An objective measure to quantify discomfort in long duration driving

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An Objective Measure to Quantify Discomfort in Long Duration Driving

By

George Mark Sammonds

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University

October 2015

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Abstract
In recent years increased emphasis has been placed on improving seat comfort in automobiles. This is partly due to research showing that prolonged driving is associated with increased risk of musculoskeletal disorders, but largely because driver comfort is now viewed as an increasingly important aspect of the competitive marketing of vehicles.

Driving is firmly cemented as a major part of most people’s daily life across the world and people are now spending more time in their vehicles than ever before. As urban congestion continues to rise, commuting distances and durations will progressively increase, subjecting drivers to the risks of long duration driving more often. Consequently the automotive industry has invested in designing seats that perform better under increased usage durations and ergonomics has played a vital role in the design of new seats. However, the ability to design a successful seat relies heavily on the capacity to accurately evaluate the comfort of a vehicle seat and one major issue that has been highlighted with the current state of automotive ergonomics research is the standardisation of comfort evaluation techniques.

This research aimed to tackle these issues by investigating the effects of long duration driving on discomfort and the range factors associated with driver discomfort. Furthermore, the ultimate goal of this research was develop and evaluate a novel objective measure of driver discomfort that focused on driver seat fidgets and movements (SFMs) with the aim of standardising discomfort evaluation within the automotive industry.

Three laboratory studies and one field observation were conducted to address these aims whereby subjective and objective evaluations of discomfort were conducted during long term driving (ranging from 60 - 140 minutes). The results determined that a measure of driver SFMs can be effectively implemented into long duration driving trials to evaluate the effects of long term driving and vibration exposure on driver discomfort and subsequently used to make accurate predictions of overall discomfort. Large positive correlations have been determined between measures of SFMs and subjective ratings of overall discomfort ($r^2 > 0.9$, $P < 0.05$)
and the SFM method has been successfully repeated under a range of driving conditions.

Driver seat fidget and movement (SFM) frequency is shown to significantly increase congruently with subjective ratings over the duration of a long term drive as drivers seek to cope with increased discomfort. It is proposed that drivers will record movements in the vehicle seat when discomfort reaches a threshold that is consciously or unconsciously perceived and as the duration of driving accrues, drivers will reach this threshold with increased frequency. A measure of both SFM frequency and total accumulative SFMs have been shown to accurately predict discomfort ratings and provides the basis for discomfort evaluations to be made via remote monitoring, removing the need for subjective assessment.

During a long term drive, there becomes a point upon which improvements in seat design become ineffective as extended duration driving will result in discomfort regardless of how well the seat has been designed. It was shown that drivers will move in the vehicle seat to cope with increased discomfort and in addition, another method of combatting the negative effects of long term driving was investigated. Subjective and objective evaluation determined that breaks from driving will reduce discomfort both immediately and upon completion of a long term drive. Furthermore, these benefits were increased when drivers left the vehicle seat as discomfort was ‘reset’ when drivers took a 10 minute walk. Walking during a break from driving can be considered the ultimate SFM. Drivers are recommended to plan breaks from driving when conducting a long duration journey in order to minimise discomfort and when taking a break, drivers should take a walk rather than remain seated in the vehicle.
Acknowledgements

Firstly I would like to express my sincere gratitude to my supervisors, Professor Neil Mansfield and Dr Mike Fray. Their enthusiasm towards the subject area and depth of knowledge has been both inspiring and an invaluable resource. This research would not have been possible without their unwavering support and the time that Neil and Mike have invested in me. The opportunities provided by my supervisors have been fundamental to my learning experience but also vital in making my research at Loughborough so enjoyable. My extensive involvement in research practice and the trust placed in me to travel and experience new cultures has been unforgettable, for that I am truly grateful.

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I would also like to mention the volunteers who were so kind as to participate in the experiments conducted during this research and willingly subject themselves to the gruelling long duration driving that they were required to undertake.

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CHAPTER 1

General Introduction

Throughout the automotive vehicle design process many different disciplines are integrated in order to develop the final product, from designers, body engineers, chassis engineers, powertrain engineers and manufacturing engineers to product planners, market researchers, electronic engineers and ergonomics engineers (Bhise, 2011). This is due to the large range of requirements associated with vehicle design and can only be successful with coordination and simultaneous consideration of these many requirements; from customer requirements, engineering functional requirements and manufacturing requirements to business requirements and government regulatory requirements (Bhise, 2011). Trade-offs between the different systems of the vehicle is expected however, these systems should not only function well, but must satisfy the customers who purchase and use the products as a pleasurable experience for the end user is the ultimate aim.

The field of ergonomics is essential in ensuring that the desired experience is provided for the user. During the design process it is vital that ergonomists work in conjunction with the many different vehicle design teams; from management teams, exterior design teams and interior design teams to package engineering teams, instrument panel teams and seat design teams, to ensure that all ergonomic requirements and issues are considered at the earliest possible opportunity in the design process and resolved to accommodate the needs of the users; the drivers, passengers, assembly personnel, maintenance, and service engineers (Kolich, 2008).

Ergonomics is described as a multidisciplinary science that encompasses all the fields that have information about the human (Bhise, 2011), including psychology, anthropometry, biomechanics, anatomy, physiology and psychophysics. This involves studying human characteristics, capabilities and limitations and applying this knowledge to inform the design process and evaluate the success of the equipment and systems that people use, ranging from user improvements in safety, comfort, convenience, performance and efficiency. The ultimate goal of ergonomics
in the design process is to successfully design a product or system that achieves the best possible fit for the intended user group and the automotive industry has been a pioneer in the implementation of ergonomic principles as it is seen as a significant method to gain a lead in the market (Kolich, 2008).

Since the fuel economy crisis of the 1970s, the automotive industry has placed more emphasis on ergonomics and human factors in order to satisfy both energy-saving and comfort and convenience needs (Bhise, 2011). The inclusion of ergonomics principles in the design process has continued to grow and although ergonomics has played a role in almost every aspect of vehicle design, one significant area that has been largely affected by ergonomics is seat design.

The automobile has developed into a universal means of personal transportation and ergonomics has played a large role in focusing the priorities of seat design upon the occupant’s comfort and health (Reynolds, 1993). Most current seats appear to be designed more in keeping with ergonomic recommendations than seats from previous decades (Reed, 2000). Due to the growth of the automotive market, the diversity in seat design has increased, creating a range of unique seat designs that are in fact designed to satisfy similar design goals. Diversity in seat design is a result of the need to match seat and vehicle purpose (Reynolds, 1993) as there are many uses for automobiles today ranging from family and personal sedans to minivans and off-road vehicles to sports cars.

In recent years, there has been an increased emphasis on seat comfort in automobiles (Reed, 2000), partly because of the research showing that prolonged driving is associated with increased risk of lumbar disc herniation amongst other musculoskeletal disorders (Kelsey & Hardy, 1975), but largely because driver comfort has been viewed as an increasingly important aspect of the competitive marketing of vehicles (Reed, 2000). In order to successfully design a comfortable seat that matches the vehicle purpose, understanding of the occupant must be obtained and implemented into the design process. Furthermore, the design of a seat relies heavily on the ability to evaluate the success of the seat in fitting its intended purpose. Ergonomics plays a substantial role in testing and evaluating
automobile seats before these are deemed fit for mass production and release to the market, however automobile seat evaluation is a discipline yet to be standardised.

Driving is now firmly cemented as a major part of most peoples’ daily life across the world and vast increases in the number of drivers on the road has been witnessed over recent years. People are now spending more time in their vehicles than ever before with average commute durations showing large increases. The field of seating design must account for these escalations and emphasis must be placed on the ability of a seat to perform for longer durations with ergonomics playing a substantial role in the design and evaluation of seating in long term driving. Vehicle seat manufacturers are now required to apply more attention to a seats performance with increased usage and longer usage durations as a successful seat is now essential in making gains in the market.

1.1 Aims of the Thesis

The overall aim of the thesis is to further the ergonomic understanding and quantification of driver discomfort, particularly in long duration driving. The research will address this aim by investigating two factors; firstly this research will aim to examine the factors that affect long term driver discomfort with specific regard to prolonged vibration exposure. Secondly this research will aim enhance the vehicle seat evaluation process by developing and determining the success of a novel objective measure of driver discomfort to be implemented into the automotive industry by testing the proposed method in a range of conditions.

The following research questions lead to the development of the research objectives:

- ‘How is driver discomfort influenced by greatly extended journey durations and the associated long term exposure to vibration?’
- ‘Is there an accurate objective measure of driver discomfort that can be implemented over long duration driving?’
• ‘Can driver behaviour combat the effects of discomfort experienced in long
term driving?’
• ‘How does this knowledge impact the previous research into the field of
driver discomfort?’

Therefore the aims of this research are to:

1. Determine the effects of long duration driving on driver discomfort and gain
a greater understanding of the dynamic and temporal factors surrounding
long term driver discomfort.
2. Investigate a novel objective measure of discomfort to be implemented into
the automotive industry and determine the success of this method in
accurately predicting drivers’ perceived discomfort.
3. To determine how driver behaviour can influence driver discomfort and how
implementing the correct behaviour during a long duration drive can help
combat the effects of discomfort associated with long duration driving.

1.2 Thesis Structure

The thesis is divided into 9 chapters, a basic outline of the chapters and their
contents is provided in Figure 1. The research is comprised of an introduction and
aims of the thesis, a literature review, equipment and analysis review, 3 laboratory
studies and one field observation which all address particular issues highlighted
within the field of seat comfort evaluation and discomfort associated with long
term driving. These are then summarised by a general discussion chapter and
conclusions chapter in which it will be determined whether the aims of the thesis
have been achieved. Within the thesis there is a progression from the initial
investigation of a novel method of seat comfort evaluation to more specific
validation and testing of the proposed method against different variables under
varying conditions. This is further described by a brief chapter by chapter summary
in Section 1.3.
1.3 Chapter Summary

The first goal of this research was to review and summarise the ergonomics and human factors knowledge surrounding seat design, seat comfort/discomfort and how to successfully evaluate seat design. This is described by Chapter 2 and it was evident when conducting this review that a substantial amount and wide range of research had previously been conducted in this field with varying levels of success. Despite this range of research, a number of areas are highlighted by Chapter 2 in which more research could substantially develop the knowledge available in the field and in which little to no work has been published. These included the effect of...
long duration driving and vibration exposure on driver discomfort and how researchers can accurately and effectively measure driver discomfort over the duration of a long term drive via objective measures. Chapter 3 then describes the experimental design, general equipment and analysis techniques that were used in the various studies that combine to form this research in order to address some of the issues highlighted by Chapter 2.

The first study, described by Chapter 4, involved a laboratory experiment that investigated the effect of long duration driving and vibration exposure on driver discomfort; the longest study of its kind in the literature. Furthermore, this study aimed to evaluate the success of a novel measure of driver discomfort that had shown promise during the work conducted in Chapter 2 and Chapter 3, as no successful objective measure of driver discomfort had previously been established in the literature. This study included both subjective and objective measurements of driver discomfort and comparisons were made between the two measures in addition to analysing each individually.

The results show that driver discomfort increased across the duration of a long duration drive; however the increase in discomfort did not maintain a linear progression. These findings support the previous findings in the literature although suggest that some improvements may need to be made to the models of driver discomfort proposed by the literature. Furthermore, the results determine a strong correlation between subjective ratings of driver discomfort and the novel objective measure of discomfort implemented in the study suggesting that the method can be useful in accurately predicting perceived driver discomfort via remote measurements.

In order to explore the success of the method further and build upon the knowledge regarding driver discomfort in long duration driving obtained in Chapter 4, the study presented in Chapter 5 aimed to recreate the first study in greatly differed conditions, with a different laboratory and sample. Therefore, the study was conducted at Kinki University in Japan and used Japanese subjects, with a
different laboratory with different equipment, such as the seat design and driving simulator, and altered the vibration exposure.

