events with means below the 143 ms<sup>2</sup> of the black line were considered to be higher mental workload inducing. Error bars depict standard deviation. Scenarios all had six data points.

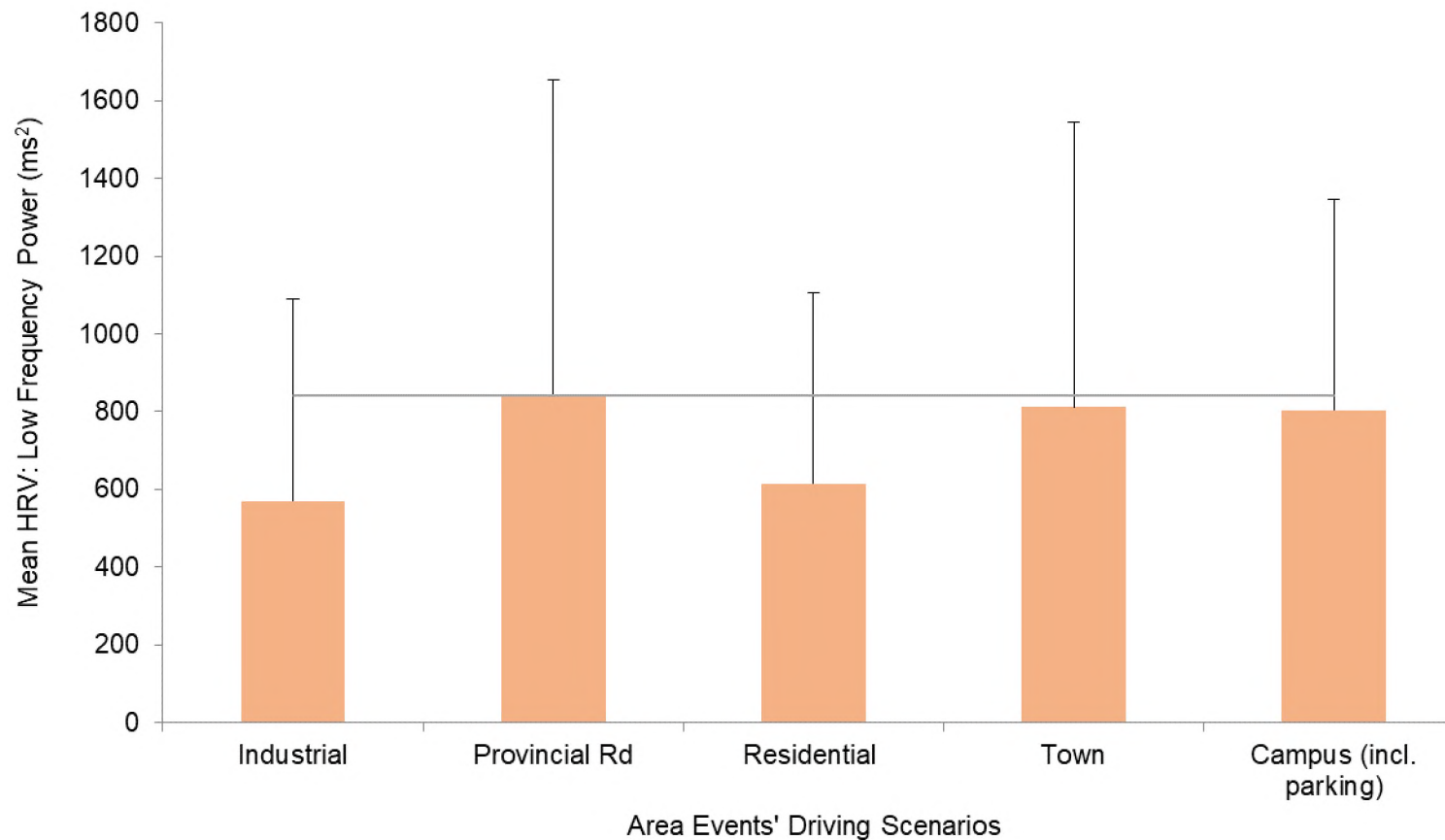


Figure 50: Mean low frequency responses to the Area Events' driving scenarios. Events with means above the grey line at 840 ms<sup>2</sup> were considered to be higher mental workload inducing. Error bars depict standard deviation. Scenarios each had six data points.

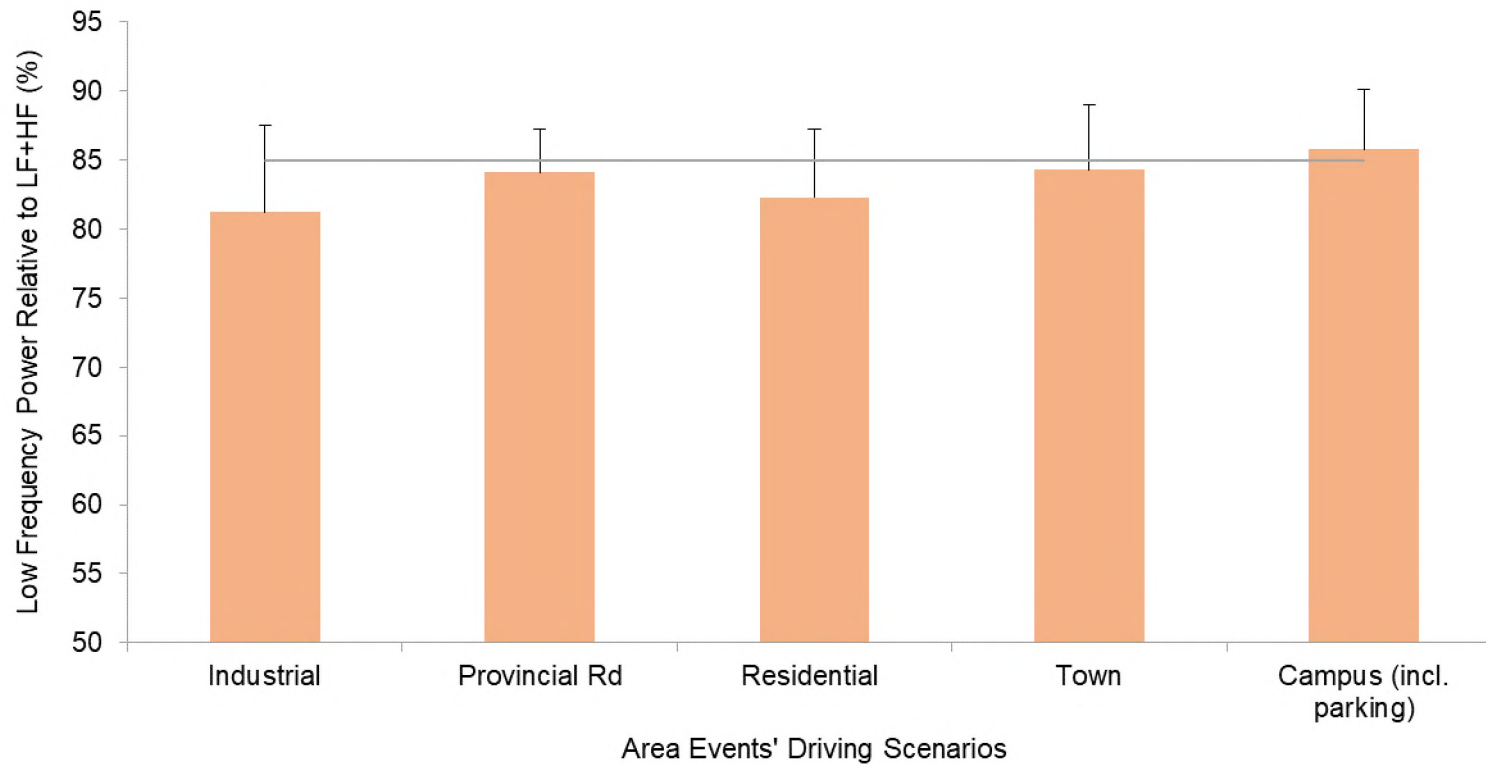


Figure 51: Mean relative low-frequency power in response to Area Events' driving scenarios. Events with means above the grey line's 85% were considered to be higher mental workload inducing. Error bars depict standard deviation. Scenarios had six data points each.

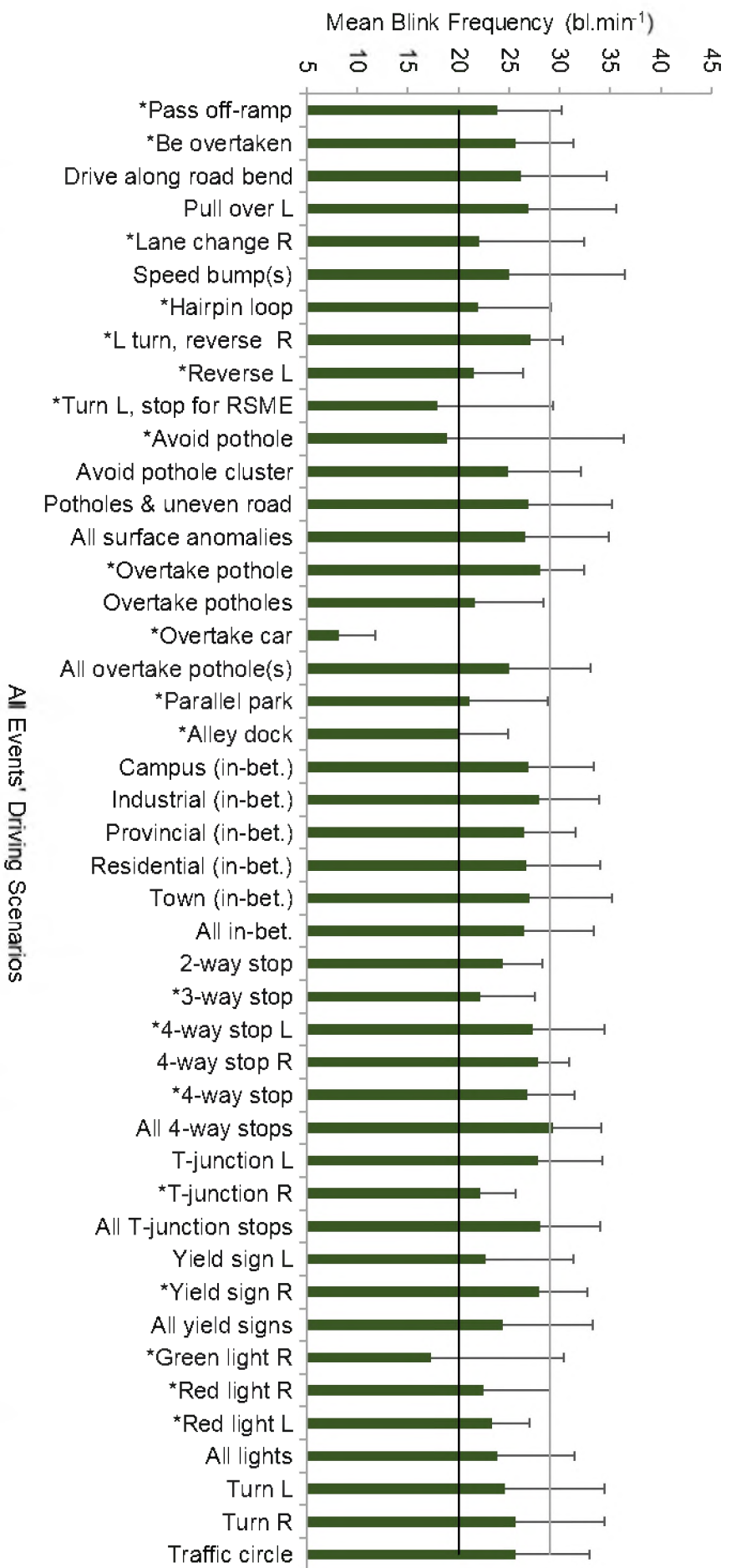


Figure 52: Mean blink frequency responses to the All Events' driving scenarios. Events with means above or equal to the grey line's 29 bl.min<sup>-1</sup> and events with means below or equal to the black line's 20 bl.min<sup>-1</sup> were considered to be higher mental workload inducing. Error bars show standard deviation. \*Scenarios < 10 data points.

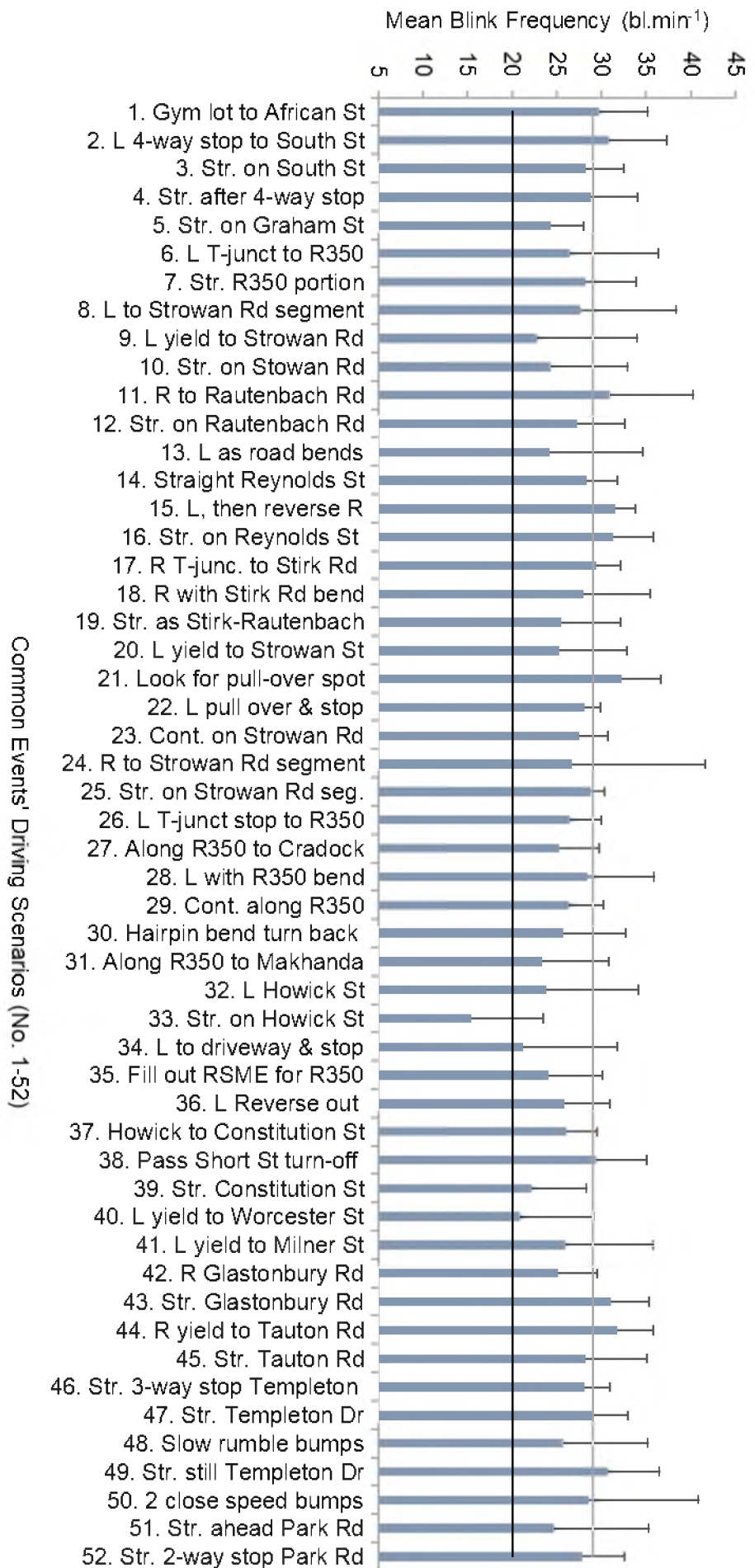


Figure 53: Mean blink frequency responses of Common Events No. 1 to 52. Events with means above or equal to the grey line's 29 bl.min<sup>-1</sup> and events with means below or equal to the black line's 20 bl.min<sup>-1</sup> were considered to be higher mental workload inducing. Error bars depict standard deviation. Scenarios had six data points each.