The results showed that driver discomfort is affected by a number of factors as discomfort was shown to increase at a quicker rate to that observed in Chapter 4 and supports the previous theories proposed in the literature regarding factors affecting long term driver discomfort. Furthermore, this study validates the objective measure of driver discomfort implemented in Chapter 4 as similarities are observed between the studies regarding correlation strength and the relationship between subjective and objective measurements of discomfort. This suggests that the method is highly successful as similarities are observed despite the alterations in design of the experiment and the increase in discomfort gradient, implying that the method is easily repeatable.

As the novel objective method was shown to be effectively repeated and implemented in different laboratory conditions, the subsequent stage of analysis was to determine the sensitivity of the method and investigate whether the method can be applied when analysing acute variations in discomfort. In addition, another question proposed by examining the literature was whether breaks from driving can help to combat the effects of driver discomfort due to long duration driving. Therefore it was determined that a study investigating the effects of breaks from driving on driver discomfort would be conducted that again included both subjective and objective assessment (Chapter 7).

However, before the experiment in Chapter 7 was conducted it was crucial to execute a study that acted as a real world check to inform the design of the experiment. Therefore, the study reported in Chapter 6 involved a field observation conducted at a UK service station whereby covert observations of drivers and passengers undertaking a break from a long duration drive were carried out. In particular, the duration of which drivers took a break from driving was recorded in addition to the type of activity drivers partook in. The results of this study were compared against the literature and the proposed guidelines available for drivers when undertaking a long duration drive to further the knowledge of driver
behaviour during long duration driving but most importantly, the results of this study were used to help inform the design of the study conducted in Chapter 7.

Therefore, Chapter 7 involved a laboratory study that aimed to evaluate the effect of breaks from driving on driver discomfort during long duration driving with specific reference to the effect of activity during a break from driving. The study aimed to build upon the findings of Chapter 4 and Chapter 5 and utilised the findings of Chapter 6 to design a study with a number of conditions. Participants were assessed subjectively across 3 conditions whereby each condition required participants to perform a different activity during a break from driving implemented into the design of the experiment. Additionally, participants were objectively assessed in order to further determine to success of the novel method and investigate the ability of the method to distinguish acute variations in discomfort across conditions.

The results of the study showed that driver discomfort during long duration driving can be effectively combatted by implementing a break from driving into a long duration drive. Furthermore, the study determined that the type of activity undertaken during a break from a long duration drive can have implications on the magnitude of discomfort reduction attained by drivers. These findings are described as having significant implications on the guidelines available for drivers regarding breaks from driving, as the benefits of breaks in terms of discomfort reduction had not previously been well defined in the findings of Chapter 2. This study proposes recommendations for drivers undertaking a long duration drive regarding the minimisation of discomfort.

Furthermore, the study in Chapter 7 further validates the novel objective measure of discomfort as a strong correlation is again observed between subjective ratings of discomfort and the objective measurements. The results also determine the ability of the method in measuring acute changes in discomfort as the objective measurements are shown to accurately depict differences observed between the conditions investigated.
Chapter 8 and Chapter 9 discuss the combined results obtained in the various laboratory studies and literature review (Chapter 2). These chapters discuss the contributions to the knowledge surrounding driver discomfort during long duration driving as to satisfy the first main aim of the thesis, as well as a detailed discussion of the success of the novel objective measure of discomfort, as to satisfy the second main aim of the thesis. The ability of the method to be implemented into the field of driver discomfort is discussed and a training form is presented whereby the method is defined in detail for future researchers who may wish to implement the same methodology and develop the findings. Within Chapter 9 any limitations of the research presented in this thesis are discussed and recommendations for future research are considered.

The thesis is concluded by Chapter 10 in which the conclusions of the thesis are summarised. This chapter determines the contributions made by the research to the existing knowledge surrounding long duration driver discomfort analysis and determines the success of the research by referring to the original aims of the thesis. This chapter is finalised by discussing the wider implications of this research in the field of discomfort.

1.4 Publications

A number of publications have been published that are based on the results obtained during this research (Table 1). In total, 5 conference papers and 1 journal paper have been submitted. In addition, 1 journal paper has been published that included the authors’ previous research that helped form the basis upon which this research has been carried out and should be mentioned.
<table>
<thead>
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<th>Paper Title</th>
<th>Journal / Conference</th>
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<tr>
<td>The Effect of Foam Composition on Long Term Car Seat Discomfort</td>
<td>48th UK Conference on Human Responses to Vibration</td>
<td>2013</td>
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<tr>
<td>Overall Car Seat Discomfort Onset during Long Duration Driving</td>
<td>5th International Conference on Applied Human Factors and Ergonomics</td>
<td>2014</td>
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<td>Effectiveness of Taking Breaks during Long Term Driving: Benefits of Leaving the Vehicle and Sitting in Another Seat</td>
<td>49th UK Conference on Human Responses to Vibration</td>
<td>2014</td>
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<td>Effectiveness of Taking Breaks during Long Term Driving: Benefits of Leaving the Vehicle and Taking a Walk</td>
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<td>2014</td>
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<tr>
<td>Effect of Long Term Driving on Driver Discomfort in Japanese Drivers – A Simulator Study</td>
<td>23rd Japan Conference on Human Response to Vibration</td>
<td>2015</td>
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CHAPTER 2

Topic Area Literature Review

This literature review describes the context surrounding the proposed research topic and discusses previous research into the field of long term driver discomfort and long term exposure to whole-body vibration, presenting the current state of knowledge in the field. Furthermore this section will discuss the previous methods of quantifying driver discomfort and debates the success of different measures of driver discomfort, including both subjective and objective assessment.

2.1 Context

In the UK, driving is now firmly cemented as a fundamental part of most people’s lives over the age of 17 and it has recently been said that the average Britons have become so reliant on their cars that most spend more than one working day (10 hours) every week driving (NTS, 2013). This compares to just 3.7 hours walking and the average yearly total mileage comes to 7,413 miles with an average cost of £1,078. The National Travel Survey 2013 stated that since the early 1970s the average distance people travel per year has increased by 47% and is mainly due to an increase in average trip lengths, which have risen by 52% since the early 1970s. The average trip length increased by 12% from 6.4 miles in 1995/97 to 7.1 miles in 2013 with over 80% of journeys with a distance of 25 miles or more conducted by car or van. This suggests that drivers are spending longer in their vehicle and the importance of research into the effects of long term driving is of growing importance.

Due to the cost of living and evolving transportation and technology advancements, it is now becoming more economically viable for people to live in suburban regions and drive to economic centres for employment (Guiness & Bradshaw, 1985; Herbert, 1972). Therefore, people are spending more time in their vehicle commuting and as urban congestion continues to rise, commuting distances and times will progressively increase, subjecting drivers to the risks of long duration driving more frequently. This can not only have negative implications on the driver, as longer
driving durations will place the individual at an increased risk of discomfort and developing musculoskeletal disorders (Gyi & Porter, 1998; Porter & Gyi, 2002) but may also effect companies on a wider scale as long duration driving has been shown to negatively affect employee attendance (Chen et al., 2005). It is speculated that injury claims will continue to rise as daily commuting time increases, highlighting the need for research into the possible risk factors associated with long duration driver discomfort.

It has been shown that for drivers who spent 4 hours a day or more driving as part of their profession, their probability of developing lower back pain was increased by 1.6% in comparison with populations who did not drive as part of their profession (Walsh et al. 1989). Drivers who drove over 25,000 kilometres per year as part of their job ‘always’ or ‘often’ experienced lower back discomfort during driving (Gyi & Porter, 1998) and furthermore, commuters who travelled distances of over 25,000 kilometres per year missed on average, 24.4 days of work per year due to prolonged driving (Porter & Gyi, 2002).

There are clear benefits of improving seat design and reducing driver discomfort experienced in long duration driving and ergonomics plays a vital role in developing the seat design process. Manufacturers have begun to place a large emphasis on the importance of research into seat comfort as a comfortable seat is now viewed as playing an essential role in gaining a lead in the market.

Research in the field of seating comfort has been conducted for over 100 years and chair makers have worked for even longer to optimise the comfort of their designs (Reed, 2000). Akerblom (1948) summarised the work that preceded his own in a thorough review and since then vast amounts of research has been conducted that aimed to provide recommendations for seat design to enhance comfort. Much of the literature is focused on office and industrial seating rather than automotive seating, however research into automotive seating has shown more development in recent years and many of the theories and recommendations determined in the wider field of seating comfort are relevant when applied to automotive seating design.
Automobile seat comfort research, often practised by individuals with a background in ergonomics, has now been developed as an applied science and is motivated by, firstly, a practical concern for the health and well-being of the consumer and, secondly, the view that comfort is a product differentiator in the eyes of the end consumer (Kolich, 2008). Until now, research investigating the interaction between a driver and a seat is limited, with even less research dedicated to investigations of driver discomfort during prolonged driving. The discipline has a tendency to be reactive to current needs rather than proactive (Kolich, 2008), negatively affecting the development of the discipline and there are many contradictory findings throughout the literature rather than a standardised foundation. However, if research into the evaluation of seat comfort can be standardised and research continues to develop the understanding of the interaction between the driver and a seat during long duration driving, this may play a major role in ensuring better design for the future.

2.2 Establishing a Definition of Comfort and Discomfort

‘Are you sitting comfortably?’ This may not be as simple a question as one may expect. Perhaps a better question would be ‘are you experiencing any discomfort?’ In the field of automotive ergonomics there has been much deliberation surrounding the terms ‘comfort’ and ‘discomfort’ and this has led to disagreement as to how the terms may relate to one another. Comfort has become a requirement for automotive manufacturers (Kolich et al., 2004) and yet there is no widely accepted definition of sitting comfort or discomfort (Leuder, 1983; Helander & Zhang, 1997).

In common parlance, comfort may refer to both comfort and discomfort (Zhang et al., 1996), suggesting that both terms are part of the same entity. Likewise, many describe comfort and discomfort as opposing ends of a continuous scale. However, others have argued that comfort and discomfort should be treated as two different constructs with different sets of underlying factors (De Looze et al., 2003).
2.2.1 Defining Comfort & Discomfort

When investigating driver comfort or discomfort it is important that the meaning of these terms is fully understood and defined, ensuring that the investigator has a clear definition of how they perceive the terms. The uncertainty that surrounds the definition of comfort and discomfort has had a negative impact on the discipline as there is no standard for how authors view the terms and has provoked much debate in the literature (Richards, 1980; Lueder, 1983; Zhang et al., 1996). The aim of this section is to investigate the definitions proposed in the literature and determine how the terms will be viewed throughout the duration of this research.

2.2.1.1 Defining Comfort

Webster’s 3rd International Dictionary of the English Language (1981, unabridged) defines comfort as a ‘state or feeling of having relief, encouragement or enjoyment’. This clearly describes a positive emotion; however Slater (1985) attempted a more specific definition: ‘a pleasant state of physiological, psychological and physical harmony between a human and the environment’ as described in Table 2.

Slater’s (1985) definition implies that comfort is a multifaceted construct influenced by multiple factors and suggests that comfort and discomfort can be interpreted as different entities as it fails to address its relationship with discomfort. However these definitions do not state whether or not comfort can be quantified.

Many authors have supported that comfort is indeed a separate construct from discomfort as comfort relates more to ‘aesthetics’ and ‘a natural feeling’ (Shackel et al., 1969). Speaking precisely the term comfort can be associated with feelings of relaxation, well-being, satisfaction, aesthetics and luxury. Kleeman (1981) observed that if a chair is appealing in style and/or well built, people will initially perceive it as being comfortable. This provides an insight into perceptions of comfort however this approach fails to consider many of the factors that negatively impact comfort ratings and disregards the fact that physiologically, humans have no comfort receptor, despite having a battery of pain receptors (nociceptors) (Mansfield, 2005). Nevertheless, Zhang et al. (1996) proposed that two identical chairs would elicit different ratings of comfort, depending on aesthetics of the material used to cover
the chairs. Helander et al. (1987) likewise demonstrated positive correlations between appearance and comfort perception.

Table 2: Definitions of comfort

<table>
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<tr>
<th>Author</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Merriam-Webster Online</td>
<td>- A feeling of relief or encouragement</td>
</tr>
<tr>
<td>Dictionary</td>
<td>- Contented well-being</td>
</tr>
<tr>
<td></td>
<td>- A satisfying or enjoyable experience</td>
</tr>
<tr>
<td>Hertzberg (1972)</td>
<td>- Absence of discomfort</td>
</tr>
<tr>
<td>Shackel et al. (1969)</td>
<td>- A natural feeling with relation to aesthetics</td>
</tr>
<tr>
<td>Slater (1985)</td>
<td>- A pleasant state of physiological, psychological and physical harmony</td>
</tr>
<tr>
<td></td>
<td>between a human being and the environment</td>
</tr>
<tr>
<td>Richards (1980)</td>
<td>- A state involving a sense of well-being, in response to an environment</td>
</tr>
<tr>
<td></td>
<td>or situation.</td>
</tr>
</tbody>
</table>

2.2.1.2 Defining Discomfort

Whereas seating comfort has been associated with aesthetics and a feeling of a ‘pleasant state’ (Table 2), discomfort is described as a different discipline and has been associated with biomechanical and fatigue factors (Zhang et al., 1996). Discomfort has been described as an ‘unpleasant state of the human body in reaction to its physical environment’ (Helander & Zhang, 1997) and is deemed to be more specific than comfort as it involves muscular and skeletal systems and is associated with pain, tiredness, soreness, numbness, and fatigue factors. Other authors describe discomfort as ‘physical loading’ and is associated with negative feelings of pain, pressure, hardness and irritation when referring to seating (Vink, 2005) demonstrating that discomfort is concerned with physical factors and stresses placed upon the human body.
Table 3: Definitions of discomfort

<table>
<thead>
<tr>
<th>Author</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merriam-Webster Online Dictionary</td>
<td>- Mental or physical uneasiness</td>
</tr>
<tr>
<td>Helander &amp; Zhang (1997)</td>
<td>- An unpleasant state of the human body in reaction to its physical environment</td>
</tr>
<tr>
<td>Shen &amp; Parsons (1997)</td>
<td>- A generic and subjective sensation that arises when human and physiological homeostasis, psychological well-being, or both, are negatively affected</td>
</tr>
<tr>
<td>(Vink, 2005)</td>
<td>- Negative feelings of pain, pressure, hardness, and irritation.</td>
</tr>
</tbody>
</table>

The definitions described (Table 3) show that discomfort can be regarded as having extremely different factors in comparison with comfort however it is important to determine a definition that relates directly to the automotive industry and research into the field of driver comfort/discomfort. Therefore further analysis will be conducted that aims to determine how the terms should be viewed in regards to automotive seating research. Furthermore, the various subjective comfort/discomfort rating scales that have been implemented across the discipline will be discussed with the aim of determining the most successful approach for the automotive industry.

2.2.2 Comfort and Discomfort as a Continuous Scale

Many researchers have treated comfort and discomfort as a continuous scale, ranging from extreme discomfort through a neutral state to extreme comfort (De Looze et al., 2003). This stems from the fact that people frequently and naturally distinguish their subjective responses across a continuum ranging from strongly positive to strongly negative (Richards, 1980) and this principle is the basis for many of the rating scales used to evaluate subjective seat comfort. An example can be seen in Figure 2.

2.2.2.1 Relevance to Automotive Seating Research

Regarding comfort and discomfort as a continuous scale has its advantages and disadvantages when assessing automotive seat comfort. A subjective questionnaire that uses a continuous scale, such as in Figure 2, does provide a recognisable format
for participants (Richards, 1980) and many researchers have applied this approach for assessing both local and overall discomfort.

![Continuous subjective rating scale](image)

### Figure 2: Continuous subjective rating scale (Karthikeyan & Sztandera, 2010)

Figure 3 and Figure 4 display a local discomfort questionnaire used by Gyi & Porter (1999), based on a previous questionnaire by Corlett & Bishop (1976). This questionnaire uses a continuous scale and requires very little explanation, allowing participants to quickly identify which descriptor best suits their perception. This is therefore a useful tool when the participant is required to perform another task whilst providing feedback, for example driving. However, some issues have been highlighted with this approach as it implies that comfort is an entity which can be quantified.
Figure 3: 7 point continuous rating scale (Gyi & Porter, 1999)

<table>
<thead>
<tr>
<th></th>
<th>Very Comfortable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moderately Comfortable</td>
</tr>
<tr>
<td></td>
<td>Fairly Comfortable</td>
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<tr>
<td></td>
<td>Neutral</td>
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<tr>
<td></td>
<td>Slightly Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Moderately Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Very Uncomfortable</td>
</tr>
</tbody>
</table>

2.2.3 Comfort and Discomfort as Separate Entities

When assessing the literature, it appears that comfort and discomfort are associated with very different factors and therefore should be viewed as separate yet complimentary entities; as discomfort is associated with biomechanical factors and although discomfort can be reduced by eliminating physical constraints, this does not necessarily produce comfort. There are in fact a number of studies of sitting comfort that demonstrate that comfort and discomfort are affected by distinctly different variables (Kleeman, 1981; Kamijo et al., 1982) and assessment should therefore be based on different criteria (Helander et al., 1987).
Similarly as comfort is associated with feelings of relaxations and well-being, the sensation of comfort may be amplified by the seat design itself, an absence of these feelings may not necessarily evoke discomfort as the adverse biomechanical conditions may not be present.

Although good biomechanics may not produce comfort, it is likely that poor biomechanics may turn comfort into discomfort and implies that comfort and discomfort should be viewed as separate entities that can interact and influence each other. Thus, if discomfort is reduced, comfort may be perceived and if discomfort is increased, comfort will decrease. Figure 5 describes this relationship.

![Figure 5: Hypothetical model of comfort and discomfort (Helander & Zhang, 1996)](image)

Paul et al. (1997) described this theory as the nurturing/pampering paradigm, indicating the need for different strategies for reducing discomfort (nurturing) and increasing comfort (pampering) and De Looze et al., (2003) developed a model (Figure 6) that described the differences between the two entities and how they interact.
This approach may be difficult to analyse as this would require two separate subjective rating scales, one for comfort and one for discomfort and as a result several researchers have conceptualised comfort as an ‘absence of discomfort… a state of no awareness at all of a feeling’ (Hertzberg, 1972). Branton (1969) concurred that comfort ‘does not necessarily entail a positive affect’ and comfort can be conceptualised as a natural feeling where only two stages are possible, comfort present or comfort absent (De Looze et al., 2003). This suggests that comfort cannot be quantified, as suggested by a continuous scale, and therefore there cannot be a graded scale to measure comfort. Furthermore, since a seat is not likely to elicit a positive physical feeling to a sitter, the best a seat can do is cause no discomfort to the sitter (Reed, 2000). Therefore it can be assumed that when determining the success of a seat, comfort can be disregarded.

2.2.3.1 Relevance to Automotive Seating Research

Many of today’s researchers have adopted the approach of focusing solely on discomfort because, in the current environment, it is more straightforward to quantify discomfort than to measure comfort (Kolich, 2008). This approach possesses all of the same benefits as treating comfort and discomfort as a

---

**Figure 6**: Theoretical model of comfort and discomfort and its underlying factors at the human, seat and context level (De Looze et al., 2003)
continuous scale and allows researchers to use several of the same methods, with marginally altered designs (Figure 7 & Figure 8). Figure 7 displays the 6 point rating scale as proposed by ISO 2631-1 (1997) that can be applied when reporting both overall and local discomfort. It follows a very similar design to the 7 point scale developed by (Gyi & Porter, 1999) but focuses on discomfort.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Not Uncomfortable</td>
</tr>
<tr>
<td>2</td>
<td>A Little Uncomfortable</td>
</tr>
<tr>
<td>3</td>
<td>Fairly Uncomfortable</td>
</tr>
<tr>
<td>4</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td>5</td>
<td>Very Uncomfortable</td>
</tr>
<tr>
<td>6</td>
<td>Extremely Uncomfortable</td>
</tr>
</tbody>
</table>

**Figure 7:** 6 point discomfort rating scale (ISO 2631-1)

- maximum
- 10 = extreme discomfort
  (almost maximum)
- 9 =
- 8 =
- 7 = very high discomfort
- 6 =
- 5 = high discomfort
- 4 = somewhat high discomfort
- 3 = moderate discomfort
- 2 = little discomfort
- 1 = very little discomfort
- ½ = extremely little discomfort
- 0 = no discomfort at all

**Figure 8:** Subjective rating scale for discomfort (Hamberg Van Reenen et al., 2008)
This design may be very useful when assessing seating discomfort as the design is simple and easy to implement and also allows researchers to solely quantify discomfort resulting in more accurate assessment. Figure 8 displays an example of a more complex rating scale for subjective discomfort by Hamberg Van Reenen et al. (2008). This scale provides an example of a design that uses a wider range of possible responses and contains more verbal discomfort descriptors to aid the subject in selecting the number which best represents their perceived discomfort level. This type of design may be very useful in obtaining more detailed responses that account for smaller changes in discomfort.

Implementing this type of scale enables the questionnaire to focus solely on the change in perceived discomfort, providing investigators with a quantifiable measure and has been widely used across the automotive discomfort research.

2.2.4 Discomfort Rating Scale Design

It is now important to determine which designs will be implemented throughout this research. The 6 point scale shown in Figure 7, is taken from ISO 2631-1 and can be used in conjunction with the local discomfort questionnaire proposed by Gyi & Porter (1999) (Figure 4) to create a local discomfort questionnaire that focuses solely on discomfort, which adheres to the criteria of this research. However for the purpose of this research it is also important to develop an overall discomfort rating scale.

The 6 point scale (ISO 2631-1) could be implemented as an overall scale however, as there are only 6 points, participants’ responses are somewhat restricted. Therefore a scale that uses a wider range would be beneficial to further increase the possibility of detecting differences between participants and acute changes in perceived discomfort. Shen & Parsons (1997) undertook a study that compared six different rating scales and found that a category partitioning scale that ranged from 0 – 50 (CP50 Scale) was highly reliable and most valid for rating perceived discomfort, therefore a similar scale should be identified. As discomfort as a discipline is not linear, this scale should aim to account for this by using an exponential format.
An example of a rating scale that fits these criteria is the Borg CR100 scale (Borg, 1998) as shown in Figure 9. The CR100 scale ranges from 0 – 120 and incorporates verbal cues in order to help subjects understand the meaning of the intensity levels. In addition to this, triangles increasing in size and blackness congruently with the values of the verbal descriptors are also included in the scale (Borg & Borg, 2002). This scale has typically been used to assess subjects’ perceived exertion or pain, with success, however with adaptations to the verbal descriptors this scale could be used to assess discomfort.
Figure 10 displays an adapted version of the CR100 scale and uses descriptors developed form the overall discomfort scale proposed by Hamberg Van Reenen et al. (2008) (Figure 8). These descriptors have been altered to aid in the understanding of the intensity levels and improve the quality of the responses. This scale has been piloted against the CP50 scale and participants were found to prefer the updated CR100 scale, in terms of both ease of use and relation to perceptions of discomfort.

Ultimately, the concept of discomfort as a single entity, rather than comfort, is more preferable because, in long term driving the sensation of the drivers is likely to be associated with biomechanics and pain rather than comfort concepts.
Furthermore, a combination of both a local and an overall discomfort scale may prove to be useful when investigating automobile seat discomfort and both the 6-point rating scale proposed by ISO 2631-1 and the adapted CR100 scale will aim to be implemented in this research.