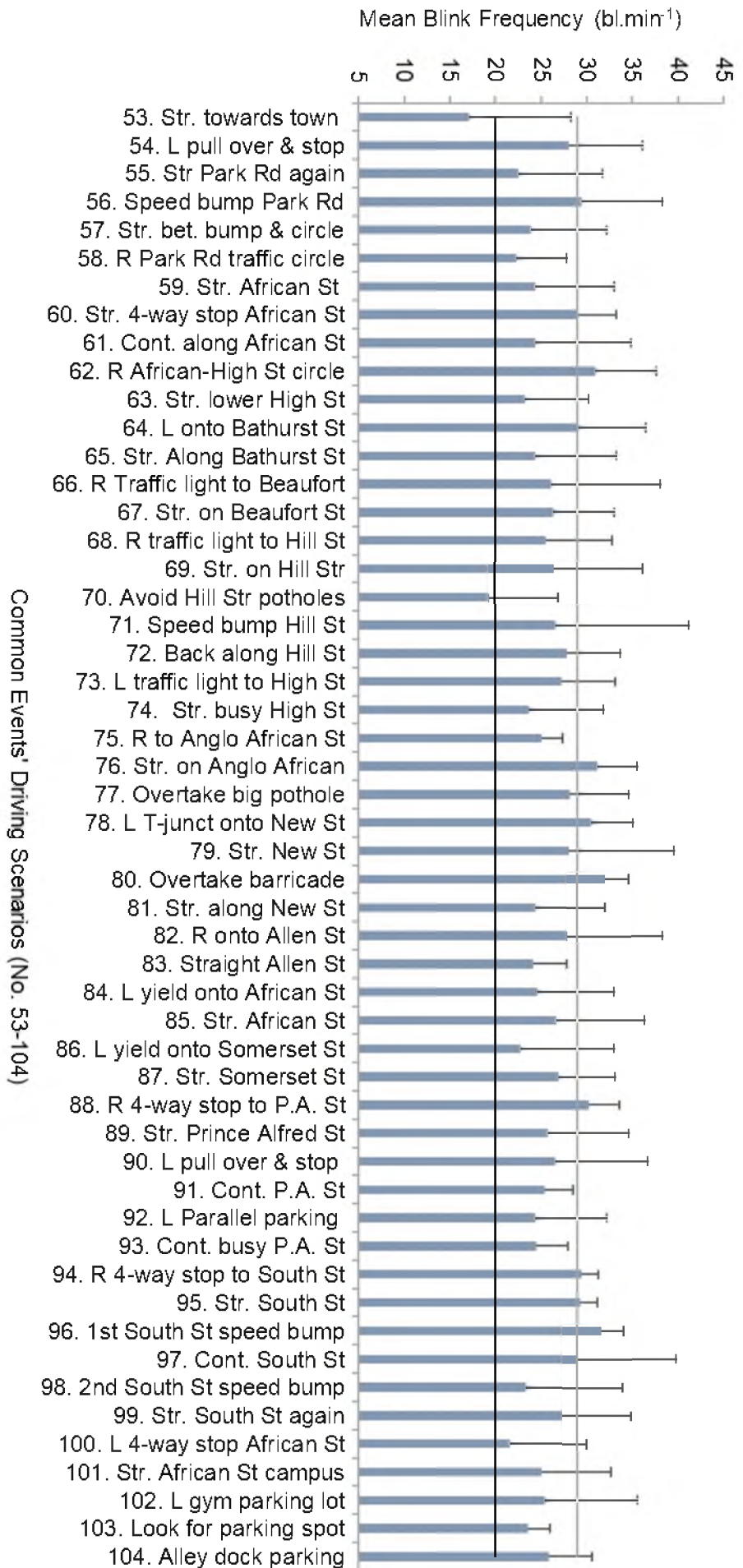


Figure 54: Mean blink frequency responses of Common Events No. 53 to 104. Events with means above or equal to the grey line's 29 bl.min<sup>-1</sup> and events with means below or equal to the black line's 20 bl.min<sup>-1</sup>, were considered to be higher mental workload inducing. Error bars depict standard deviation. Scenarios each had six data points.

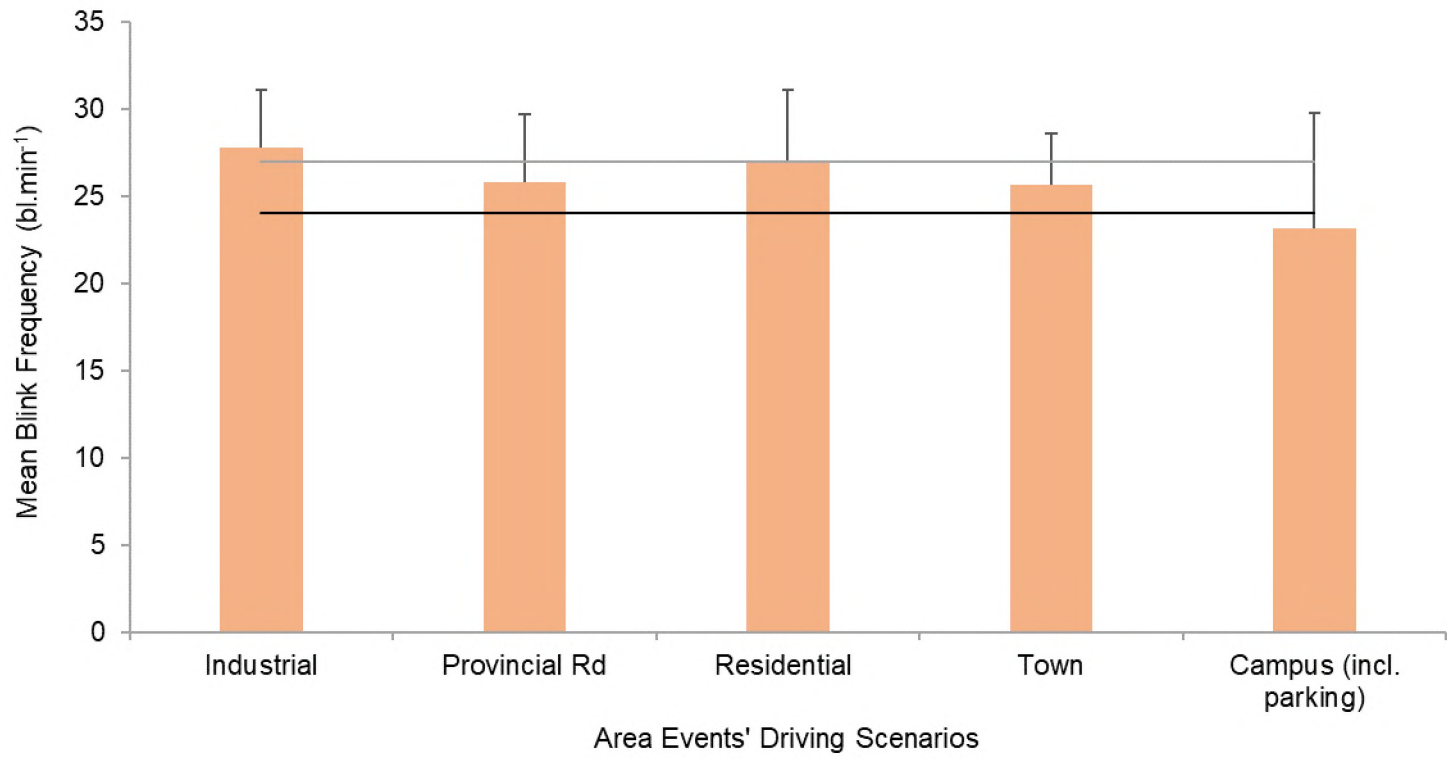


Figure 55: Mean blink frequency responses to Area Events driving scenarios. Events with means above or equal to the grey line's 27 bl.min<sup>-1</sup> and events with means below or equal to the black line's 24 bl.min<sup>-1</sup> were considered to be higher mental workload inducing. Error bars depict standard deviation. Scenarios had six data points each.

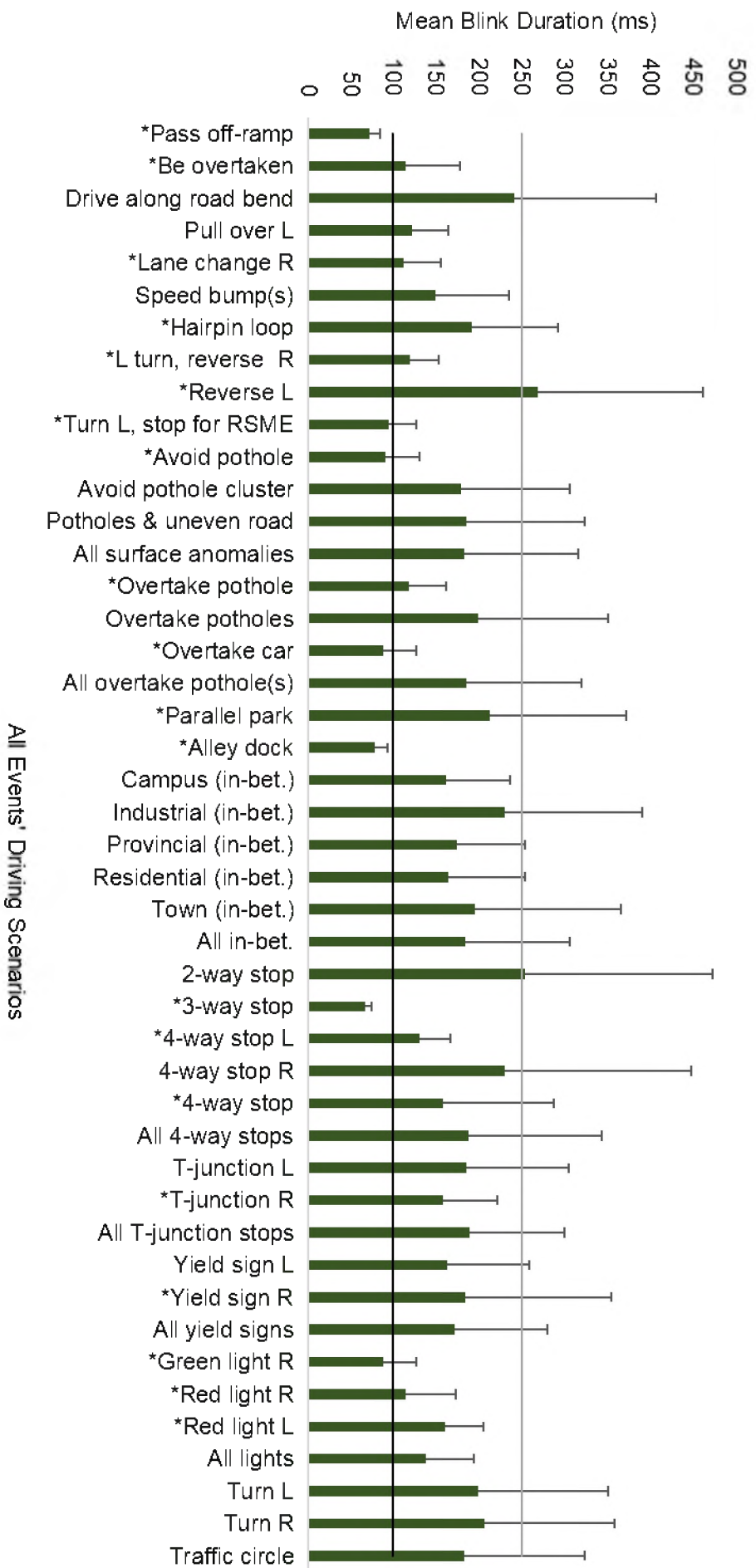


Figure 56: Mean blink duration responses to All Events' driving scenarios. Events with means above or equal to the grey line's 100 ms and events with means lower or equal to the black line's 100 ms, were considered to be higher mental workload inducing. Error bars depict standard deviation. \*Scenarios with < 10 data points.

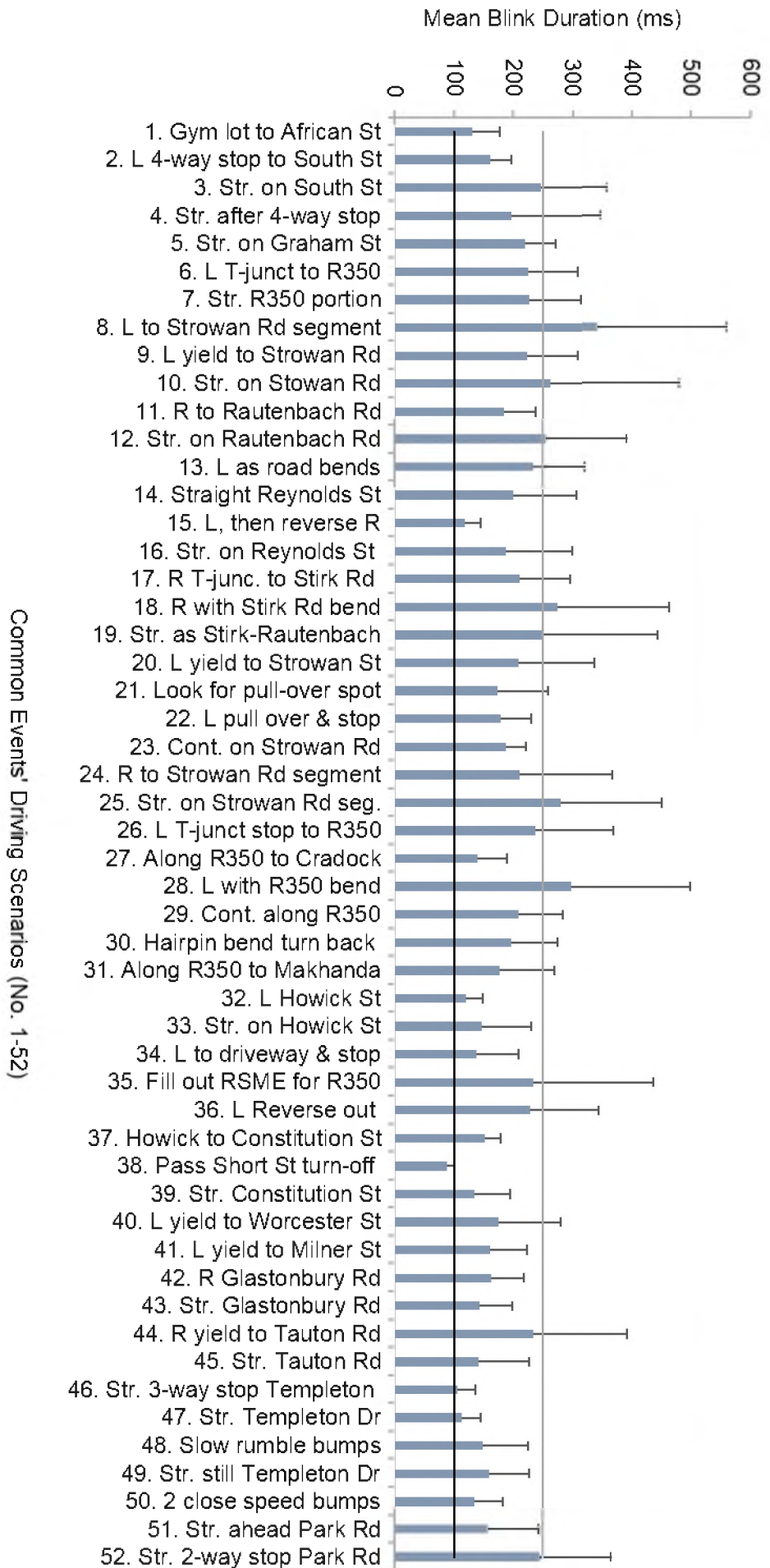


Figure 57: Mean blink duration responses of Common Events No. 1 to 52. Events with means above or equal to the grey line's 250 ms and events with means below or equal to the black line's 100 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