2.3 Factors Affecting Driver Discomfort

Now that the concept of discomfort has been clearly defined for the purpose of this research, it is now crucial to understand the factors that contribute to the perception of automobile seat discomfort and this section will outline the various factors as determined by the literature.

2.3.1 Individual Factors

Ergonomics as a discipline is dominated by the ongoing conundrum that each person is different, yet when designing a product or environment, an ergonomist must ensure that this environment caters for all potential users. Ergonomics involves ‘designing for the most’ to ensure that most users within the intended population of the users of the product can in fact use the product appropriately (Bhise, 2011). The field of vehicle ergonomics is no exception and design decisions must be made with a good knowledge of physical and cognitive ergonomics, anatomy, physiology and biomechanics of the individual, especially regarding the seated posture (Gyi, 2013).

2.3.1.1 The Seated Posture

Automotive sitting can be regarded as a completely separate research discipline when compared to the widely studied field of office sitting because of the special driving conditions, although there may be some similarities. Fundamentally, driving as a task involves prolonged sitting, a static and constrained posture, vibration and muscular effort (from steering, braking, reversing etc.), all loading the spine to varying degrees and ultimately leading to a higher chance of musculoskeletal symptoms and increased discomfort (Gyi, 2013). The posture is therefore a restricted seated working posture in which the driver must interact with and operate automotive control components. One of the most important contributions that ergonomics can provide the vehicle design process is information concerning
occupant sizes and their preferred postures (Porter & Gyi, 1998). In particular, the driving postures, position and angles of the seat are very important when designing an automotive driving workstation for comfort and performance. However, the preferred driving posture and position and angle of seat are diverse according to the drivers’ anthropometry and personal preferences. Many studies have aimed to determine the preferred driving posture via analysis of joint angles (Porter & Gyi, 1998) with some success however individual differences between drivers complicates the task. One crucial factor to understand when investigating the factors affecting driver discomfort is the issues surrounding a seated posture as a seated posture involves extremely different anatomical and physiological factors when compared to a standing posture (Gyi, 2013).

The efficiency of any posture from a biomechanics viewpoint can be determined by the degree to which it loads the skeleton and postural muscles (Gyi, 2013) and postural stress is a result of gravitational forces acting on the body and the forces required by muscle activity to maintain the required posture (Troup, 1978). Nachemson et al. (1986) showed that the muscular effort required for sitting is greater than for standing and previous studies have shown that intradiscal pressure in the spine is 40% higher in sitting than in standing (Andersson et al., 1974).

![Figure 11: Rotation of the pelvis when changing from standing to a seated posture (Gyi, 2013)](image-url)
When commencing the driving task and changing from a standing to a seated posture, backwards rotation of the pelvis flattens the curve of the lumbar spine and therefore its shape is altered (Figure 11). In a well-designed seat the issues that accompany this seated posture are reduced as the weight of the trunk is taken by the backrest, muscles are relaxed and the curve of the spine is supported. However, in a poorly designed seat the lumbar curve is flattened increasing pressure within the discs and ultimately leading to increased discomfort and poor spine health (Gyi, 2013; Porter & Gyi, 2002).

In addition to spinal loading, there is an element of static muscle work present in the seated driving posture. Contraction of muscle tissue leads to compression of the blood vessels thereby reducing blood flow, disrupting nutrient delivery and metabolite removal, ultimately producing muscle fatigue and acute discomfort (Hermann & Bubb, 2007; Gyi, 2013). This is a result of maintaining one posture for an extended duration; as the seated posture and driving task leads to inactivity, which in turn may cause injuries and discomfort (Magnusson & Pope, 1998) and poor seated postures alone are generally considered to contribute to high risks of musculoskeletal pain (Porter & Gyi, 2002).

The issue that surrounds the discomfort associated with the driving posture is that this posture is almost completely unavoidable as the majority of popular vehicles today base the design of the vehicle around the seated posture. Furthermore, a factor that adds complicity to the issue is that human beings will have different preferences regarding seat posture due to varying anthropometry, making the design of the ‘perfect’ seat even more difficult to achieve.

2.3.1.2 Anthropometry

Due in large part to Akerblom’s (1948) research, ergonomics criteria related to anthropometry have long been considered a key aspect of comfortable seating. From this perspective designers must ensure that a range of people, from small to large, fit in the seat and can access the most comfortable posture. In general, automotive seat designs are specified by a target population, with the constraining
values of appropriate dimensions (usually 5\textsuperscript{th} percentile female to 95\textsuperscript{th} percentile male).

Comfortable seating design for a driver is best achieved by extreme adjustability; however this is often impracticable due to the associated cost and design issues with implementing such a system. Generally the greater the number of adjustable features in the vehicle, the more likely it is that a range of comfortable postures and a good ‘fit’ can be achieved by the driver (Gyi, 2013). For example, seat length or cushion length is an important determinant of thigh support. A cushion that is too long can put pressure on the posterior portion of the occupant’s legs near the knee resulting in local discomfort as a result of reduced blood flow to the legs (Reed et al., 1994). Therefore cushion length is constrained by the buttock-to-popliteal length of the 5\textsuperscript{th} percentile female segment of the population, or the smallest person whom the design aims to include.

Knowledge and understanding of driver anthropometry is crucial when designing a vehicle seat and many studies have aimed to further the knowledge of driver anthropometry and its relationship with posture. However, these studies more often than not carry the same burden as research into driving posture, individual differences complicate the task.

\textit{2.3.1.3 Culture}

It is worth noting that as anthropometry varies between countries, cultural differences can elicit similar differences in terms of discomfort perception. Seats are therefore required to satisfy culture-based preferences and expectations of seat comfort. Kolich (2008) explains that Western Europeans are generally thought to prefer firmer seats as compared to North Americans. This adds another dimension to the issues that surround the concept of individual differences and again highlights the need for extreme adjustability or a well-defined population for which the vehicle is designed.
2.3.2 Vehicle Packaging

Packaging is the name used in the automotive industry to describe the placement and design of the various components and systems in the vehicle space (Herriots & Johnson, 2013). Furthermore packaging is not only concerned with fitting these components into the vehicle itself but doing so in a harmonious way and most importantly in a way that considers the ergonomic needs of the driver and passengers. The seating package design entails a number of factors including the positioning of the driver and all other occupants, eyelipses, various reach, clearance and visibility zones (e.g. hand reach envelopes, head clearance contours and fields of view), and other relevant vehicle details (such as steering wheel, floor, pedals, seats, arm rests, gear shifter, parking break, mirrors, hard points, fiducial points, eye points sight lines) and dimensions (Bhise, 2011) (Figure 12).

![Figure 12: Illustration of a basic vehicle package layout (Bhise, 2011)](image)

Vehicle packaging is thought to be a primary determinant of seat comfort and defines roominess (headroom, legroom, shoulder room, and hip room) (Kolich, 2008) and the ease of use of the vehicles primary and secondary controls. It is therefore an obvious assumption that the same seat, when placed in two different vehicle packages, will receive different comfort ratings. Vehicle packaging is closely related to anthropometry and posture and automotive ergonomists and designers have highlighted the importance of good vehicle packaging in reducing automotive seat discomfort with much research into the optimum seat height, eye point, and pedal/steering wheel positions to improve the driver experience (Bhise, 2011; Gyi, 2013).
2.3.3 Social Factors

Another parameter that may influence perceptions of automotive seat discomfort is the social factors of the vehicle. The same seat, sold under a different nameplate, may receive different comfort ratings (Kolich, 2008). Nameplate is related to the purchase price of the vehicle and both nameplate and purchase price can be considered social factors.

The ‘meaning’ or impression of a brand resides in the minds of consumers based on what they have learned, felt, seen and heard over time (Keller, 1993) and a person’s experience can have a huge influence on expectations of a vehicle seat’s quality. In the automotive industry, for example, brands such as Hyundai or Skoda continue to fight deeply-held negative images among some consumer groups, whilst at the same time reporting impressive gains in vehicle quality (Homer, 2008). Furthermore, Volkswagen pulled its ‘Phaeton’ from the U.S market because American consumers were not willing to buy the 6-figure ‘best car in the world’ if it had a VW nameplate. In contrast, Mercedes manages to maintain a relatively favourable brand image in spite of the quality issues related to some models. These facts demonstrate the influence of social factors on the success of a vehicle and show that no matter how well a vehicle seat has been designed; there are some individual perceptions that cannot be altered by improvements in design.

2.3.4 Seat Factors

Many of the factors discussed up until this point are largely dependent on the individual, or the drivers own preferences. However, one set of factors conceivably manipulated by design with definite effects are seat factors. Kolich (2008) defined these factors and include such variables as seat stiffness, geometry, contour, breathability and styling. Stiffness refers to the resilience of the seat system, geometry defines seat shape in terms of width, length and height, whereas contour deals with the profile of the seated surface (Kolich, 2008). Breathability in regards to foam density and fabric construction may affect automobile seat discomfort in extreme environmental conditions, especially when taking into account the thermal environment of the vehicle (Kolich, 2008) and therefore is included as a seat factor.
Furthermore, styling is included as it was previously explained that aesthetic quality of the seat may affect perceptions of comfort in the same way as nameplate or purchase price of vehicle. Kolich (2008) outlines the factors affecting automobile seat comfort discussed until this point in a conceptual model as shown in Figure 13.

![Figure 13: Factors affecting subjective perceptions of automobile seat comfort (Kolich, 2008)](image)

### 2.3.5 Dynamic Factors

Although Kolich’s (2008) conceptual model summarises many of the factors influencing automobile seat comfort, this model fails to acknowledge one important concept; the fact that the vehicle is a dynamic environment. Kolich (2008) describes only static factors such as seat factors, individual factors and vehicle package factors; however these do not encompass all of the issues when referring to overall car seat discomfort.

All vehicles expose their occupants to some form of vibration. This vibration can be a result of the inherent motion of the vehicle, such as manoeuvring, due to in-vehicle sources such as motors, or due to the surface on which the vehicle is travelling (Mansfield, 2013). This vibration is usually transmitted through the seat but can also be transmitted through contact with the hands or feet, and via headrests.

At low magnitudes vibration exposure can be annoying or distracting (Mansfield, 2005), however as magnitude increases, in turn it can cause activity interference, discomfort and in some cases exposure to vibration can be a health hazard with known affects including lower back pain, neck pain, shoulder pain and increased prevalence of other musculo-skeletal disorders (Gyi & Porter, 1999; Ebe & Griffin, 2000a,b; Paddan et al., 2012; Basri & Griffin, 2012). Most non-professional drivers are unlikely to approach health risk thresholds unless they drive for extended periods of time, drive off-road or drive on poor road surfaces and therefore, are at
most risk of feeling discomfort due to exposure to vibration. However, Bovenzi & Zadini (1992) stated that lower back symptoms were reported among bus drivers at whole-body vibration exposure levels lower than the health based exposure limits proposed by ISO 2631-1 (1997), suggesting that the health effects of vibration exposure cannot be ignored and that repeated exposure to vibration levels experienced during normal road driving may not only lead to discomfort. Exposure to whole body vibration has widespread and varied effects on the human body, but these effects are not particularly clear and easy to quantify as the body does not have one receptor for vibration exposure (Ravnik, 2011). This has complicated vibration perception analysis in drivers, however much literature has aimed to determine the effect of vehicle vibration on the human.

According to Ebe’s model of seat discomfort (Ebe & Griffin, 2000a,b) automobile seat comfort is defined as having two factors, static and dynamic. Static factors are described as the seat factors associated with seat stiffness and posture; factors which do not change in response to the dynamic environment of the vehicle as defined in Kolich’s (2008) conceptual model and discussed previously (Sections 2.3.1, 2.3.2, 2.3.3 and 2.3.4). However Ebe & Griffin (2000a,b) also describe dynamic factors that are associated with the whole-body vibration experienced from the dynamic environment of the vehicle. The concept of Ebe’s model (2000a,b) is that overall seat discomfort is determined by both the static and dynamic factors of the seat and as vibration magnitude increases, the importance of the dynamic factors increases accordingly (Mansfield, 2005).