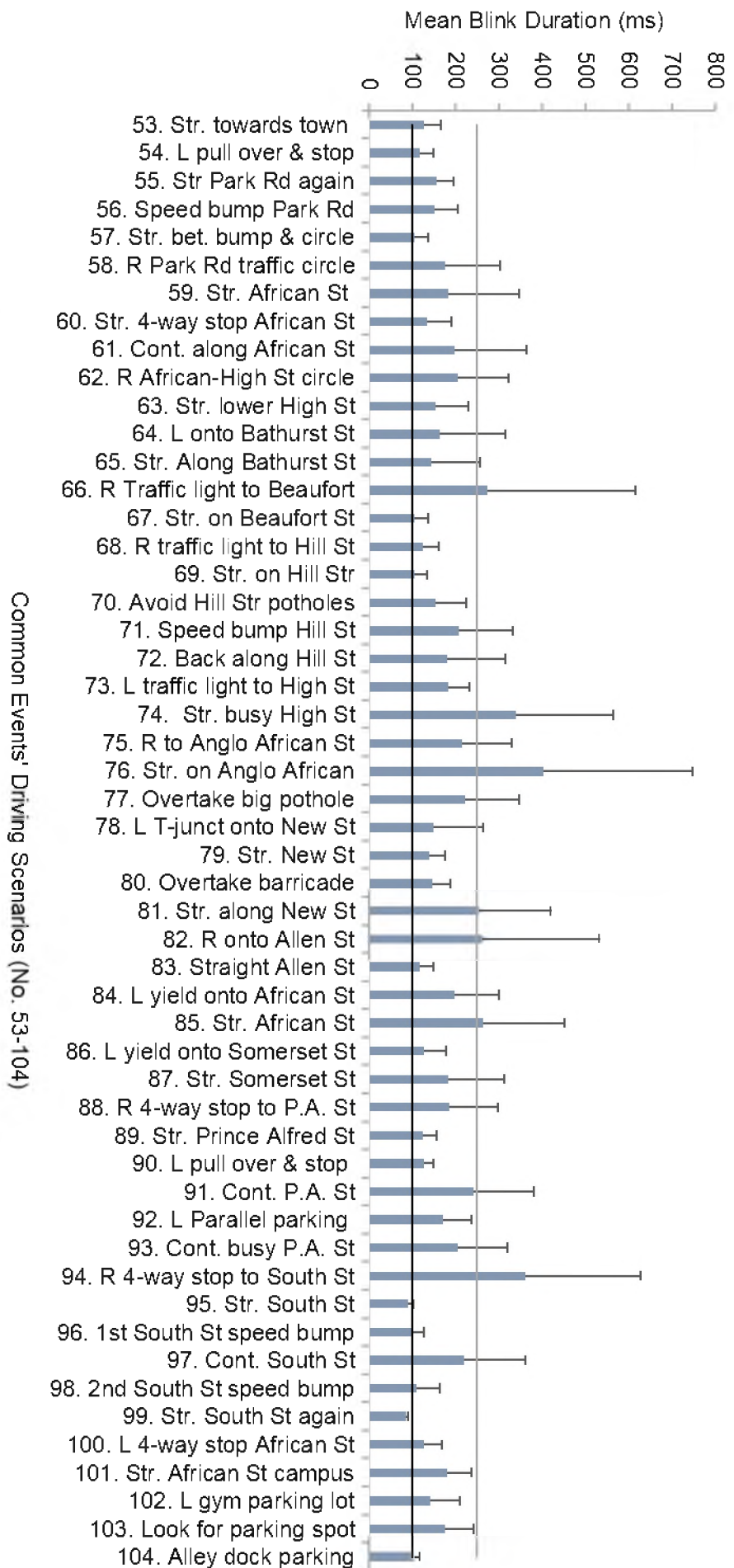


Figure 58: Mean blink duration responses of Common Events No. 53 to 104. Events with means above or equal to the grey line's 250 ms and events with means below or equal to the black line's 100 ms were considered higher mental workload responses. Error bars denote standard deviation. Scenarios consisted of six data points each.

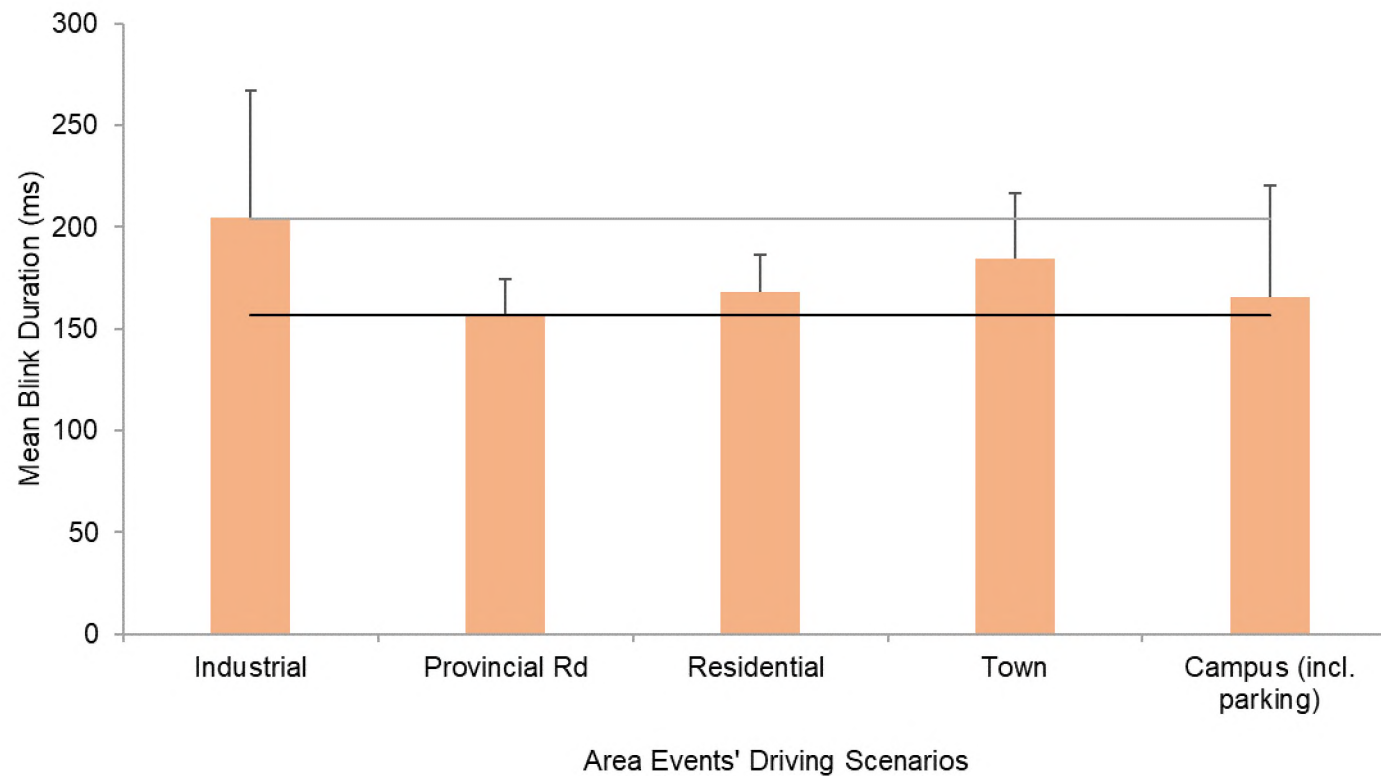


Figure 59: Mean blink duration responses to the Area Events' Driving scenarios. Events with means above or equal to the grey line's 204 ms and events with means below or equal to the black line's 157 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

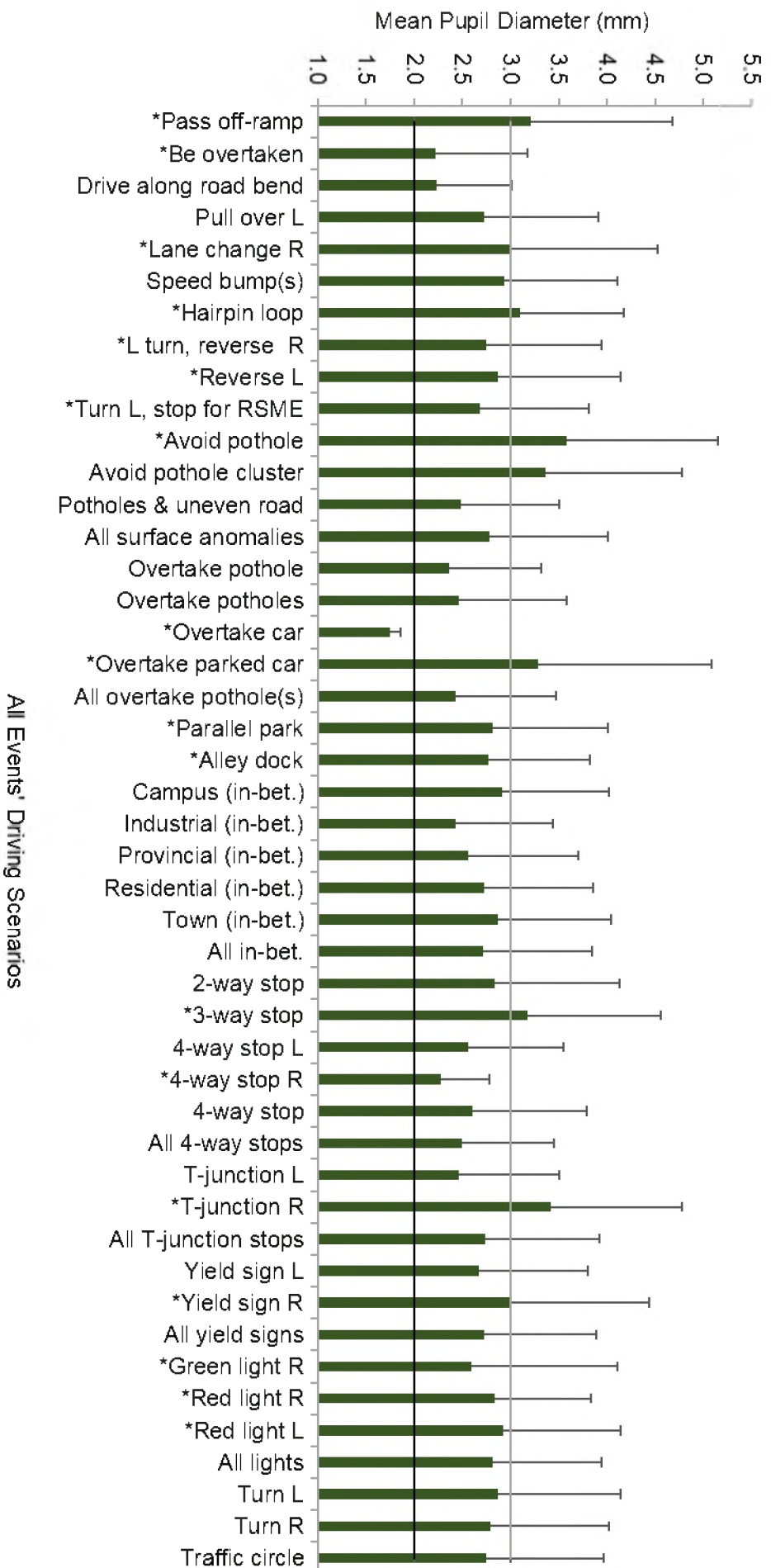


Figure 60: Mean pupil diameter responses of All Events' driving scenarios. Events with means above or equal to the grey line's 3 mm and events with means below or equal to the black line's 2 mm were considered to be higher mental workload inducing. Error bars denote standard deviation. \*Scenarios < 10 data points.

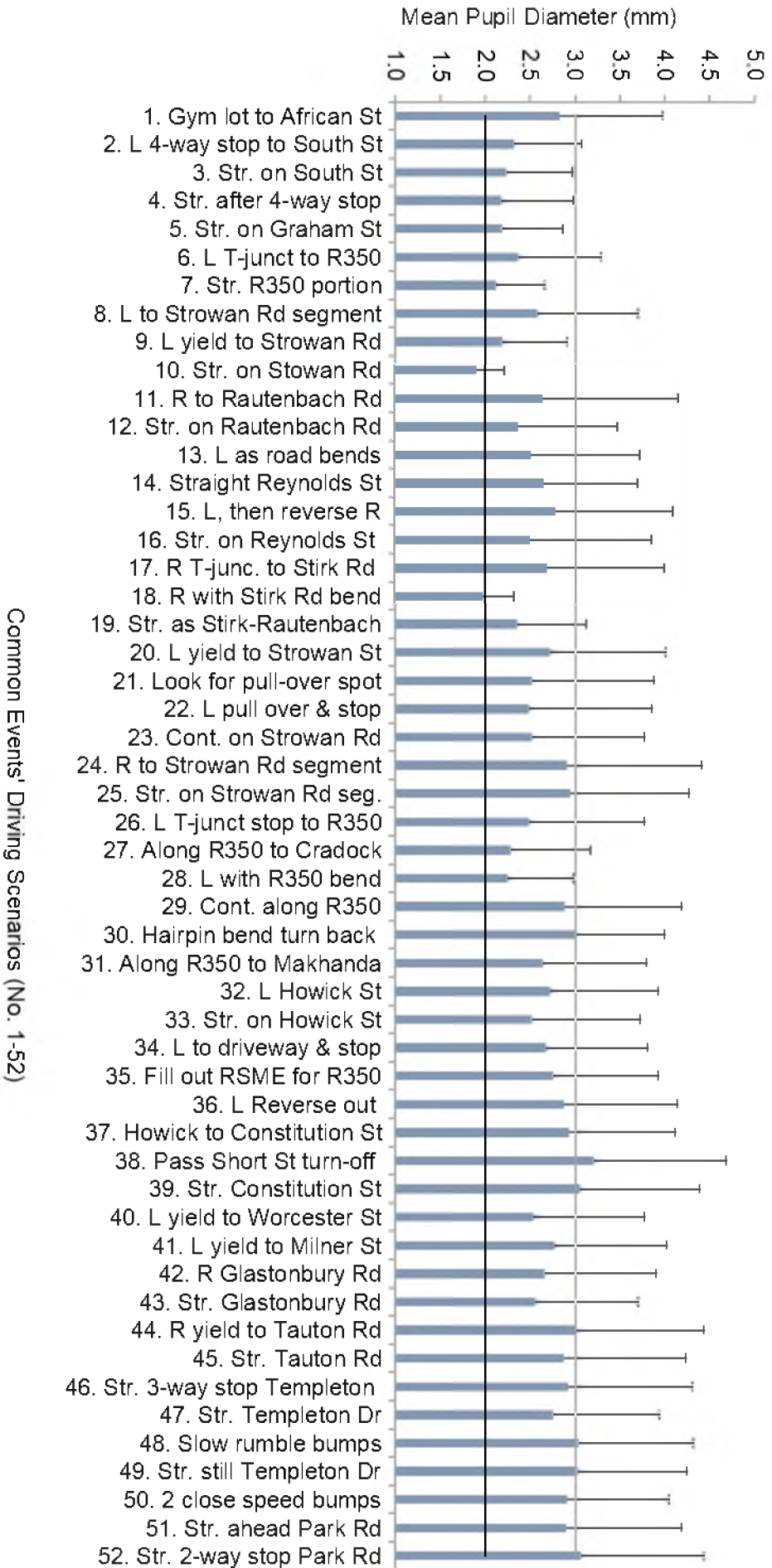


Figure 61: Mean pupil diameter responses of Common Events No. 1 to 52. Events with means above or equal to the grey line's 3 mm and events with means below or equal to the black line's 2 mm were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

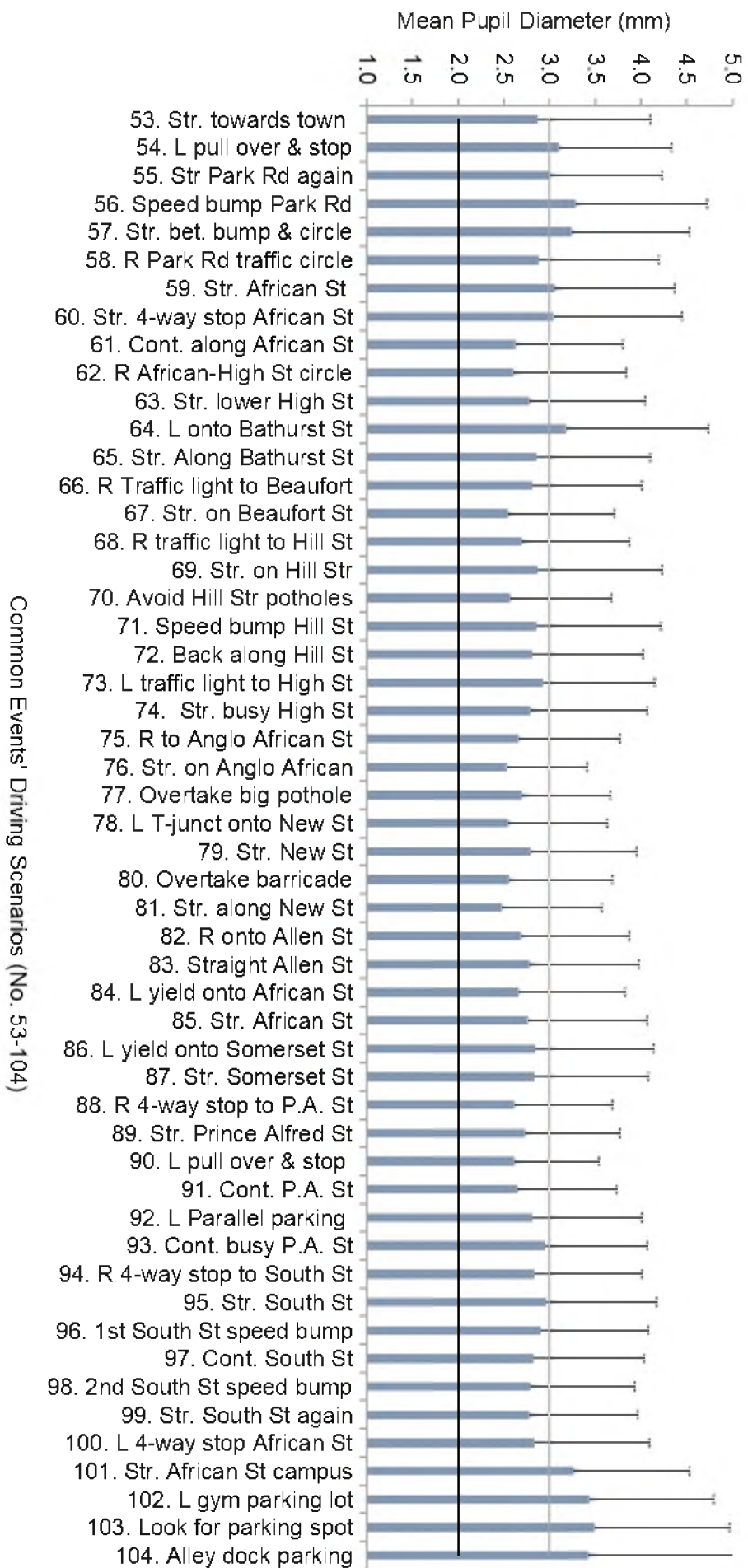


Figure 62: Mean pupil diameter responses of Common Events No. 53 to 104. Events with means above or equal to the grey line's 3 mm and events with means below or equal to the black line's 2 mm were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

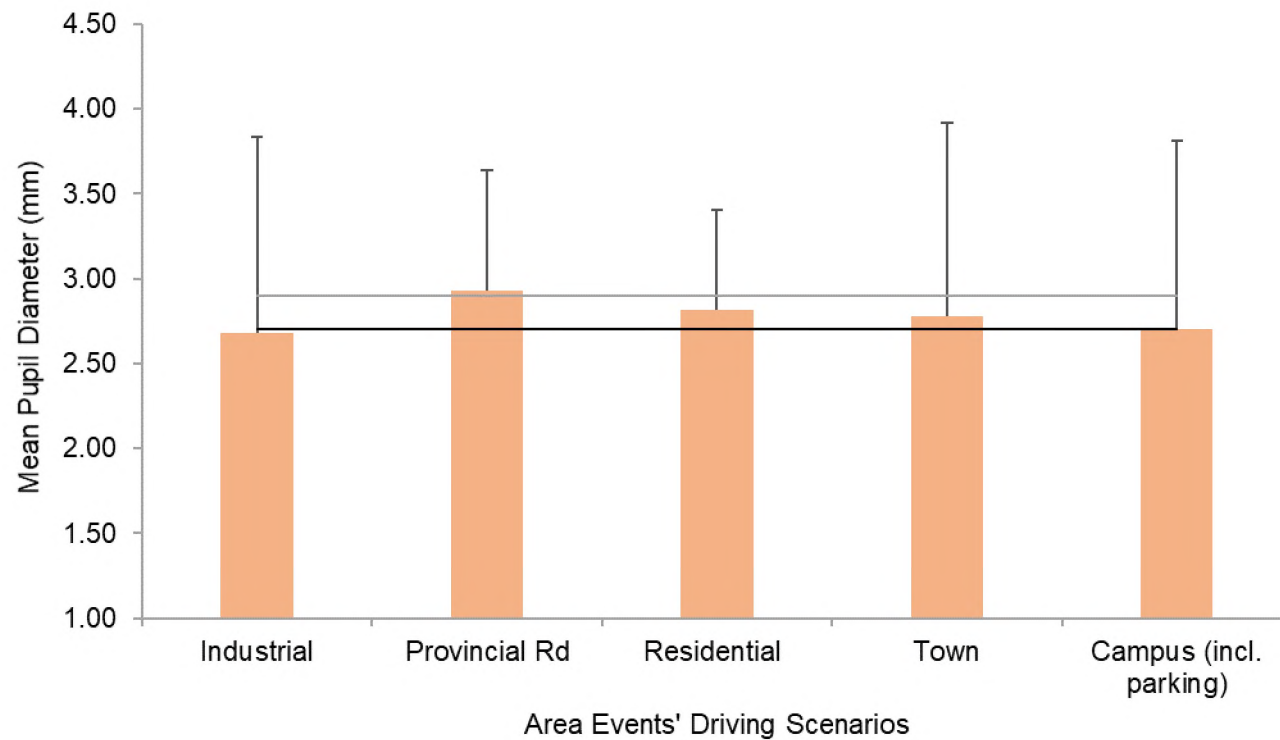


Figure 63: Mean pupil diameter responses to Area Events. Events with means above or equal to the grey line's 2.9 mm and events with means below or equal to the black line's 2.7 mm were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

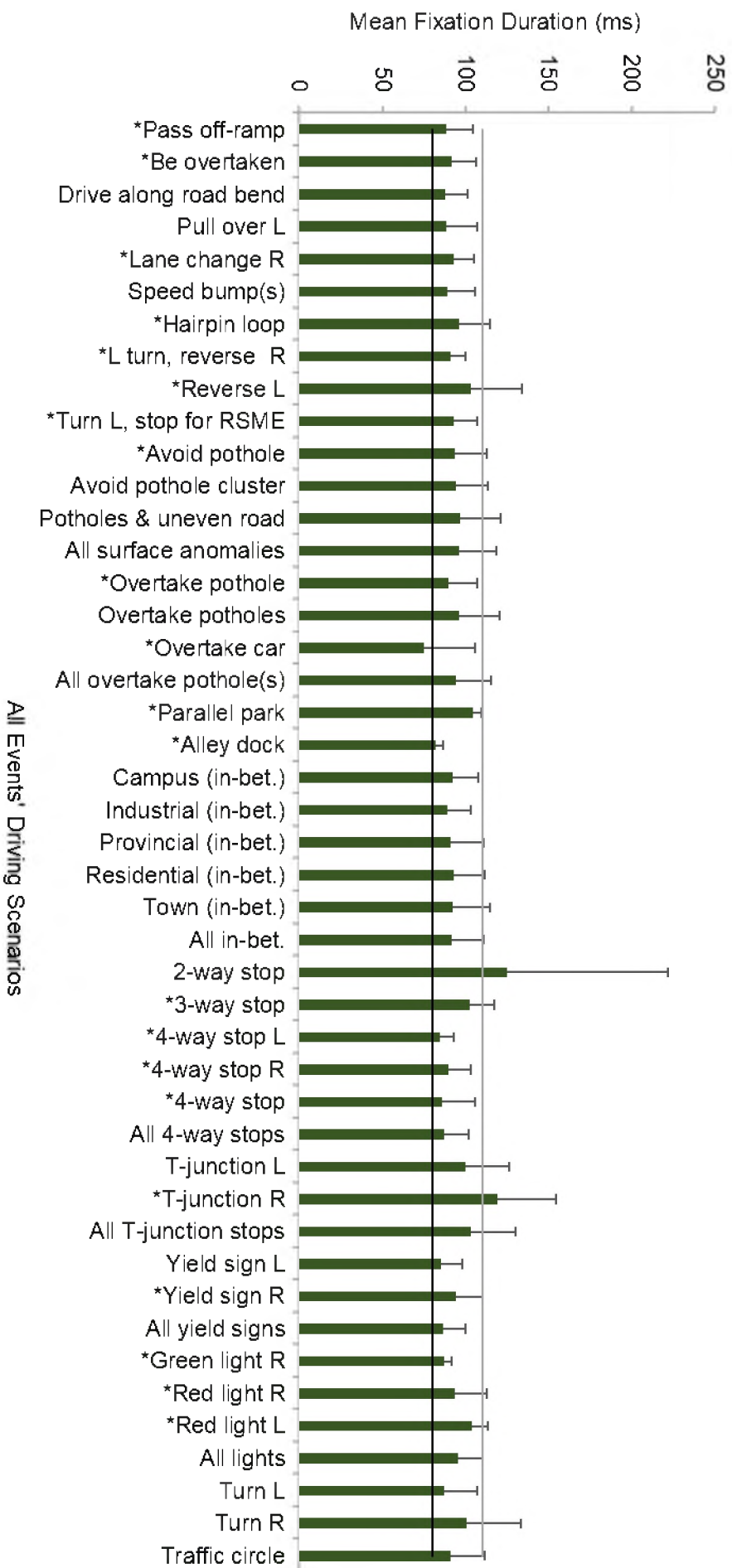


Figure 64: Mean fixation duration responses to All Events' driving scenarios. Events with means above or equal to the grey line's 110 ms and events with means below or equal to the black line's 80 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. \*Scenarios < 10 data points.

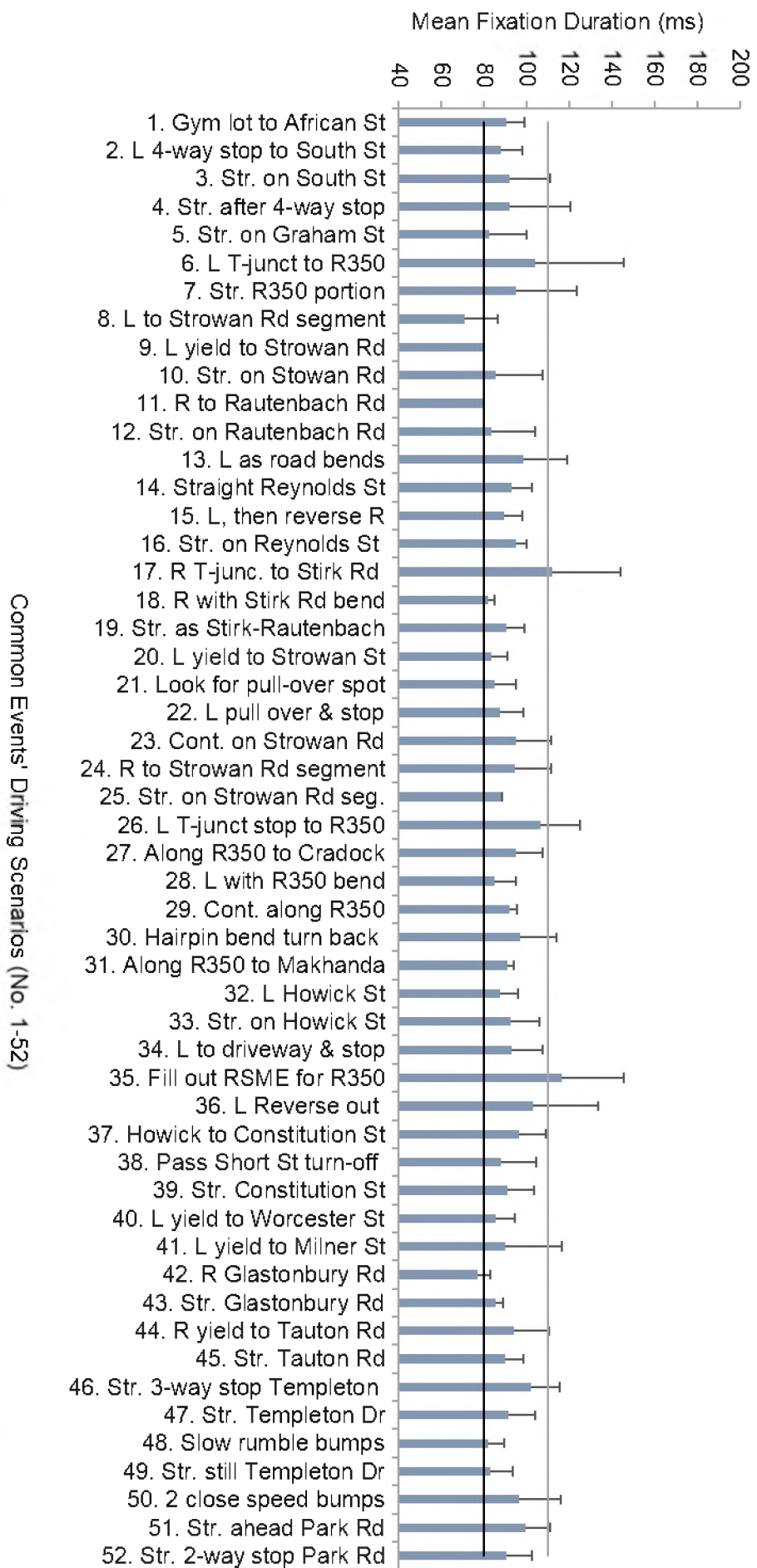


Figure 65: Mean fixation duration responses of Common Events No. 1 to 52. Events with means above or equal to the grey line's 110 ms and events with means below or equal to the black line's 80 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