![Figure 14: Ebe’s model of overall car seat discomfort (Ebe & Griffin, 2000a,b)](image)
The model is formed by addition of the discomfort caused by the static factors to the discomfort caused by the dynamic environment (Figure 14). For a car that is not moving there is zero vibration, or a static environment, and the discomfort experienced corresponds to the assessments of comfort made in the showroom, without test driving the vehicle and when first impressions of seating discomfort are made (Mansfield, 2005). As vibration magnitude increases, the relative importance of the dynamic factors increases and dynamic discomfort will increase more rapidly for seats with poor dynamic characteristics.

This dynamic discomfort has often been referred to as ride comfort and the occupants’ perception of ride comfort is based upon road shock, impact and vibration transmitted through the automotive seat (Reynolds, 1993). Ride comfort has been associated with vibration since the 1940s (Lay & Fisher, 1940) and since then ample research has investigated a wide range of different vibration characteristics and the effect of these on the driver.

It has been established in the literature that the effect of whole-body vibration exposure on discomfort and health of drivers is dependent on a number of factors: the frequency, duration and magnitude of the vibration, the position at which contact between body and vibration occurs, vibration waveform and the posture and orientation of the body (Mansfield, 2005). Many laboratory studies have determined the effect of frequency on comfort (Shoenberger & Harris, 1971; Miwa & Yonekawa, 1971; Howarth & Griffin, 1988), often using semantic rating scales, and has shown that perceptions of vibration are most sensitive at those frequencies where the body has its biomechanical resonances (Mansfield, 2013). The resonant frequency of the human body ranges from 2 Hz for the lower limbs, 4-8 Hz for the trunk and shoulders and up to 50-200 Hz for the hands (Chaffin & Andersson, 1991). Furthermore the direction of the vibration complicates the theory as horizontal vibration affects different body segments as opposed to vertical vibration that affects mostly the thorax (Qassem & Othman, 1996). This is represented by the frequency weightings modelled in ISO 2631-1 (1997) (Figure 15) however it has been suggested that these weightings do not accurately represent the contribution of horizontal vibration (Marjanen & Mansfield, 2010; Mansfield & Maeda, 2011).
The direction of vibration therefore affects the primary use of these frequency weightings and it has been shown that particular weightings are relevant for particular contexts. Rimmel & Mansfield (2007) outlined these contexts (Table 4).

### Table 4: Frequency weightings used in ISO 2631-1, ISO 2631-2, ISO 5349-1 and BS 6841, and contexts of use (Rimmel & Mansfield, 2007)

<table>
<thead>
<tr>
<th>Filter</th>
<th>Direction</th>
<th>Primary Context of use</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_b$</td>
<td>Vertical</td>
<td>Seat vibration</td>
<td>BS 6841</td>
</tr>
<tr>
<td>$W_c$</td>
<td>Fore-aft</td>
<td>Backrest vibration</td>
<td>ISO 2631-1, BS 6841</td>
</tr>
<tr>
<td>$W_d$</td>
<td>Fore-aft and lateral</td>
<td>Seat vibration</td>
<td>ISO 2631-1, BS 6841</td>
</tr>
<tr>
<td>$W_e$</td>
<td>Roll, pitch, yaw</td>
<td>Rotational seat vibration</td>
<td>ISO 2631-1, BS 6841</td>
</tr>
<tr>
<td>$W_f$</td>
<td>Vertical</td>
<td>Motion sickness</td>
<td>ISO 2631-1, BS 6841</td>
</tr>
<tr>
<td>$W_g$</td>
<td>Vertical</td>
<td>Activity interference</td>
<td>BS 6841</td>
</tr>
<tr>
<td>$W_h$</td>
<td>Fore-aft, lateral and vertical</td>
<td>Hand-arm vibration</td>
<td>ISO 5349-1</td>
</tr>
<tr>
<td>$W_i$</td>
<td>Vertical</td>
<td>Head vibration</td>
<td>ISO 2631-1</td>
</tr>
<tr>
<td>$W_k$</td>
<td>Vertical</td>
<td>Seat vibration</td>
<td>ISO 2631-1</td>
</tr>
<tr>
<td>$W_m$</td>
<td>All</td>
<td>Building vibration</td>
<td>ISO 2631-2</td>
</tr>
</tbody>
</table>
As described in Table 4, four of the frequency weightings are directly related to seat vibration exposure and a further two frequency weightings are related to the vehicle environment; Backrest vibration and hand-arm vibration. These frequency weightings are especially important when understanding how the vehicle environment may affect the user as vibration near the resonant frequency of the body in each direction is noted to have the greatest potential for discomfort and injury. The resonant frequency for a seated person is centred around 5Hz in the vertical direction and 1-2Hz in the horizontal direction (Wilder et al., 1982; Paddan & Griffin, 1988; Fairley & Griffin, 1989; Matsumoto & Griffin, 1998; Mansfield & Griffin, 2000).

The frequency of vibration is not only important when understanding the effect on the human. The dynamic response of a vehicle seat is also a function of frequency, and is defined as a measure of transmissibility; the ratio of the vibration on the seat surface to the vibration at the base of the seat. Transmission is associated with the dynamic factors of the seat and automotive seats are capable of amplifying or attenuating the vibration exposure. As a result the performance of a seat is not a constant and as road roughness changes, so does the ability of a seat to attenuate vibration (Mansfield, 2013) (Figure 16).

![Figure 16: Typical transmissibility for a conventional seat measured in the laboratory using random vertical vibration (Mansfield, 2013)](image-url)
In addition to frequency, magnitude has been shown to negatively affect overall car seat discomfort (Ebe & Griffin, 2000a,b; Mansfield et al., 2014) with discomfort increasing with increasing magnitudes of vibration. Drivers may be exposed to varying frequencies and magnitudes of vibration over the duration of a drive and there is little research demonstrating how discomfort changes as vibration frequency and/or magnitude changes.

Another factor affecting vibration comfort is the waveform of the signal (Mansfield, 2005). Previous research has shown that shocks can cause more discomfort than other stimulus types of the same frequency weighted r.m.s vibration magnitude (Mansfield et al., 2000). The interaction between magnitude, frequency content, and stimulus waveform is important and although complex, all of these factors must be accounted for in order to fully understand the effect on the human being, especially regarding comfort and health effects.

Several epidemiological studies have demonstrated strong evidence for a relationship between whole body vibration and health effects, in particular high levels of discomfort and lower back pain (Morgan & Mansfield, 2014). A national survey that considered Danish employees at work determined a predictive odds ratio of 1.28 proposed for LBP for those exposed to WBV (Xu et al., 1997). Other studies (Bovenzi & Hulshof, 1999) have suggested that the likelihood of developing LBP is severely increased with an odds ratio of 2.3 in an exposed population to WBV when compared to an unexposed population. As a result, automotive manufacturers have now highlighted the importance of dynamic factors and have endeavoured to design improved dynamic environments for drivers, as a comfortable experience is not only desired by consumers, but is required.

However, vibration is not always a negative sensation, movements and forces acting upon the body can provide feedback to the individual on the situation at hand (Morgan, 2011). Vibration in a vehicle, for example, is an immediate cue to the driver that the engine is running and can also be utilised to provide information regarding speed and road surface type. Therefore lack of feedback can result in reduced work performance (Sjoflot, 1985) and a lack of vibration in a vehicle may
have negative implications on a driver’s ability to perform the driving task. However, research suggests that vibration exposure and automobile discomfort are positively correlated and many manufacturers are developing methods of providing feedback to drivers whilst minimising the vibration exposure. This issue may become increasingly important in the future as with the increase of electric vehicles, the amount of feedback to the driver may decrease. Therefore, the need for an in depth understanding of vehicle vibration exposure is crucial for vehicle design in the future.

### 3.3.5.1 Standards and Guidelines

The risks and negative effects of whole body vibration exposure have been well recognised and documented in the past, with a primary interest in health effects and the likelihood of injury. The EU physical agents (vibration) directive (PA(V)D) established exposure ‘action’ and ‘limit’ values for whole body vibration and the mandate detailed in the PA(V)D has been incorporated into the ‘Control of Vibration at Work Act’ (HMSO, 2005) and is enforced by HSE. An exposure action value (EAV) of 0.5ms$^{-2}$ A(8) r.m.s. and an exposure limit value (ELV) of 1.15ms$^{-2}$ A(8) r.m.s. in the worst axis is currently specified.

ISO 2631-1 (1997) is an international standard that provides guidance on the evaluation of exposure with consideration of health and comfort effects. It is the widely accepted evaluation criteria for evaluating whole-body vibration as part of overall-in vehicle comfort. Some estimations are provided that provide predictions for effects of vibration on comfort and the following values are specified to provide indications of likely discomfort responses to various magnitudes of overall vibration total values:

- Less than 0.315 m/s$^2$: Not uncomfortable
- 0.315 m/s$^2$ to 0.63 m/s$^2$: A little uncomfortable
- 0.5 m/s$^2$ to 1 m/s$^2$: Fairly uncomfortable
- 0.8 m/s$^2$ to 1.6 m/s$^2$: Uncomfortable
- 1.25 m/s$^2$ to 2.5 m/s$^2$: Very uncomfortable
- Greater than 2 m/s$^2$: Extremely uncomfortable
This method is widely applied across the field of automotive ergonomics however further research has highlighted issues with this approach of discomfort assessment (Kaneko et al., 2005; Maeda et al., 1996; Maeda et al., 2008; Ordonez & Hammershoi, 2004) as it is problematic to determine the appropriate presumed reaction concerning the degree of comfort based on the physically recorded vibration level (Maeda et al., 2008). For example, Kanenko et al. (2005) show that when random signals are applied as vibration stimuli, even if the frequency weighted r.m.s. acceleration by the ISO 2631-1 is the same, signals made up of different frequency spectra will elicit different evaluations of comfort. Research has expressed doubts regarding frequency weighting curves (Maeda et al., 2008; Morioka & Griffin, 2006), multiplication factors (Maeda & Mansfield, 2006) and averaging methods (Maeda, 2005) used in this method and it has been suggested that the method outlined in ISO 2631-1 does not provide accurate results that can be compared across environments.

This highlights that accurate evaluations of comfort or discomfort due to vibration exposure are difficult to obtain and that the perception of overall discomfort is a more complex discipline suggesting that other factors must be taken into account.

2.3.6 Temporal Factors

Another factor affecting automobile seat discomfort not included in Kolich’s (2008) conceptual model (Figure 13) is the duration spent driving. Many cars are purchased on the basis of their comfort in the showroom (Mansfield, 2005). A showroom analysis will include all of the factors described but Kolich (2008) however this can be extremely misleading as the dynamic environment of the vehicle has not been considered but perhaps equally importantly, the duration of sitting has been ignored. Sitting in one posture for a prolonged duration will lead to an increase in discomfort irrespective of whether vibration is present (Messenger, 1992).

Research into the field of driver discomfort has demonstrated that a ‘showroom’ analysis is not sufficient as it fails to encompass many of the other factors affecting overall car seat discomfort. Porter et al. (2003) found that short term evaluations of automobile seat discomfort are inadequate as the effects of fatigue and long term
sitting have not been accounted for. Previous studies (El Falou et al., 2003; Porter et al., 2003; De Carvalho & Callaghan, 2011; Smith et al., 2015) have shown that the sensation of overall discomfort increases over time. Ravnik et al. (2008) found that time spent driving had the most rapid and most influential effect on subjective perceptions of discomfort and demonstrated that driving for durations of more than 1 hour should be considered highly critical in terms of discomfort.

Mansfield (2005) developed an updated version of Ebe’s 2 factor model of overall car seat discomfort that encompasses these issues by including another axis; time. Mansfield’s (2005) 3 factor model (Figure 17) demonstrates that overall car seat discomfort will increase over time with fatigue and includes these factors in the model as ‘temporal factors’. Previous research has recommended that driving trials have a duration of at least 2 hours to differentiate between seat designs (Gyi & Porter, 1999) and Porter et al. (2003) showed that although some seats are considered uncomfortable after 15 minutes of driving, others that are initially considered to be comfortable become uncomfortable after about one hour; demonstrating the importance of temporal factors on influencing overall car seat discomfort with extended periods of driving.

![Figure 17](image-url)

**Figure 17:** Updated 3 factor model of overall car seat discomfort including static, dynamic and temporal factors (Mansfield, 2005)
Previous research has implemented a range of trial durations when exploring overall car seat discomfort, from 60 seconds to 135 minutes (Kolich, 2003a; Durkin et al., 2006; Gyi & Porter, 1999) and findings demonstrate that temporal factors greatly influence drivers’ overall car seat discomfort as significant changes in discomfort have been shown to occur at approximately 80 – 110 minutes of driving (Gyi & Porter, 1998). Previous research has also shown that both drivers and passengers of cars become fatigued during long term journeys (Duchene & Lamotte, 2001; Lamotte et al., 1996) and that such physiological degradation and fatigue can have a negative influence on driver performance as well as reductions in driver comfort (El Falou et al., 2003). Mansfield et al. (2015) showed that discomfort will increase significantly after only 40 minutes of driving, even with no exposure to vibration, highlighting the importance of temporal factors when assessing automobile seat comfort and encouraging consumers to test vehicles for a prolonged duration before making judgements about perceived vehicle comfort. However, currently the understanding of how discomfort initiates and progresses during a long duration driving situation is not well understood in the surrounding literature.

2.3.7 Dynamic Fatigue Factors

Another factor that complicates Mansfield’s 3 factor model (2005) is that not only does discomfort increase with sitting duration, with no exposure to vibration, vibration exposure duration may be associated with LBP and high levels of discomfort to a greater extent than the vibration exposure itself (Lis et al., 2007). It has been explained that as time increases, discomfort increases, however experimental work has shown that the increase in discomfort occurs more rapidly when there is vibration compared to when there is not (Mansfield, 2013; Mansfield et al., 2015; Ravnik, 2011). Therefore the presence of vibration becomes increasingly important over long-term driving, and as a result measures to minimise the vehicle occupant’s vibration exposure become more important. The combination of temporal factors, associated with a prolonged seated posture, with dynamic factors of vibration become increasingly influential on driver discomfort during long term driving (Ravnik, 2005) and long term driving vibration exposure is
among the highest risk factors for neck and back injuries as well as discomfort (Ravnik, 2011).

Consequently, Mansfield (2013) further updated the 3 factor model of overall car seat discomfort to include another factor; dynamic fatigue (Figure 18). This is described as the interaction between time and vibration exposure and duration of vibration exposure is therefore shown to lead to increases in overall car seat discomfort.

![Dynamic fatigue factors](image)

**Figure 18**: Improved model of overall car seat discomfort including dynamic fatigue (Mansfield, 2013)

Some early studies argued against this theory, as Clevenson et al. (1978) performed an experiment upon which during of vibration exposure varied from 15 seconds to 1 hour. Upon completing the pre-determined exposure times participants were asked to rate their discomfort and the results showed that discomfort decreased with increasing vibration exposure duration. However, this method is to be questioned as inter subject variability has not been accounted for and does not describe the participants change in discomfort over the duration of exposure. Furthermore, Oborne & Clarke (1975) found that ratings of discomfort did not change with duration of travel when participants were asked studied on a train and on a
hovercraft and El Falou et al. (2003) measured the change in discomfort over 150 minutes with and without vibration exposure and found no time dependency due to vibration exposure.

However, many more recent studies have investigated and demonstrated the effects of long term sitting (temporal factors) and the effects of vibration (dynamic factors and dynamic fatigue factors). Through a series of studies involving motion and long-duration sitting, Mansfield et al. (2014) showed that discomfort increases both with vibration magnitude and with sitting duration, and that the presence of vibration causes an increase in the rate of change in discomfort. Furthermore, Mansfield et al. (2015) showed that overall car seat discomfort increased significantly with duration of driving supporting previous studies (El Falou et al., 2003; Kyung & Nussbaum, 2008) and increased more rapidly when vibration was present supporting the findings of Mansfield et al. (2014).

2.3.8 Environmental Factors

Having already discussed many of the factors that affect automobile seat comfort outlined by Kolich (2008) in addition with the dynamic, temporal and dynamic fatigue factors proposed by Ebe & Griffin (2000a,b) and Mansfield et al. (2014) it is important not to forget that the vehicle is also affected by a number of other environmental factors. Vibration exposure can be classified as an environmental factor, however, after discussing the dynamic environment of the vehicle in detail this section will highlight some of the other environmental factors that must be addressed to fully understand vehicle and automobile seat comfort. These factors will not be examined in as close a detail as the dynamic environment; however it is crucial that these factors are considered as they must be controlled during future work to accurately determine the effects of long term driving on driver discomfort.

2.3.8.1 Thermal Factors

With the ultimate goal across much of the transport industry being improvements in driver and passenger comfort, one factor that must not be ignored is the thermal environment of the vehicle. Determining thermal comfort in automobiles is a complex task, as many variables are attributed to thermal comfort and due to the
fact that automobile environments are susceptible to temporal fluctuations in their thermal environments (Brooks & Parsons, 1999). Previous research has reported that poor thermal conditions may negatively affect driver performance (Norin & Wyon, 1992) however; more importantly poor climatic conditions may negatively affect perceptions of comfort (Hodder, 2013). The thermal environment in a vehicle can mostly be controlled via air velocity as this is the parameter that occupants have the greatest control over via the ventilation system in the vehicle and can be actively used to improve thermal comfort (Hodder, 2013).

Another major factor affecting thermal comfort of a vehicle is the seat. The interaction between the occupant and the seat provides a significant avenue for heat gains and losses (Hodder, 2013) and seat designers must consider the thermal properties of the design as seats can be made with a variety of materials and geometry. Oi et al. (2012) and Brooks & Parsons (1999) found that heated seats can improve driver comfort when exposed to cold environments whereas Madsen (1994) showed that ventilated seats could improve the removal of heat and therefore reduce discomfort in hot environments. Zhang et al. (2007) supported these findings by determining the effect of both seat heating and seat cooling on thermal sensation.

The material used for the vehicle seat also has a large part to play in thermal comfort. Fung & Parsons (1993) investigated a number of different seat materials and determined that different materials elicit different thermal discomfort ratings, with hydrophilic seat coverings found to be the most satisfactory as these aid in transporting the moisture away from the surface of the seat (i.e. sweat). Furthermore, a later study by Fung (1997) found that it is possible to rank seating materials with regards to their ability to remove moisture; however it was not possible to rank the materials in terms of good thermal comfort. Similarly Cengiz & Babalik (2007) found no significant difference between three different vehicle seats in a field trial. It is important that these factors be understood when investigating the comfort of vehicle seats as even if these thermal factors are not being investigated, these factors must be controlled and understood if any assessments of discomfort are to be accurate and reliable.
2.3.8.2 Vision Factors

The same also applies for vision factors. Over recent years there has been a large increase in the number of studies focused on the relationship between vision and driving. However, few studies have investigated driver comfort related to vision factors in the vehicle as most focus on vision and driving safety (Owsley & McGwin, 2010). Howarth & Bullimore (2005) suggested that poor visual conditions may have a negative impact on discomfort and although vision factors will not be explored during this research it is important that these factors be considered when conducting automotive discomfort research.

2.3.8.3 Noise Factors

In vehicle driving, noise factors are closely related to dynamic factors as sound and vibration are intrinsically linked. Occupants are exposed to sound resulting from the presence of vibration throughout the many systems of the vehicle, due to the engine and the road surface. Road induced noise also increases with the roughness of the road (Parizet et al., 2010; Mansfield, 2005). Negative perceptions of the noise produced by the vehicle may have negative connotations on the perception on the overall comfort of the vehicle and when implementing a multifactorial approach to vehicle comfort evaluation, the effects of noise should be considered.

2.3.9 Improved Model of Factors Affecting Overall Car Seat Discomfort

As this literature review has highlighted many factors not included in the conceptual model proposed by Kolich (2008), an improved conceptual model has been proposed that aims to encompass all of the other factors discussed in this section including major references (Figure 19).
Figure 19: Improved summary of factors affecting overall car seat discomfort

Overall Car Seat Discomfort

Vehicle Factors
- Transmission Type
- Steering Wheel Position
- Vehicle Packaging

Seat Factors
- Softness
- Breathability
- Geometry
- Aesthetics
- Pressure Distribution

Temporal Factors
- Time
- Fatigue
- Rest

Individual Factors
- Demographics
- Culture
- Purchase Price

Social Factors
- Vehicular Human Factors
- Position of Contact
- Posture/Orientation

Environmental Factors
- Vibration
- Thermal
- Vision
- Noise

Kolch, 2008
Mansfield, 2005
Elbe & Griffin, 2000
Gyr, 2013
Kolch, 2008
Porter & (col. 1998)
Kolch, 2008
Mansfield, 2005
Holder, 2013
Kolch, 2008
Mansfield, 2005

Ac. Temperature
Mean Radiant Temp
Eye Position
Road

Gripping
Metabolic Rate

Exposure Duration
Vibration Dose
Magnitude
Wearing
2.4 Measuring Driver Discomfort

As the factors surrounding overall car seat discomfort have been discussed, the next question to be addressed is how to accurately quantify overall car seat discomfort. Many different methods are in place to measure sitting comfort across the field of automotive ergonomics; however this has only lead to further complicating the understanding of the concept (De Looze et al., 2003). Fortunately, these different methods can roughly be categorised as two types of measurement; firstly, the various subjective methods that are in place, such as the questionnaire and scale designs addressed earlier in this chapter (Section 2.2). Subjective methods can be regarded as the most direct, considering that discomfort is a subjective feeling (Richards, 1980). Secondly there are the various objective measures implemented which are becoming increasingly more important as researchers look to standardise driver discomfort measurement.

Discomfort assessment in general is a challenging task due to its multidimensional nature and the different modalities in the perception of discomfort (Zhang et al., 1996). The usual approach is to correlate objective measures, such as seat interface pressure, with the perceived discomfort reported subjectively by the driver by employing questionnaires to compare with the objective data. The main issue is that the validity of subjective measure relies heavily on the ability of the subject to accurately describe their perceived discomfort level as a variety of extraneous factors may influence the participants’ decision (Hermann & Bubb, 2007).

The perception of discomfort is based on sensory inputs being mediated by environmental variables and as the sensory system is a complicated and intricate system, its response to pain and discomfort varies largely from person to person (Hermann & Bubb, 2007). When attention is drawn to the sight of injury, pain is experienced. However, if an injury occurs whilst a person is engaged in an important task, pain can be mediated, attenuated or even absent and this can also be the case with discomfort. Chemicals in the blood interfere with the pain pathway resulting in the person being unaware of the pain or discomfort (Thorfinn et al.,
Therefore, for subjects engaged in a driving task, accurate subjective responses may be difficult to obtain.

Memory recall of this perception may also be impaired or distorted and only consciously perceived discomfort can be rated and expressed (Zhang et al., 1996). Even if the discomfort experienced is remembered, subjects often find it difficult to choose the right descriptors for describing their individual discomfort level at that time. It is equally difficult to describe slight differences in perceived discomfort (Fenety et al., 2000). Therefore, the reliability of subjective responses has been questioned.

2.4.1 Objective Measures of Overall Car Seat Discomfort

Consequently, objective measures may hold some advantages over subjective measures as they require less time to report, a smaller number of participants, are less prone to measurement error or bias, and can be applicable earlier in the design process (Lee et al., 1988). However, good objective measures for predicting overall car seat discomfort are difficult to find in both the literature and practice (Zenk et al., 2012) as there are many different objective measures in use across the automotive industry and each of these accompany their own issues.