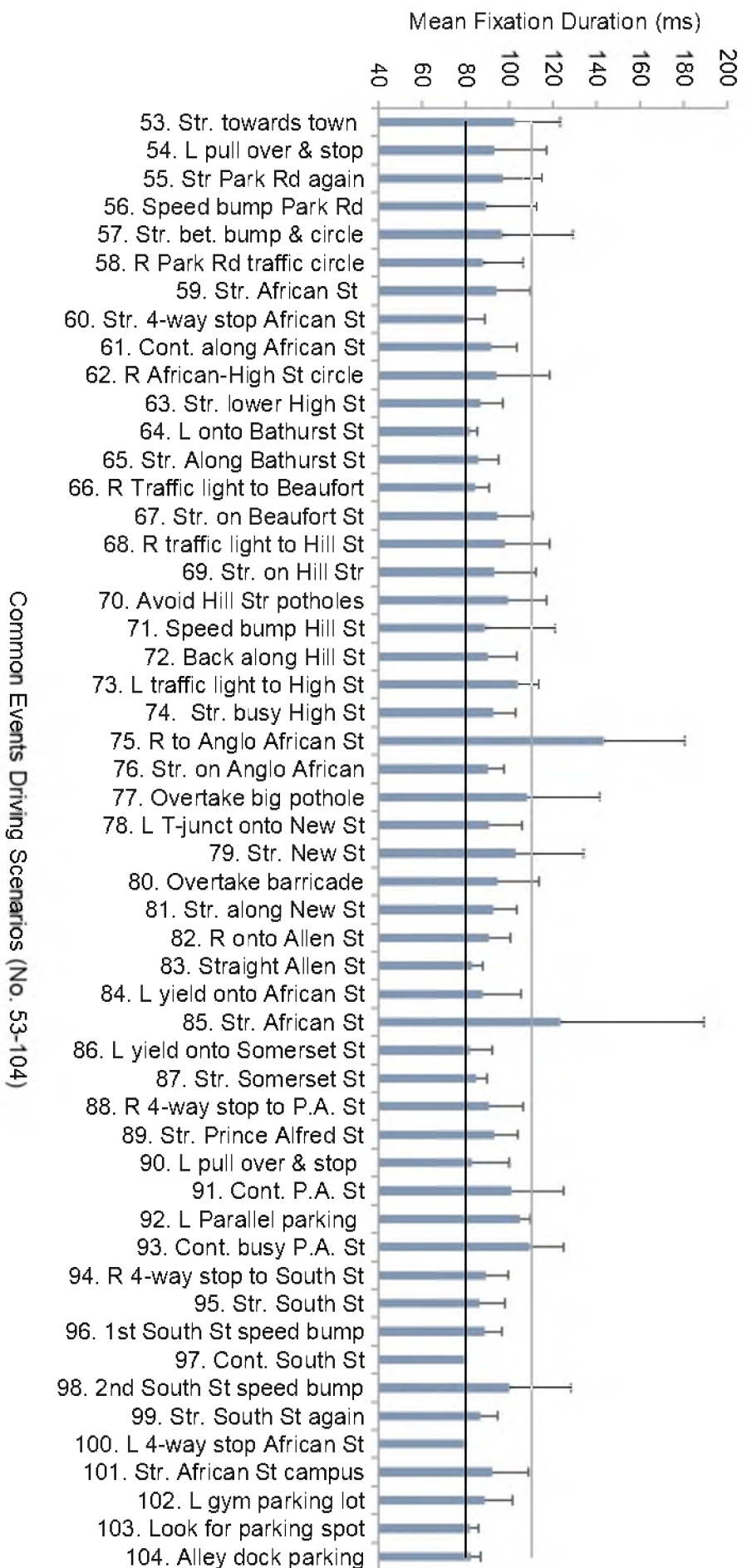


Figure 66: Mean fixation duration responses of Common Events No. 53 to 104. Events with means above or equal to the grey line's 110 ms and events with means below or equal to the black line's 80 ms were considered to be higher mental workload inducing. Error bars denote standard deviation (SD). No. 97 and 100 had a SD of < 0.1. Scenarios consisted of six data points each.

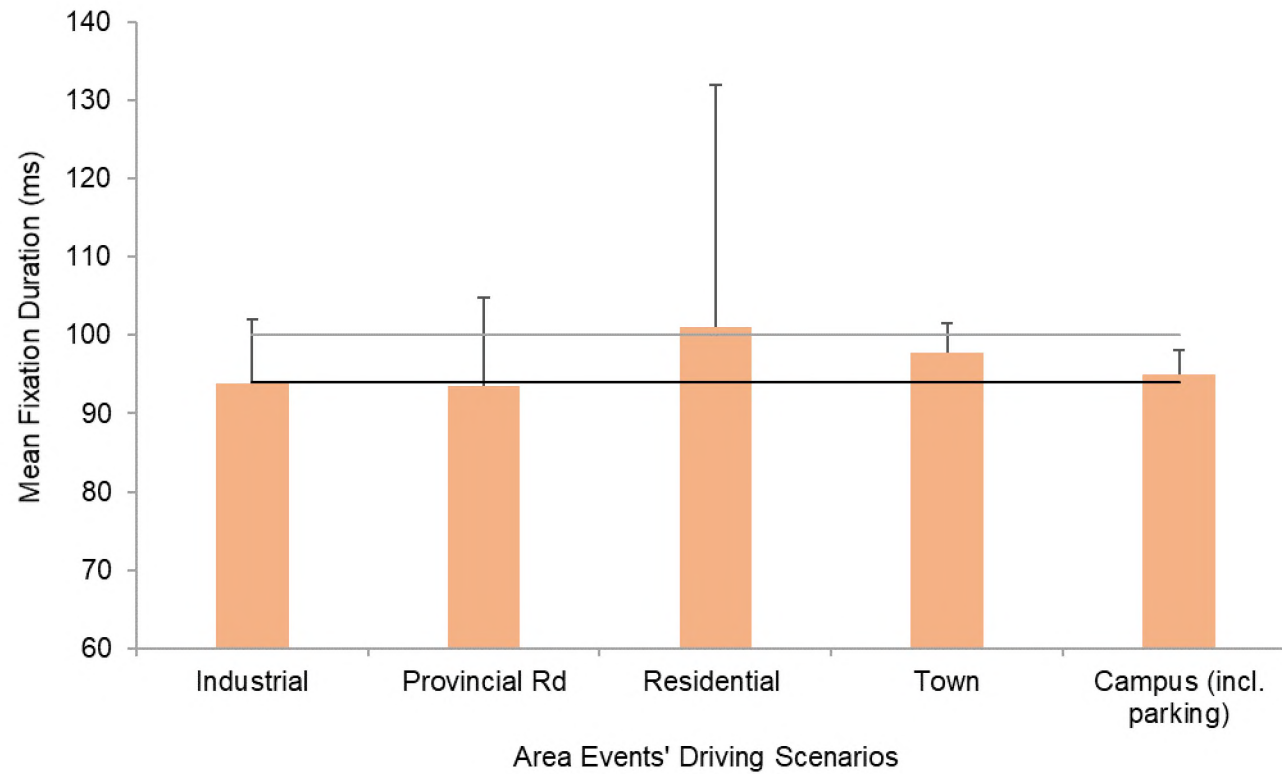


Figure 67: Mean fixation duration responses to Area Events. Events with means above or equal to the grey line's 100 ms and events with means below or equal to the black line's 94 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

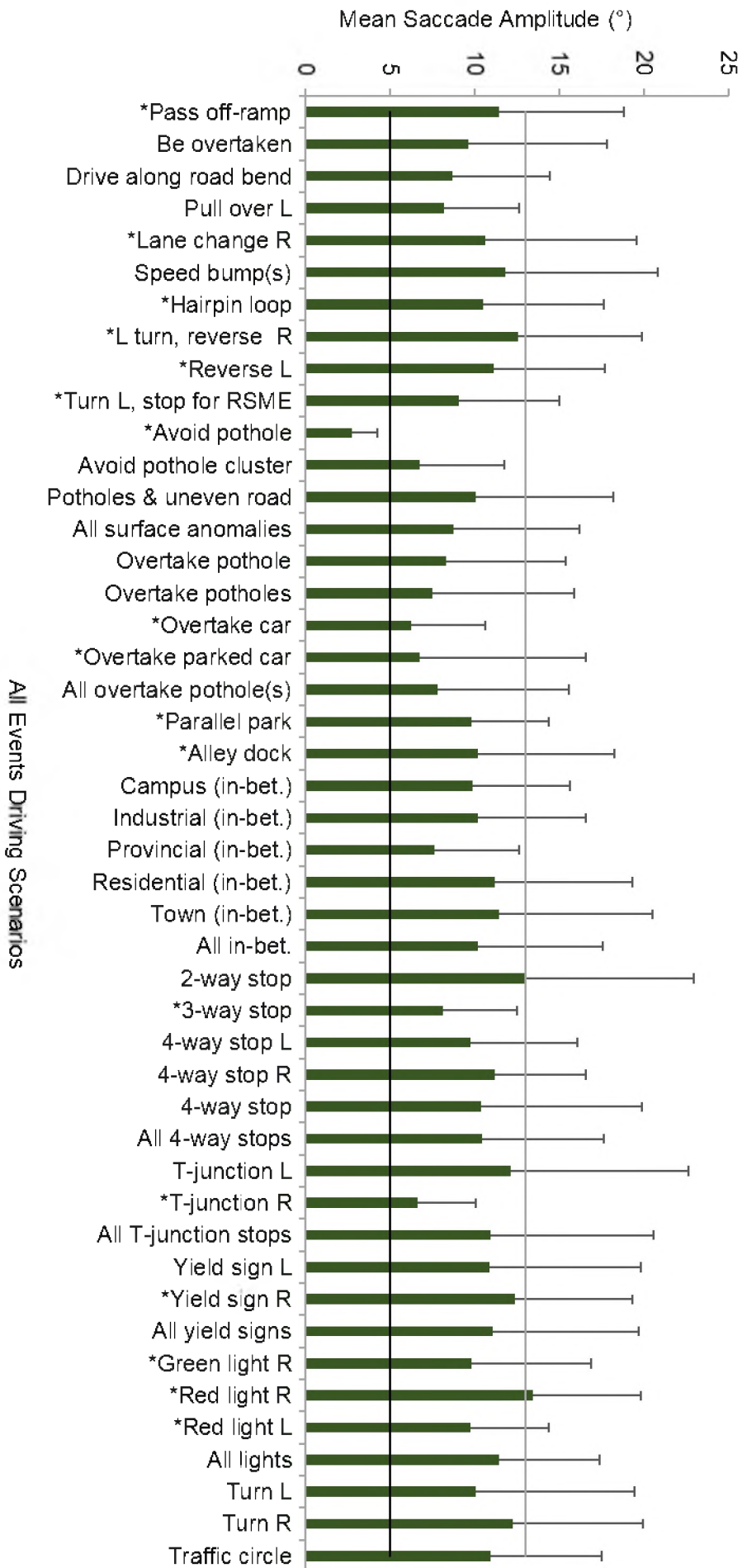


Figure 68: Mean saccade amplitude responses of All Events' driving scenarios. Events with means above or equal to the grey line's 13° and events with means below or equal to the black line's 5° were considered to be higher mental workload inducing. Error bars denote standard deviation. \*Scenarios < 10 data points.

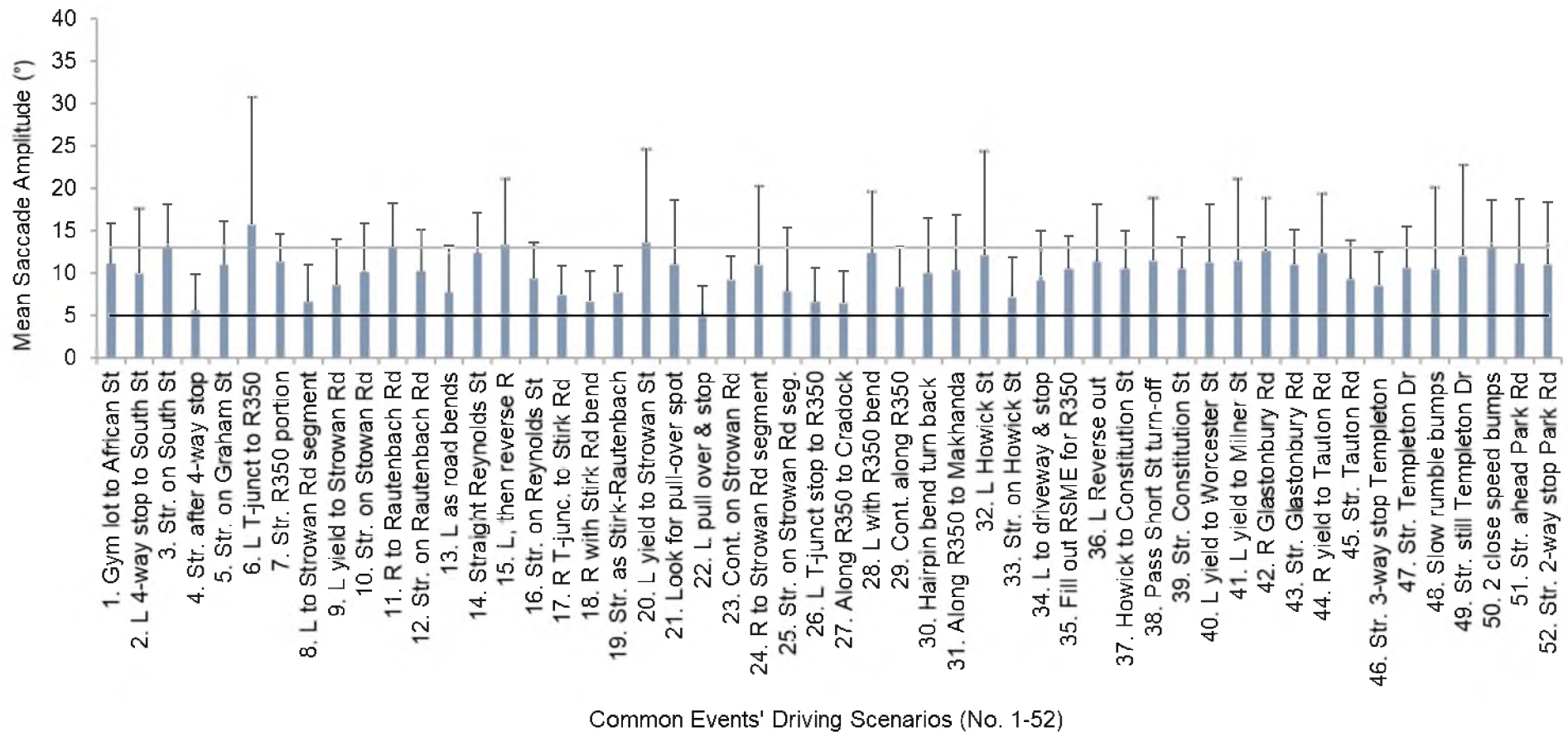


Figure 69: Mean saccade amplitude responses of Common Events No. 1 to 52. Events with means above or equal to the grey line's 13° and events with means below or equal to the black line's 5° were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