Objective measures are indirect; implying that, at best, they give an indication of an individual’s sitting comfort, but in fact, they do measure something else (De Looze et al., 2003). Only if correlations between objective measures and subjective discomfort are present can the objective measures form a useful addition to subjective measures. Therefore, finding a useful method of measuring overall car seat discomfort is one of the greatest challenges currently facing automotive seating researchers. A number of techniques have been investigated within the field of sitting discomfort with varying levels of success, including:

- Electromyography (EMG)
- Intramuscular pressure in paraspinal muscles of the lumbar region
- Spinal shrinkage
- Postural angles
- Pressure distribution at the occupant-seat surface
• In-chair movements (ICMs)
• Settling down time (SDT)
• Actigraphy
• Sonometry

The success of the varying methods will be analysed with aim of determining the extent to which these methods may be useful for the purpose of this research. This literature review will not discuss all of the above points but focus on methods that have held some success in previous research and that are easily applicable into the automotive industry.

2.4.1.1 Electromyography

Surface electromyography (SEMG) is a commonly used tool in the study of muscle activity since it provides a non-invasive index of muscle activation (Duchene & Goubel, 1993). Invasive methods of electromyography (EMG) are uncommon within the automotive industry as they place more demand on the participants, are difficult to execute and take more time. The SEMG signal is often used to study the onset of fatigue (Bigland-Richie et al., 1983). Using Fast Fourier Transform (FFT) to calculate the frequency component of the SEMG signal can calculate fatigue (De Luca, 1997), as well as quantifying the increase in muscle activation required to sustain muscle force. The reduction in the mean or median frequency of the signal can then be used to identify the onset and progression of muscular fatigue (Krogh-Lund & Jorgensen, 1993; Ng & Richardson, 1996). The decrease in firing rate of the motor neurons (reduced median frequency) is well matched to the slowing in relaxation that occurs with sustained muscle activation and the accumulation of potassium ions (K+) in the extracellular space (Bigland-Richie et al., 1983). Additionally, the increased motor unit activation with fatigue can be represented as an increased SEMG signal during sustained force at submaximal levels.

However, this is not a direct measure of discomfort and the study of SEMG activity from postural muscles can cause many problems for the researcher. The low magnitude of the postural SEMG signal decreases the signal-to-noise ratio, while postural SEMG activity is often masked by other electrical activity and noise (El
Thus, although spectral analysis of SEMG activity may provide a useful tool to analyse fatigue in car seats (Hosea et al., 1986), it is first necessary to extract the postural SEMG segments from the long term recording.

As a result of these issues, the reliability of SEMG was questioned by De Looze et al. (2003), among other researchers, and states that no statistical relationships have been established between any measure of muscle activity and ratings of discomfort, except for one study (Lee et al., 1988). In this study the increase in back and shoulder muscle activation over time was significantly related to the increase in discomfort over time. However, in five other studies mentioned by De Looze et al. (2003), the correlations between SEMG and discomfort variations were studied across seat conditions and only in some cases were tendencies observed. Other studies that find significant correlations between driver discomfort and muscle activity have conducted the experiment in a static environment and therefore cannot be regarded as complete as the dynamic environment of the vehicle has not been accounted for (Kolich et al., 2001). Ultimately, methods of EMG analysis should be questioned when used as a predictor for discomfort as the perception of discomfort does not necessarily require the presence of muscular fatigue (El Falou et al., 2003).

2.4.1.2 Pressure Distribution

Another widely investigated technique is pressure distribution analysis. The development of advanced sensing and evaluation technologies has made it possible to measure the pressure distribution at the occupant-seat interface (Reed et al., 1991) using thin, flexible tactile sensor arrays (pressure mats) that enable researchers to study pressure distribution between larger portions of the occupant-seat interface.

The use of this technology allows a wide variety of experiments to be conducted, in real time, without requiring modification to the seats under investigation (Kolich & Taboun, 2004). However, this method comes with its own advantages and disadvantages. Kolich & Taboun (2004) outline the advantages of the system as data
resolution, high speed data collection, real time displays, and portability. However one major disadvantage reported is repeatability.

The method is based on the theory that a good seat cushion will produce pressure distribution for occupants with a wide range of anthropometry that show peaks in the area of the ischial tuberosities with gradual reduction in pressure toward the front and sides of the cushion (Količ & Taboun, 2004). Drummond et al. (1982) found that 18% of the occupant’s body weight is taken up by each ischial tuberosity. Therefore the pressure under the distal half of the thigh should be minimal. Previous research has stated that the underside of the thigh has minimal resistance to deformation until the tissue nears its compression limit against the femur, leading to considerable restriction of blood flow and ultimately discomfort.

Furthermore, with respect to the seat back, Kamijo et al. (1982) found higher lumbar pressure peaks in seats judged to be comfortable compared with lower values in uncomfortable seats. Although a seatback with adequate lumbar support will produce pressure peaks in the lumbar region, excessively high pressure due to a very firm lumbar support can lead to discomfort in long term sitting (Vergara & Page, 2000; Reed et al. 1991).

The aim is therefore that there should be no isolated high pressure points in other contact regions such as the lumbar region and the ischial tuberosities as the physiological consequence of high pressure is an interruption in blood flow to the surrounding soft tissues, which as discussed previously is the prerequisite for discomfort (Odell, 1978: Bader et al., 1986).

As a result, many researchers have, for some time, considered occupant-seat interface pressure distribution to be one of the most influential factors in automotive seat discomfort (Hertzberg, 1972; Kamijo et al., 1982; Diebschlag et al., 1988) and after De Looze et al. (2003) reviewed the present literature pressure distribution was found to have the clearest association with subjective ratings of overall car seat discomfort (Thakurta et al., 1995; Vergara & Page, 2000; Kamijo et al., 1982).
However, many studies have argued the opposite and many issues have been highlighted with pressure distribution as a tool for predicting overall car seat discomfort. Lee & Farraiulo (1993) conducted a study where 100 participants evaluated 16 visually similar car seats. Subjects were asked to report their perceived discomfort in 10 body areas after a short term evaluation of the seat (2 mins). Despite the high number of participants, this study reported no correlations between pressure and subjective comfort. Much of the literature has aimed to link quantitative measures such as peak pressure (Gyi & Porter, 1999) and total seat pressure (Kolich & Taboun, 2004) with subjective measures of discomfort with little success.

Another issue surrounding successful pressure distribution studies is the duration in which the subjects evaluated the seat. Many studies implemented durations of 2-10 minutes which, due to temporal factors, is insufficient as reported discomfort may vary considerably with time (Gyi & Porter, 1999; Mansfield et al., 2015). Furthermore, many studies using this method did not require participants to conduct a driving task whilst providing evaluations of comfort which in turn may affect the validity of results as a naturalistic driving posture did not have to be maintained. Gyi & Porter (1999) aimed to address these issues of time and task by implementing trial durations of 135 minutes and a driving simulator in order to ensure that posture and task was naturalistic. It was concluded that interface pressure data is unsatisfactory when predicting increased discomfort and that this technique is not robust enough to provide such information to the automotive industry in ‘real-world situations’.

The method of assessing pressure distribution itself holds many flaws. The main fault being that in order to record pressure distribution data, a pressure mat is used that participants are required to sit on whilst in the vehicle seat. This comes with its own issues as, as discussed earlier, the aesthetics of a seat can heavily influence perceptions of comfort (Zhang et al., 1996) and furthermore presence of the mat may alter some of the other static factors of the seat such as breathability, stiffness and style. Furthermore, the anthropometry of the subjects can heavily influence the quality of the results produced by the pressure mapping equipment. The method
may be useful for short term evaluations of comfort for one individual however, with a large sample, comparisons between subjects becomes difficult due to the issues associated with individual differences and assessments made over a long duration are also problematic. Many issues have been highlighted with using pressure distribution as a measure of long term comfort and this is largely due to the fact that although pressure distribution may change over time, this change is not nearly as great as that observed in subjective discomfort and few studies have been successful in correlating long term discomfort and changes in pressure distribution. The main issue however, stems from calibration. Kyung & Nussbaum (2008) described two major issues with calibration of pressure mats, the first being ‘creep’ where measurement drift is observed under a constant load, and the second being ‘hysteresis’ where there is a displacement pattern between loading and unloading of the matt. If the calibration of the measuring equipment is difficult and unreliable, this in turn reduces the quality of the data obtained. These issues highlight the problems with using pressure distribution as a long term method to assess discomfort and although this method has shown some promise in predicting overall car seat discomfort and differences between static comfort of seat designs, there are an excessive number of faults with this method to be considered successful.

2.4.1.3 Dynamic Measurements

Although it can be concluded that pressure distribution is not sufficient in predicting subjective overall car seat discomfort, a study by Na et al. (2005) examined dynamic body pressure distribution data and managed to show a significant correlation between body pressure alterations and subjective discomfort ratings. This finding suggests that dynamic pressure distribution data may be a more useful tool for the assessment of seated discomfort than data obtained from static measurements, however many of the same issues are still apparent with dynamic pressure distribution.

Many previous investigators have recorded the objective measures implemented discontinuously, this approach may be termed as ‘static’ (Fenety et al., 2000). However, the use of ‘dynamic’ measurements, such as continuous pressure
distribution, relates back to a suggestion by Branton (1969) that sitting should not be viewed as a posture but rather a behaviour and, therefore, should be described on a continuous dynamic basis. This contention is supported by the assertion that any sitting posture, no matter how well positioned the spine and how equal the distribution of pressure, cannot be maintained for a significant period of time without becoming uncomfortable (Graf et al., 1993).

Branton’s (1969) original work involved studying the patterns of postural shifts of train passengers on long journeys, and this lead to the development of a methodology that used In-Chair Movement (ICM) as a measure of discomfort after a study showing a link between increases in discomfort and increases in ICM and fidgeting was carried out (Fenety et al., 2000).

2.4.1.4 In-Chair Movement

In-Chair Movement (ICM) has previously been used to determine the effects of sitting in chairs on the body and perceived discomfort. When a person first sits down, they appear comfortable and move little, however, over time (45-180 mins) increasing discomfort has been shown to lead to significant increases in ICM (Bendix et al., 1985; Jensen & Bendix, 1992; Fenety et al., 2000) and frequent ICMs have been shown to be associated with sitting discomfort (Bhatnager et al., 1985; Fenety & Walker, 2002). The rationale behind this methodology is that people move unconsciously when seated with the purpose of relieving pressure of compressed body parts with impeded blood flow (Hermann & Bubb, 2007, Odell, 1978). ‘Fidgeting’ or ICMs may be a direct result of the compromised blood flow and coincides with the literature surrounding capillary closure time when seated in a fixed position. The insufficient blood supply initiates the urge in the sitter to change position to reinstate normal or at least improved blood flow. Therefore the amount of time between those movements may relate to discomfort created by tissue compression.

A basic model describing this theory was developed by Fujimaki & Noro (2005) which suggested that as sitting duration increases, discomfort also increases, described as the ‘stable condition’. When discomfort reaches a certain level, it is
proposed that the sitting condition will be shifted to the ‘unstable condition’. This is followed by a further more rapid increase in discomfort that culminates with a ‘macro movement’ in order to reduce some of the discomfort. The reduction of discomfort by these movements becomes less effective across the duration of sitting as discomfort increases and the pattern repeats. This theory is described by a theoretical model (Figure 20).