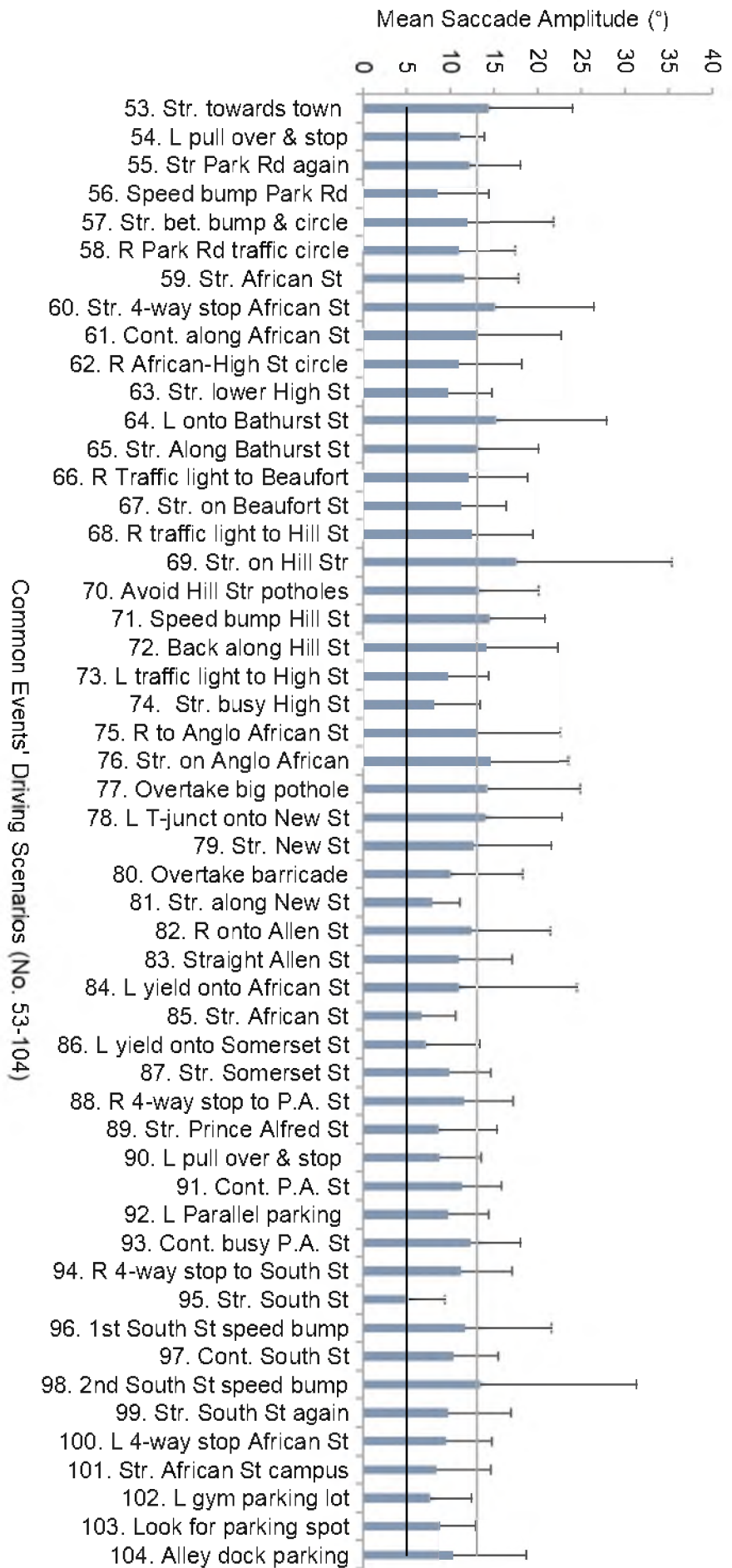


Figure 70: Mean saccade amplitude responses of Common Events No. 53 to 104. Events with means above or equal to the grey line's 13° and events with means below or equal to the black line's 5° were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

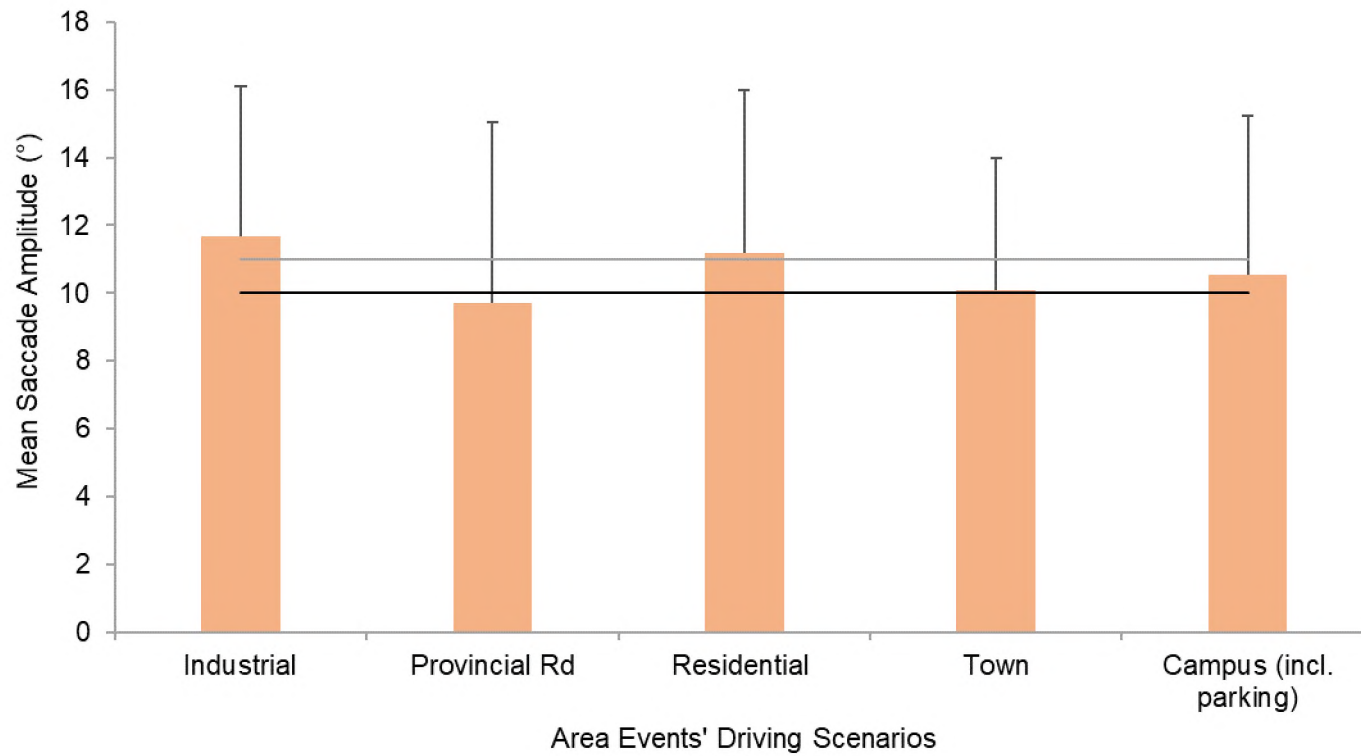


Figure 71: Mean saccade amplitude responses of Area Events. Events with means above or equal to the grey line's 11° and events with means below or equal to the black line's 10° were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

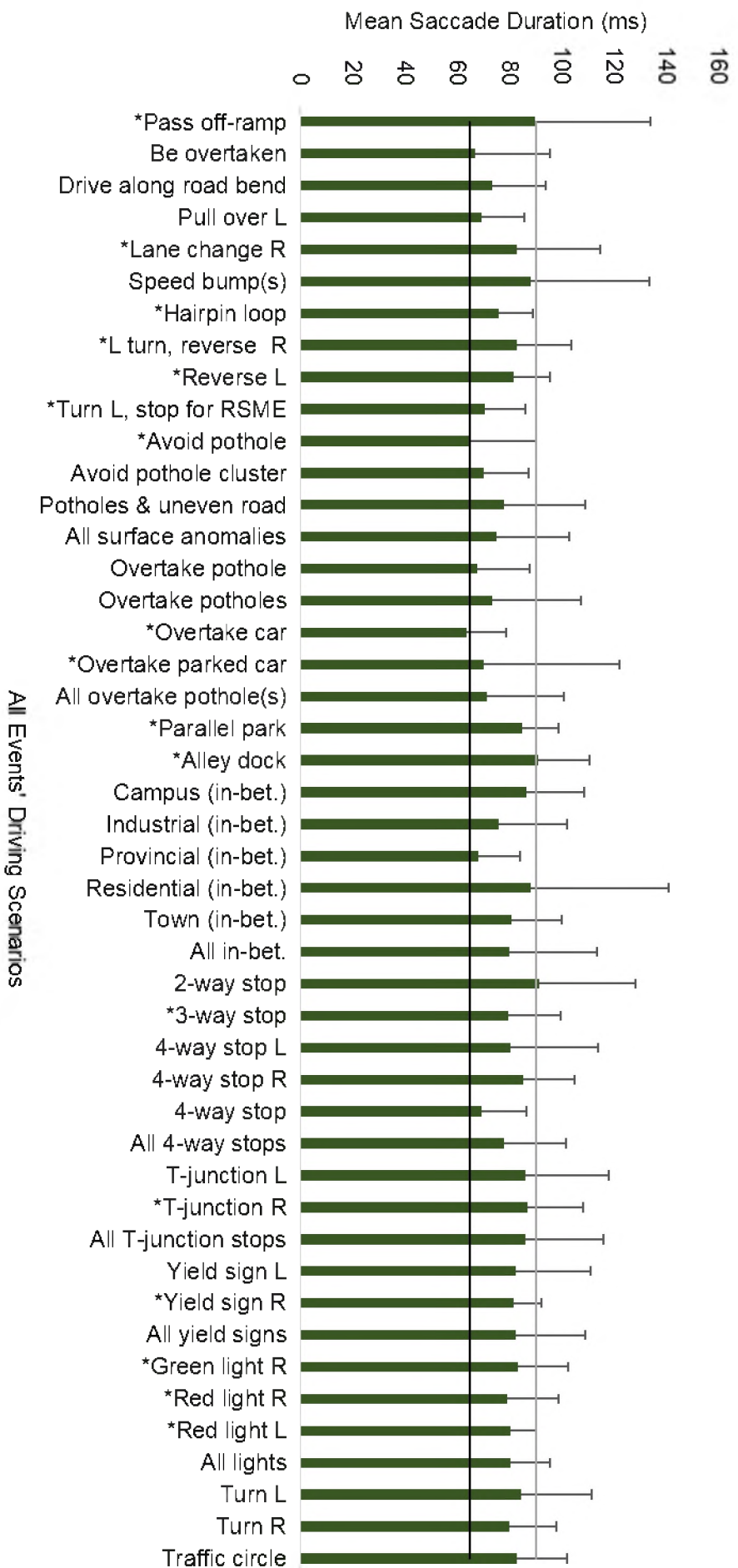


Figure 72: Mean saccade duration responses to All Events' driving scenarios. Events with means above or equal to the grey line's 90 ms and events with means below or equal to the black line's 65 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. \*Scenarios < 10 data points.

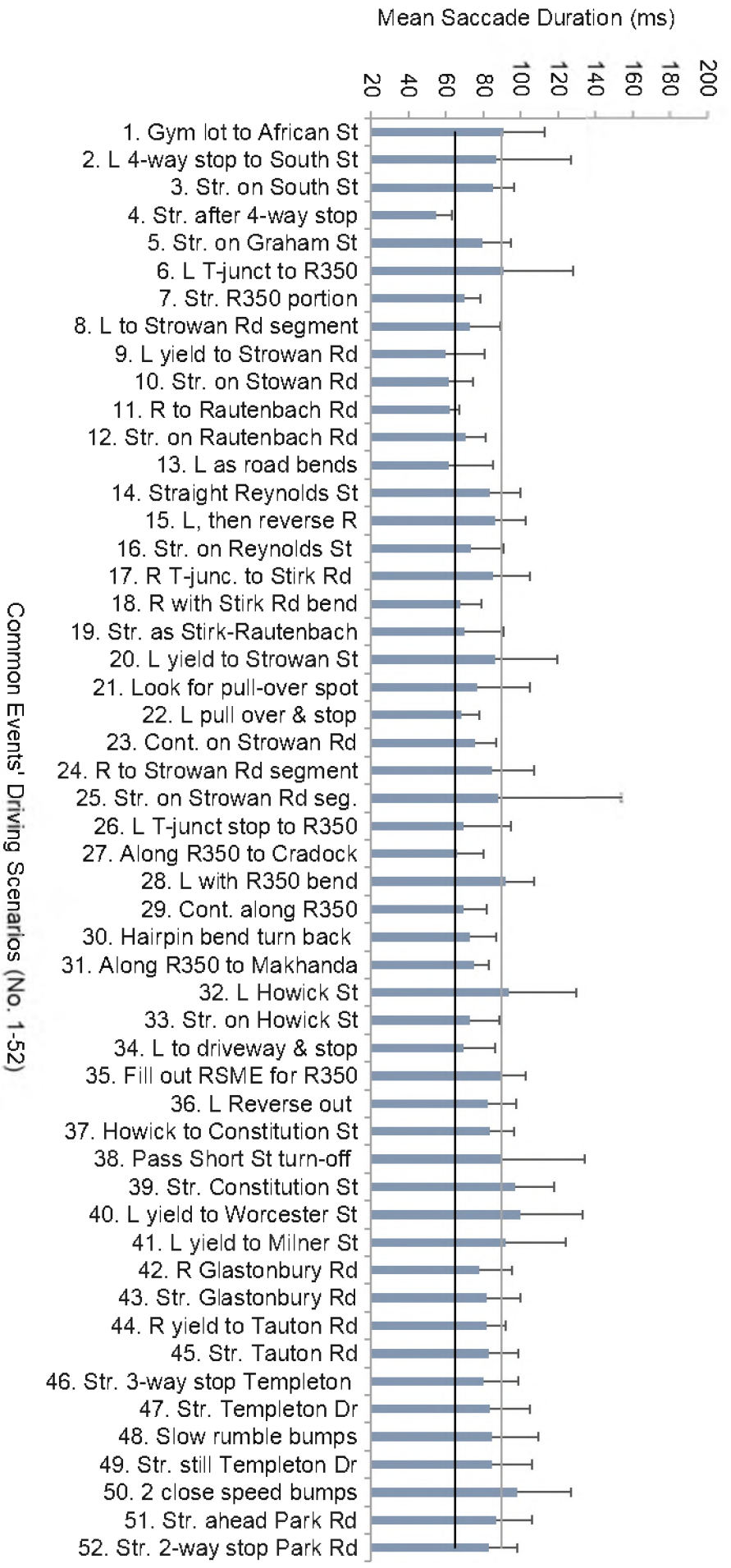


Figure 73: Mean saccade duration responses of Common Events No. 1 to 52. Events with means above or equal to the grey line's 90 ms and events with means below or equal to the black line's 65 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

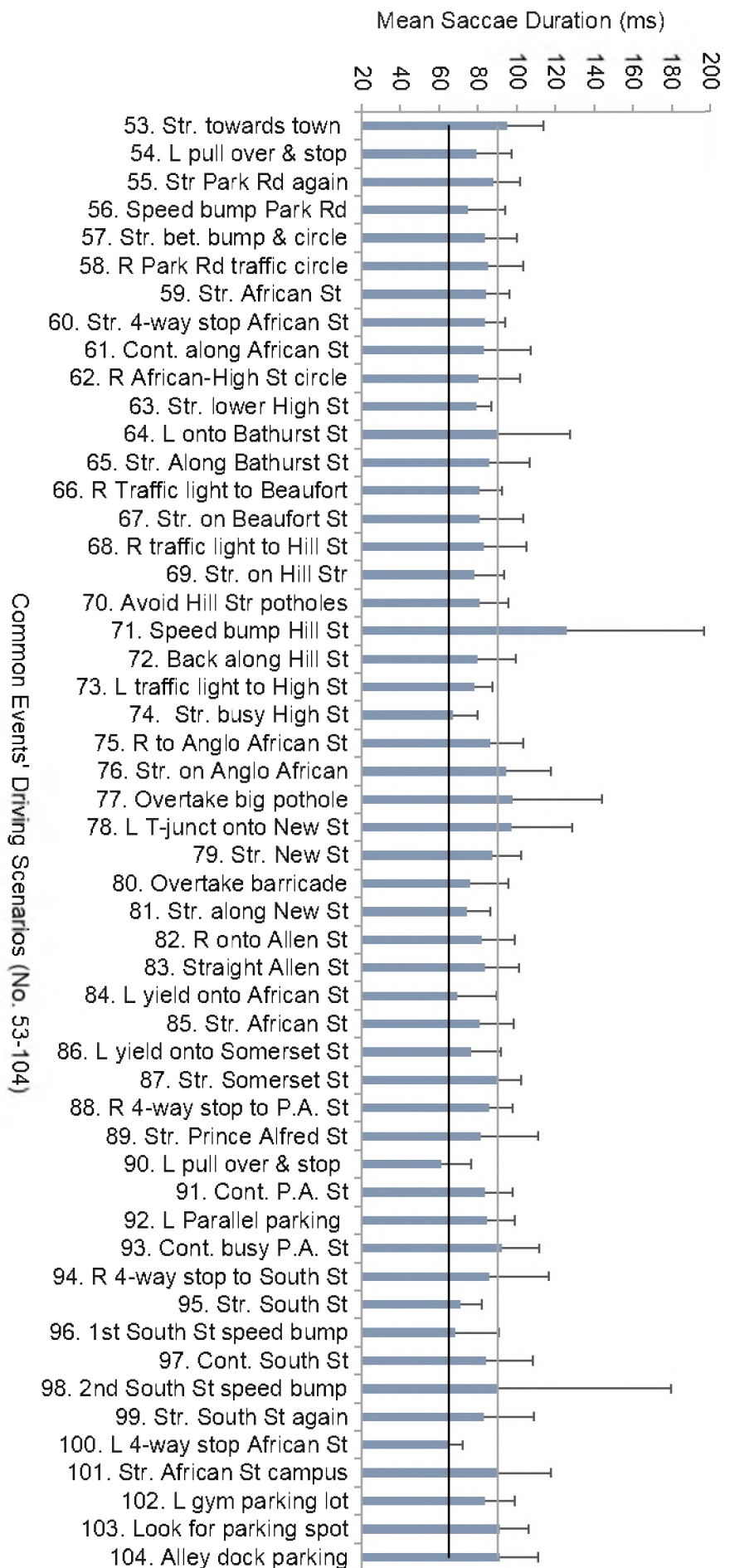


Figure 74: Mean saccade duration responses of Common Events No. 53 to 104. Events with means above or equal to the grey line's 90 ms and events with means below or equal to the black line's 65 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

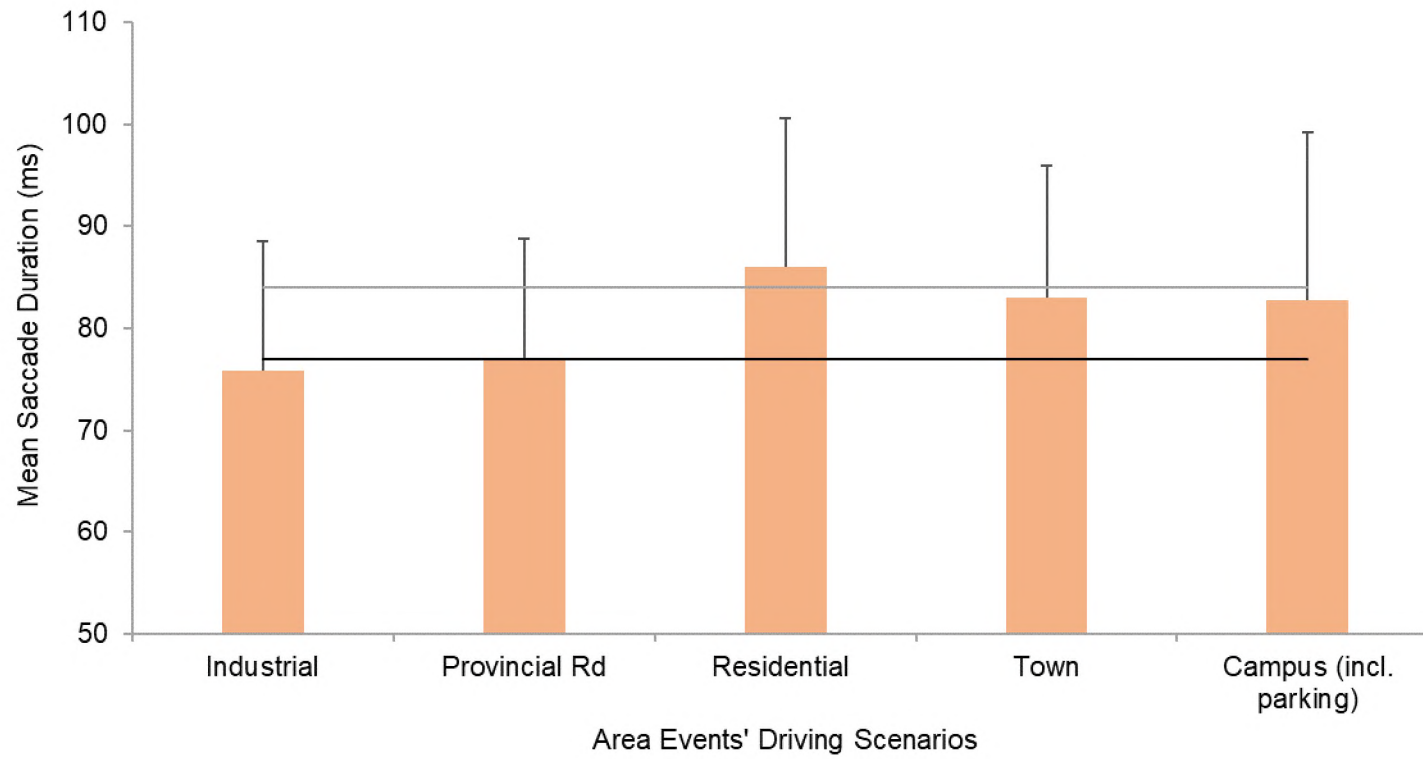


Figure 75: Mean saccade velocity responses of Area Events. Events with means above or equal to the grey line's 84 ms and events with means below or equal to the black line's 77 ms were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

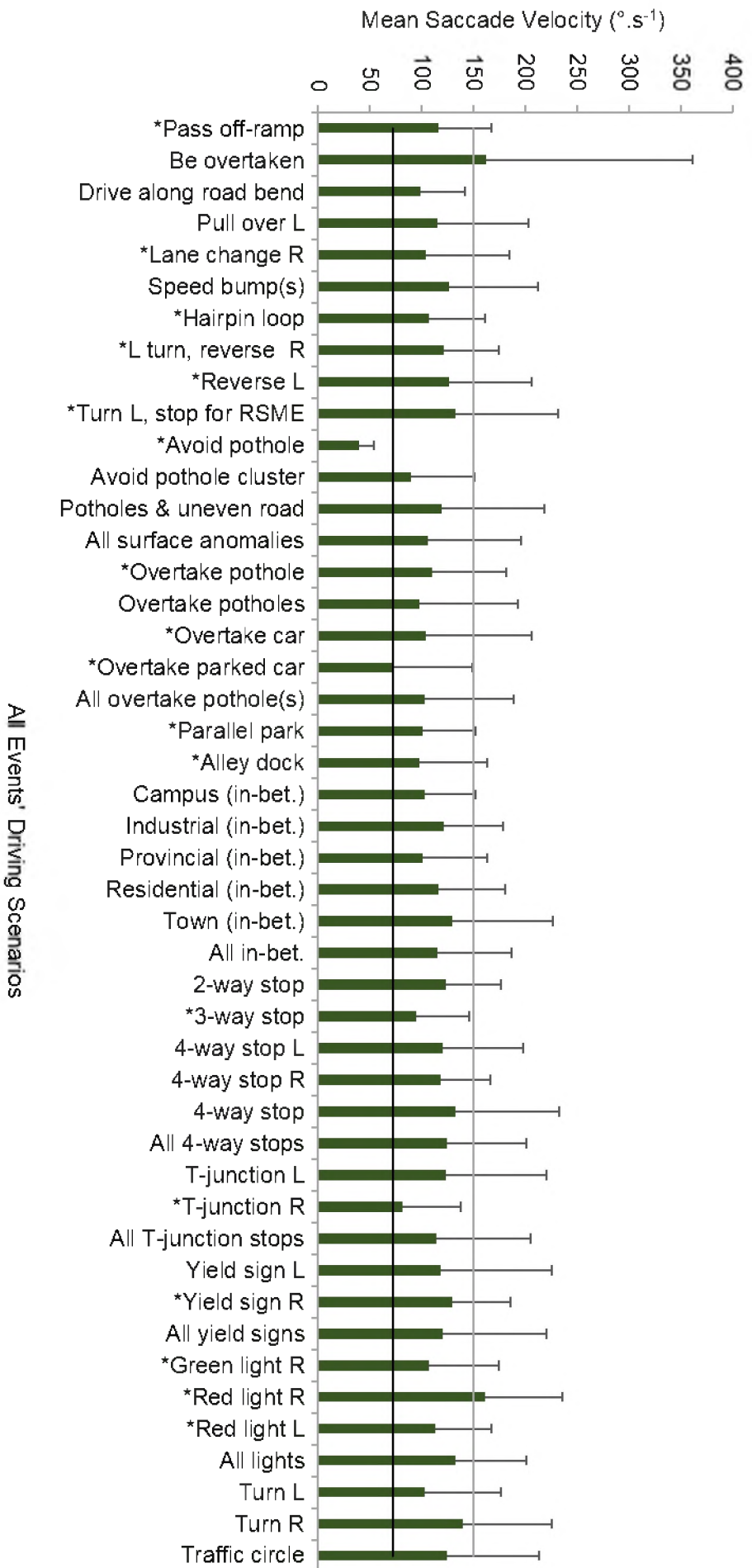


Figure 76: Mean saccade velocity responses to All Events' driving scenarios. Events with means above or equal to the grey line's  $150^{\circ} \cdot s^{-1}$  and events with means below or equal to the black line's  $72^{\circ} \cdot s^{-1}$  were considered to be higher mental workload inducing. Error bars denote standard deviation. \*Scenarios < 10 data points.

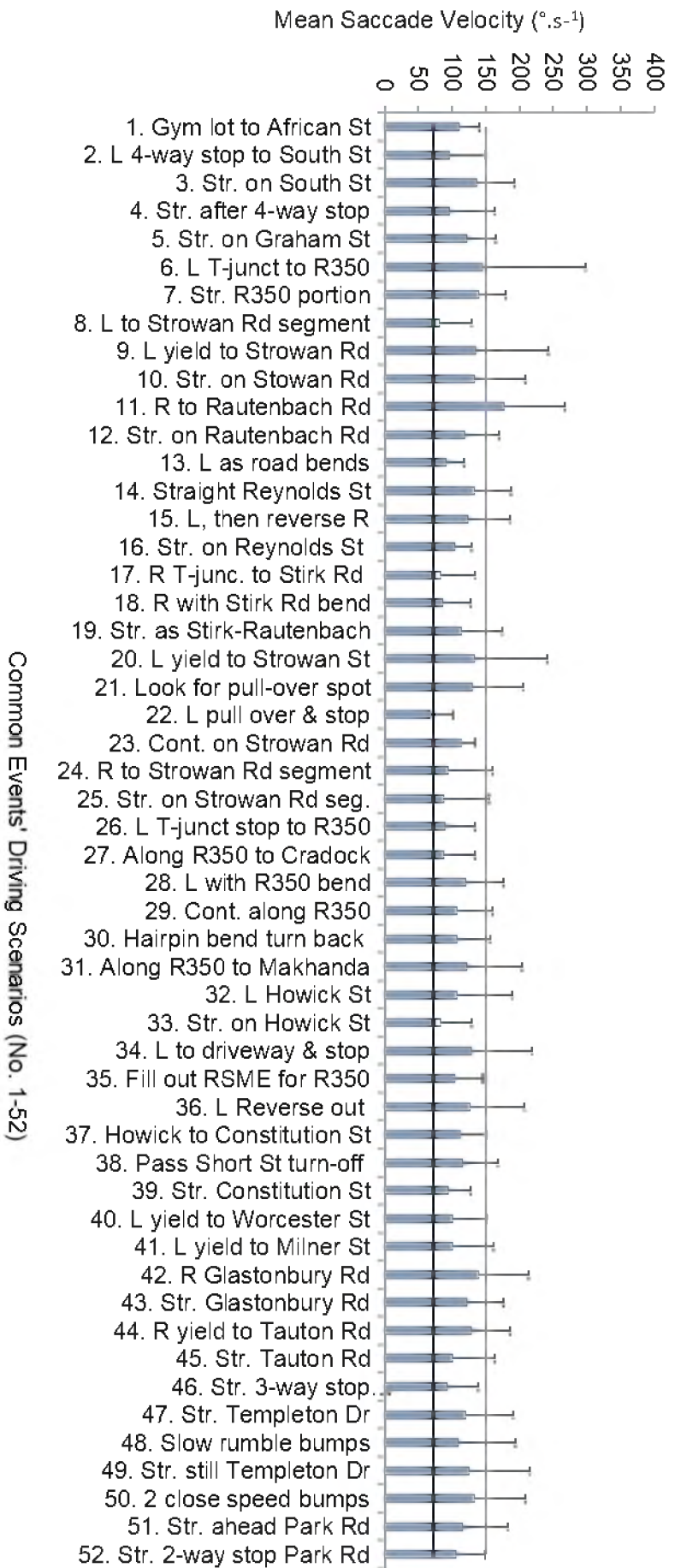


Figure 77: Mean saccade velocity of Common Events No. 1 to 52. Events with means above or equal to the grey line's  $150^{\circ} \cdot s^{-1}$  and events with means below or equal to the black line's  $72^{\circ} \cdot s^{-1}$  were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

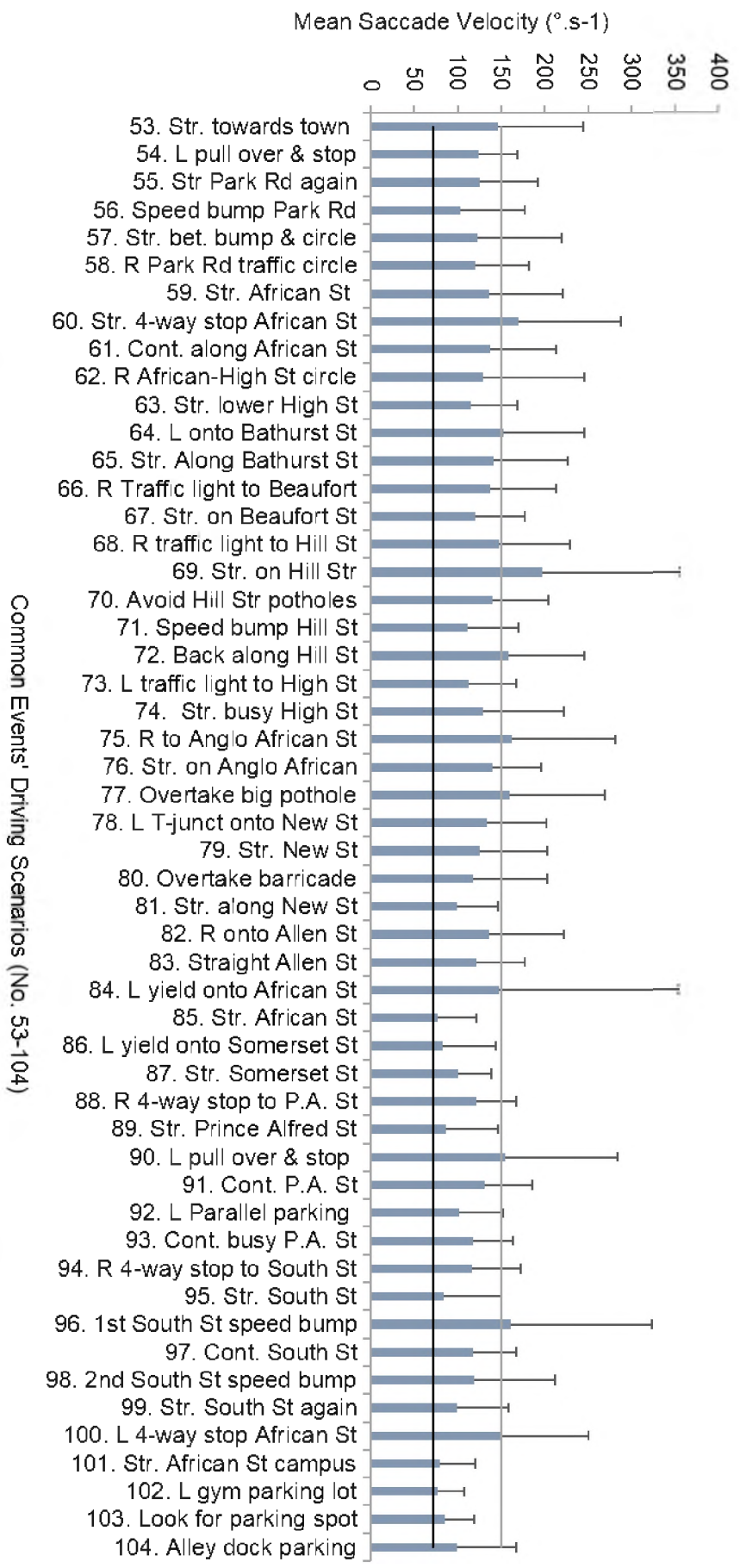


Figure 78: Mean saccade velocity of Common Events No. 53 to 104. Events with means above or equal to the grey line's  $150^{\circ} \cdot s^{-1}$  and events with means below or equal to the black line's  $72^{\circ} \cdot s^{-1}$  were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

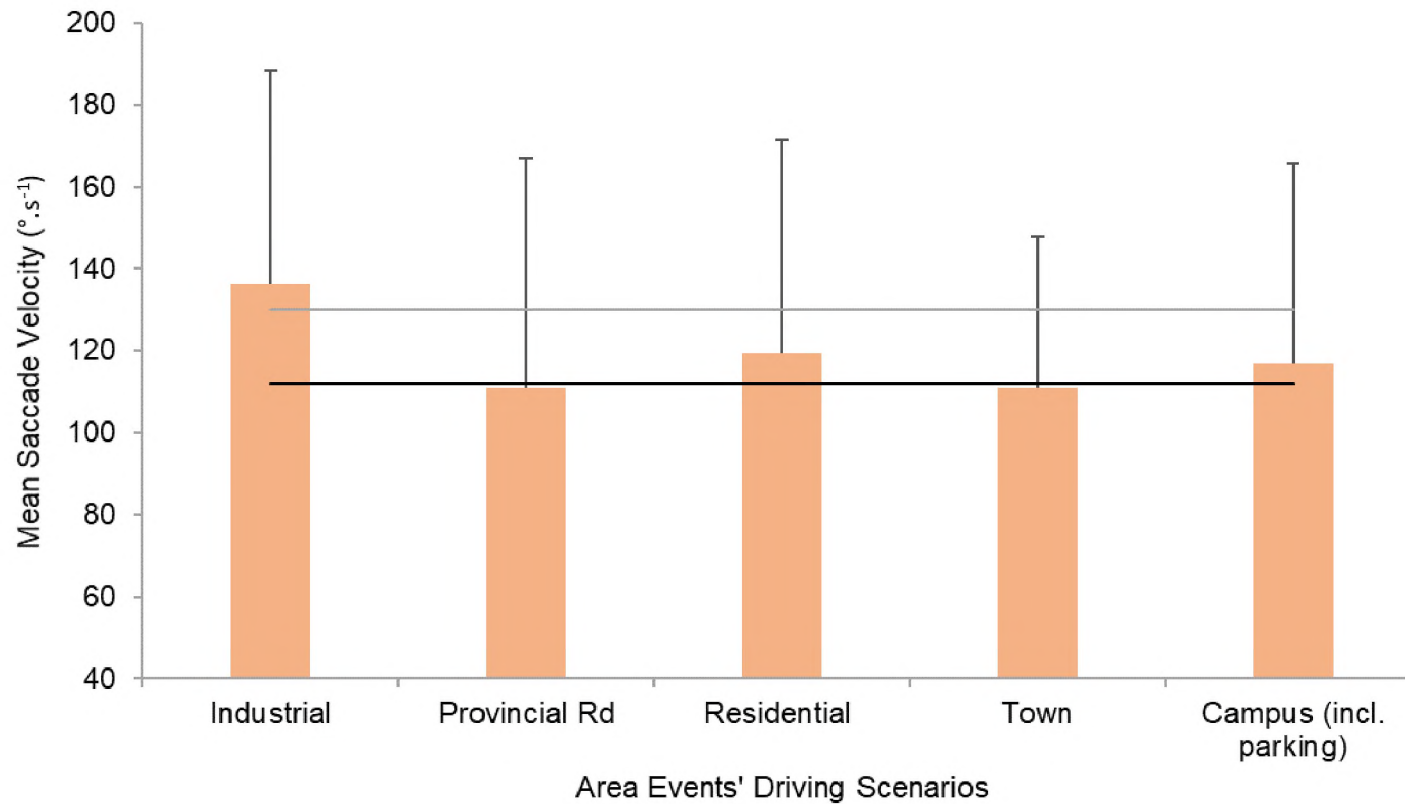


Figure 79: Mean saccade velocity responses of Area Events. Events with means above or equal to the grey line's 130°.s<sup>-1</sup> and events with means below or equal to the black line's 112°.s<sup>-1</sup> were considered to be higher mental workload inducing. Error bars denote standard deviation. Scenarios consisted of six data points each.

## Appendix G: Two-way Frequency Distribution Tables

### G1 All Events

Table X lists the 19 events found to elevate mental workload according to at least one variable. The number of times a mental workload indicator 'identified' a higher mental workload event is totalled in the last row labelled 'Frequency Distribution of MWL Indicators'. The last column labelled 'Frequency Distribution of Events' consists of the total number of times each driving scenario was identified as increasing mental workload.

*Table X: Frequency distribution table of higher mental workload scenarios from the All Events meta-grouping for each measure.*

All Events	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Frequency Distribution of Events
Overtake moving car	1	1		1		1				1				1		1		7
Move around pothole		1			1			1				1		1		1		6
Pass confusing off-ramp		1	1		1						1					1		5
Overtake parked car	1	1	1		1							1						5
Straight at 2-way stop							1		1		1						1	4
Alley dock											1					1		2
Straight at 3-way stop					1											1		2
Right turn T-junction					1		1											2
Maintain speed while being overtaken													1					1

All Events	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Frequency Distribution of Events
Turn L and stop for RSME														1		1		2
Lane change to right		1																1
Hairpin loop					1													1
Reverse to the left																	1	1
Move around several potholes					1													1
Overtake pothole		1																1
Navigate (all directions) 4-way stop streets															1			1
Right at green light													1			1		2
Right after red traffic light									1				1					2
Turn right general									1									1
<b>Frequency Distribution of MWL Indicators</b>	<b>2</b>	<b>6</b>	<b>2</b>	<b>1</b>	<b>7</b>	<b>1</b>	<b>2</b>	<b>1</b>	<b>3</b>	<b>1</b>	<b>3</b>	<b>2</b>	<b>2</b>	<b>4</b>	<b>1</b>	<b>7</b>	<b>2</b>	

## G2 Common Events

The list of Common Events comprises 76 events which spans Table XI across several pages. The numbering is not consecutive as events not exceeding any of the variable's thresholds of higher mental workload were excluded. The numbering is based on that used for all of the Common Events bar graphs of Appendix F.

Events are named according to the actions taken by participants (as instructed by the researcher) as well as its location. Each event was encountered by each participant once along the set route.

The mental workload indicators used for Common Events are the same as those used in the All Events meta-grouping. This is because they are appropriate in the assessment of mental workload for short duration events.

The number of times a mental workload indicator 'identified' a higher mental workload event is totalled in the last row labelled 'Frequency Distribution of MWL Indicators'. The last row labelled 'Frequency Distribution of Events' consists of the total number of times each driving scenario was identified as increasing mental workload.

Table XI: Frequency distribution table of higher mental workload common events.

Common Events	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Freq. Distribution of Events
1. Drive from the gym parking lot on African St until the corner of South St										1				1				2
2. Turn left onto South Street at 4-way stop street.														1				1
3. Driving along the South Street portion between African and Worchester Street.								1										1
4. Drive straight through barely marked 4-way stop street									1									1
6. Turning left from Graham St to the R350								1		1								2
8. Left from the R350 onto Stowan Road					1											1		2

Common Events	Common Events																	
	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Freq. Distribution of Events
9. Turn left at the yield sign at the Strowan Rd bend	1									1								2
10. Driving on Strowan Rd portion by Ikhaia Vet Clinic				1						1						1		3
11. Right turn onto Rautenbach Rd								1	1			1		1				4
12. Drive along stretch of Rautenbach Rd																1		1
13. Curve left along road bend on Rautenbach Rd (entering industrial area)									1									1
15. Change direction by turning left and reversing right (at the Roadworthy building driveway)								1						1				2
16. Drive along poorly tarred Meadery Rd														1				1
17. Right turn at T-junction onto Stirk Rd (from Meadery Rd)						1								1				2
18. Curve right along road bend on Rautenbach road (leaving industrial area)				1												1		2
20. Turn left at yield sign from Rautenbach to Strowan St (leaving industrial area)									1									1

Common Events	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Freq. Distribution of Events	
	21. Looking for a spot to pull-over on Strowan Rd														1				1
22. Pull over and stop on Strowan Rd to take RSMME for the Industrial area								1										1	
25. Drive on short segment of Strowan Rd (before left turn onto the R350)	1	1	1								1				1			1	5
28. Curve left along road bend on R350 provincial main road											1							1	2
30. Perform a hairpin loop to turn the car around.					1														1
32. Turn left into Howick St										1	1								2
33. Driving on Howick Street													1						1
35. Filling in RSMME of the Provincial road drive						1					1								2
38. Driving past confusing off-ramp		1	1								1				1	1			6
39. Driving along Constitution street					1						1								2
40. Left turn at yield sign from Constitution St onto Worcester St											1								1

Common Events	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Freq. Distribution of Events
	41. Left turn at yield sign from Worcester St onto Milner St										1							
42. Right turn to Glastonbury Rd						1												1
43. Driving along most of Glastonbury Rd with several potholes														1	1			1
44. Right turn at yield sign from Glastonbury to Taunton Rd				1										1	1			2
47. Drive ahead on Templeton Drive														1	1			1
48. Slow for rumble bumps on Templeton Drive				1											1			1
49. Drive between the rumble bump and speed bump portions on Templeton Drive				1										1				2
50. Slow for speed bumps on Templeton Drive (corner Miles Street)								1			1							2
52. Drive straight at the 2-way stop street on Park Rd				1														1
53. Driving down Park road which approaches Kingswood School								1			1			1				3

Common Events																		
	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Freq. Distribution of Events
54. Pull over for RSME reading on Park Rd				1														1
56. Reduce speed for speed bump on Park Road				1										1				2
57. Driving on section between speed bump and traffic circle on Park Rd				1														1
59. Drive along African Street towards the 4-way stop street				1														1
60. Drive straight after 4-way stop street on the corner of African and Caldecott St				1	1			1				1		1				5
61. Drive ahead on African Street towards the next traffic circle.								1										1
62. Turn right at the African-High St traffic circle														1				1
64. Turn left from lower High St to Bathurst St				1				1		1		1		1				5
65. Drive ahead on Bathurst Street								1										1
66. Turn right at green traffic light from Bathurst St onto Beaufort St																1		1

Common Events																		
	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Freq. Distribution of Events
69. Driving onto Hill Street which has many potholes and parked cars		1	1					1				1						4
70. Move around several larger potholes on Hill St								1						1				2
71. Reduce speed for speed bump on Hill St								1		1								2
72. Driving along Hill St after speed bump and before traffic light intersection								1				1						2
74. Driving along busy upper High St																1	1	1
75. Turn right on High St to Anglo African St.						1		1				1						3
76. Driving down narrow and busy Anglo African St								1		1				1			1	4
77. Overtake large pothole at the end of Anglo African St								1		1		1						3
78. Left turn at stop street T-junction from Anglo African to New St								1		1				1				3
80. Overtake large barricaded pothole on New St		1	1											1				3
81. Driving along busy New St																1	1	1

Common Events	Common Events																	
	Heart Rate Frequency	Heart Rate Variability: SDNN	Heart Rate Variability: rMSSD	Pupil Size [LOWER]	Pupil Size [UPPER]	Fixation Duration [LOWER]	Fixation Duration [UPPER]	Saccade Amplitude [LOWER]	Saccade Amplitude [UPPER]	Saccade Duration [LOWER]	Saccade Duration [UPPER]	Saccade Velocity [LOWER]	Saccade Velocity [UPPER]	Eye Blink Frequency [LOWER]	Eye Blink Frequency [UPPER]	Eye Blink Duration [LOWER]	Eye Blink Duration [UPPER]	Freq. Distribution of Events
82. Right turn from New onto Allen St																	1	1
85. Driving along African Street (after left turn from Allen St.)						1											1	2
87. Drive ahead on Somerset St.										1		1						2
88. Right turn at 4-way stop street from Somerset St to Prince Alfred Rd.														1				1
90. Pullover left outside drama dept (Prince Alfred) for RSM E									1			1						2
92. Perform parallel parking to the left on Prince Alfred Street on campus						1												1
93. Driving along Prince Alfred St with many parked cars and pedestrians around											1							1
94. Right turn at 4-way stop from Prince Alfred St to South St															1		1	2
95. Driving onto South Street with several small potholes							1								1	1		4
96. Reduce speed for 1st speed bump on South St													1					2



### G3 Area Events

The orientation of Table XII differs from previous tables. The events, consisting of the five areas comprising the set route, are listed at the top of each column. The dependent variables are listed at the beginning of each row. Consequently, the mental workload indicator's total frequency is given in the last column. The last row labelled 'Frequency Distribution of Events' consists of the total number of times each driving scenario was identified as increasing mental workload.

HRV spectral analysis and RSME are additional mental workload indicators which were not used in the All and Common Events meta-groups. These variables could be used for Area Events as the events are longer in duration.

*Table XII: Frequency distribution table of higher MWL areas according to each measure.*

Area Events MWL Indicators	Industrial Main	Provincial Main	Residential Main	Town Main	Campus End (incl. parking)	MWL Indicators Frequency Distribution
Heart Rate Frequency	1				1	2
Heart Rate Variability: SDNN	1					1
Heart Rate Variability: rMSSD	1					1
Heart Rate Variability: high frequency power			1		1	2
Heart Rate Variability: low frequency power		1				1
Heart Rate Variability: LF power relative to (LF + HF)					1	1
Pupil Size [LOWER]	1				1	2
Pupil Size [UPPER]		1				1

Area Events MWL Indicators	Industrial Main	Provincial Main	Residential Main	Town Main	Campus End (incl. parking)	MWL Indicators Frequency Distribution
Fixation Duration [LOWER]		1				1
Fixation Duration [UPPER]			1			1
Saccade Amplitude [LOWER]		1		1		2
Saccade Amplitude [UPPER]	1		1			2
Saccade Duration [LOWER]	1	1				2
Saccade Duration [UPPER]			1			1
Saccade Velocity [LOWER]		1		1		2
Saccade Velocity [UPPER]	1					1
Eye Blink Frequency [LOWER]					1	1
Eye Blink Frequency [UPPER]	1		1			2
Eye Blink Duration [LOWER]		1				1
Eye Blink Duration [UPPER]	1					1
RSME		1		1		2
<b>Frequency Distribution of Events</b>	<b>9</b>	<b>8</b>	<b>5</b>	<b>3</b>	<b>5</b>	