Figure 20: Theoretical model of sitting condition and discomfort in prolonged sitting (Fujimaki & Noro, 2005)

Sitting in chairs with obvious design differences, for example wooden versus padded, has been shown to significantly affect ICM in most cases (Fenety et al., 2000; Mark et al., 1985) but not all (Jurgens, 1989). As occupants subconsciously change their posture to minimise the effects of discomfort while sitting, discomfort is not perceived unless the chair severely compromises basic design criteria (Helander & Zhang, 1997). This knowledge is widely accepted and applied in reducing discomfort in wheelchair users however it has rarely been implemented in the automotive industry. The measurement of ICM and discomfort in long term driving is somewhat problematic since some movement is task related. Fenety et al. (2000) investigated chairs outside of the automotive industry and adapted an interface pressure mat to collect continuous ICM data by tracking a subject’s centre of pressure (COP) at the occupant-seat interface. Although this proved successful, such a method would be problematic to implement into the automotive industry as task related movement and vibration exposure complicate data collection, in addition to the issues discussed with using pressure mats.
Nevertheless, this method shows promise as it has been shown that during prolonged sitting both subjective discomfort and ICM increase over time in a linear fashion, with similarly steep slopes (Bhatnager et al., 1985) and numerous laboratory studies have shown that ICM increased with time whether subjects read (Grandjean et al., 1960), drove an automobile simulator (Rieck, 1969), piloted a boat simulator (Jurgens, 1989) or worked at VDU tasks (Michel & Helander, 1994). Therefore the assumption on which these and other studies using ICM or similar postural variables are based on is that individuals will increase the frequency and/or magnitude of their movements, at a conscious or unconscious level, as duration of sitting increases in a manner that is influenced by their perceived level of discomfort (Fenety et al., 2000).

Vehicle ergonomists are often asked, “What is the most comfortable posture?” by designers. The correct answer to this question is “The next one” (Mansfield, 2005) as it is natural to continually change postures to use and rest alternative muscle groups. Therefore it has been proposed that a comfortable seat will allow the driver to move in the seat and a range of possible body positions. Callaghan & McGill (2001) suggest that there is no single ideal seated posture and that a variable posture is the best strategy to minimise muscle tissue overload. Furthermore, Ravnik et al. (2008) stated that with prolonged sitting, a correct ergonomic posture is not sufficient and a constant change in posture is necessary.

Previous research into automotive seat design has suggested that sitting should be dynamic (Reynolds, 1993) and that occupants should be able to change their spinal posture rather than be fixed in a predetermined ‘best’ spinal geometry. This supports the theory that a well-designed seat will allow for changes in torso posture, however the frequency and pattern of such posture changes may be equated to the discomfort experienced due to the seat design.

Therefore, according to Liao & Drury (2000), shifts in posture are a distinguishable signal of discomfort. It is important to note that automotive sitting is widely different to office or chair sitting because of the special conditions required by the driving task (Ernst, 1992) and that a variable posture is difficult to achieve because
of the restrictions of the safety features of the vehicle, such as the seatbelt, and moreover the requirements of the driving task. Modern seats are more often than not designed to fix the driver in a predefined posture rather than to allow dynamic sitting, mainly due to ergonomic principles and safety reasons (Adler, 2007).

With this in mind, a measurement of ICM in automotive seating may be a direct indicator of sitting discomfort and if this method can be implemented effectively into the automotive industry, such a finding creates opportunity to less subjectively study a driver’s discomfort and opens the door for measurements to be made by remote monitoring.

Adler (2007) is one of the few investigators to implement the theory of ICM into the automotive industry and suggested that behaviour modification of drivers may be an objective reaction to seating discomfort that runs in conjunction with subjective perceptions of discomfort. Adler (2007) determined that postural adaptations increase with time and in addition subjective discomfort ratings could be reliably predicted by posture changes. A model to demonstrate this theory was proposed that was only true for long-term assessments of overall car seat discomfort (Figure 21).

Adler (2007) found that all drivers change their posture over time and that posture variations can be described by posture changes, posture adaptations and activity. Furthermore, it was demonstrated that subjective ratings of discomfort can be predicted by certain parameters of postural adaptation in prolonged driving and therefore suggests that an evaluation of driver behaviour and ICM is an encouraging objective method to pursue when evaluating overall car seat discomfort.
Although promising, Alder’s (2007) method also possesses its own issues. The method proposed implements the use of Sonometry in order to measure driver posture alterations whereby sensors are applied to the subjects’ body in various locations. This approach is somewhat invasive on the subject and does not allow for discrete measurement as subjects are aware they are being monitored. This may impact the validity of the findings as drivers may alter their behaviour due to being aware that they are being monitored and furthermore, the attachment of sensors may have some negative implications on the discomfort experienced, altering the perception of the seat being tested. During Adler’s (2007) research, measurements were only taken on the back and neck of the subjects limiting the results regarding driver movements as these measurements do not encompass all possible movements. Nevertheless, a positive correlation between the number of movements and driving time was established.
Another issue regarding Adler’s (2007) findings was that although a correlation was established between driver posture adaptations and subjective discomfort, predictions of subjective discomfort were only successful using measurements of trunk and lower back movements. Perhaps these are the only movement types that influence discomfort; however this finding must be investigated further. Moreover, the subjective rating scale used to correlate with the objective measurement of movements was unsatisfactory and possessed many of the issues with rating scales highlighted previously. Comparisons will need to be made with a more robust method of subjective evaluation. Ultimately, a measure of driver movements has shown promise and further research evaluating the relationship between subjective discomfort and driver movements should be conducted.

2.5 Predicting Driver Discomfort

The eventual goal of objective assessment is to use objective measures to predict driver discomfort. There are various methods that are currently in place across the automotive industry that aim to predict car seat discomfort and all come with varying levels of success and validity. The prediction of discomfort is itself a difficult task as discomfort is subjective and furthermore the varying methods in place complicate the task. However, if a successful method could be implemented into the automotive industry there is a great opportunity for shorter duration tests on new seat designs and tests to be performed much earlier in the design process.

A common method in predicting discomfort experienced from vibration exposure is outlined in ISO 2631-1 and explained earlier, whereby subjective discomfort is predicted to increase with increasing magnitude of vibration. Ranges of total exposure are outlined that are proposed to correlate with the 6 point semantic rating scale described by the standard. This method has some clear issues as it fails to encompass many of the factors effecting overall car seat discomfort and suggests that all seats elicit the same perceptions of discomfort. It fails to account for the duration of the sitting and vibration exposure, therefore disregarding factors such as temporal factors and dynamic fatigue factors. Although this method may be useful in gaining a brief insight into what may be expected, this method lacks
validity and should not be used in order to predict discomfort over time and to make judgements on design issues regarding long term discomfort.

Another method that aims to address many of the issues associated with the method proposed by ISO 2631-1 (1997) is described by Mansfield et al. (2014). As discussed previously, long-term overall car seat discomfort can be defined as a combination of static factors, fatigue factors, vibration factors and dynamic fatigue factors and any method that aims to predict overall car seat discomfort should aim to encompass all of these factors. Mansfield et al. (2014) used this theory to develop a model for predicting overall car seat discomfort. Regression analysis showed that the model should include factors able to represent the static discomfort (a constant for the seat), fatigue discomfort (a component which depends on time), vibration discomfort (a component which depends on the vibration magnitude), and dynamic fatigue (a component of interaction between the vibration exposure and duration). These variables are therefore expressed by Mansfield et al. (2014) as:

$$\Psi = s_s + f_t t + d_v a + i_{tv} ta$$

Where:

$\Psi$ is the rating of discomfort,

$s_s$ is the static discomfort constant,

$f_t$ is a fatigue constant,

$d_v$ is the vibration discomfort constant,

$i_{tv}$ is an interaction constant,

$t$ is the time (mins) and

$a$ is the frequency weighted r.s.s. acceleration.

For the modelling used in this equation, 1.4 multipliers have been applied to horizontal axis, as detailed in ISO 2631-1 (1997). This model has been deemed to be successful in predicting overall car seat discomfort (Mansfield et al., 2014;
Mansfield et al., 2015) however there are some issues that require further work in order to improve this methodology. The model still requires the user to perform some experimentation in order to determine the constants $s$, $f$, $d$, and $i$, as at this stage it is not possible to predict these directly from the fundamentals of the seat design or vibration waveform. However, with further research and experience, it may be possible to benchmark some variables. Furthermore, the model was designed using continuous vibration exposure and therefore cannot be directly applied to scenarios where vibration is intermittent or varies in magnitude. Further research is required to validate and develop the model further to include non-stationary signals, and the recovery time following cessation of vibration exposure. Ultimately, the method proposed by Mansfield et al. (2014) is promising and research should aim to further validate this method and tackle the remaining issues highlighted with the method. If this model can be updated or a similar model can be produced, this may provide a useful tool for the automotive industry.

2.6 Combatting the Effects of Driver Discomfort

Aside from optimal seat design, little research has been conducted that investigates other methods of combatting discomfort when driving. Driver behaviour whilst seated has been shown to have an impact on perceptions of discomfort and perhaps more emphasis should be placed on drivers to be aware of and regulate their discomfort, as improvements in seat design can become ineffective with extended duration driving.

2.6.1 Breaks from Driving

It is recommended by Ravnik et al. (2008) that during long duration driving, drivers should stop often and move around as much as possible; supporting the theory that drivers will move in the seat in order to minimise discomfort. Ravnik et al. (2008) found that breaks and time spent outside the car can decrease the symptoms of discomfort. A study was designed whereby drivers conducted 100 minutes driving, had a 15 minute break and then carried out a further 65 minutes driving during which discomfort was shown to decrease to near zero at the end of the 15 minute break from driving. The findings of this study highlighted the benefit of breaks from
driving in terms of discomfort, however during the same study; results reported that 83% of drivers were not stopping often when driving long distances suggesting that drivers are unaware of the potential benefits or chose to ignore these and accept levels of increased discomfort.

It is likely that both of these theories are true as drivers are unlikely to stop when driving in order to reduce discomfort as the perceived benefits, in terms of discomfort, do not outweigh the desire to arrive at the destination quickly. Furthermore, the discomfort benefits are likely not fully understood by drivers. This is largely due to the fact that little research has investigated the effect of breaks from driving on driver discomfort and therefore drivers are likely to be unaware of any potential benefits, largely because these simply have not been determined.

Much of the current literature surrounding breaks from driving focuses solely on the safety benefits of breaks and the majority of studies into driving behaviour concern the effect of rest breaks on accident risk (Horne & Reyner, 1999; Horne & Reyner, 1995). Blanco et al. (2011) conducted a study involving 97 truck drivers where the impact of breaks from driving were analysed. It was concluded that when non-driving activities were introduced during the drivers shift, creating a break from the driving task, these breaks significantly reduced the risk of being involved in a safety critical event during the hour after the break. The majority of such studies have inferred a relationship between rest breaks and risk, via the analysis of driving performance and fatigue. It is reported that fatigue is best managed when drivers can identify the onset of fatigue and coincide rest breaks with these periods (Feyer & Williamson, 1995) and that improvements in fatigue were observed with the implementation of a 30 minute break 3 hours into a 7 hour drive (Drory, 1985). Furthermore, Stave (1997) reported that taking a 4 minute break whilst undertaking a 3 hour journey at the point at which errors began to occur led to an almost complete eradication of errors following the break. This suggests that breaks from driving can have a positive impact on fatigue, attention and performance. However, fatigue does not necessarily produce discomfort and the direct impact of breaks on drivers’ perception of discomfort has seldom been investigated.
The positive benefits on safety, however, have been extensively researched and widely advertised to drivers. For example, the ‘THINK! Don’t drive tired’ campaign, developed by the UK Department for Transport, which advises drivers to take a 15 minute break every two hours to minimise the chance of the driver being involved in a sleep, or fatigue, related accident, which was derived from the work summarised in Horne & Reyner (1999). Furthermore, some manufacturers have aimed to advise drivers on the safety benefits of taking breaks from driving as Mercedes-Benz have recently implemented an attention assist system ‘intended to help drivers recognise when they are drowsy or inattentive and encourage them to take a break’. This attention assist system uses a sensitive steering angle sensor to monitor the way in which the driver is controlling the car and if a steering pattern emerges that shows characteristics of ‘drowsy driving’, the system warns the driver to take a break by showing a coffee cup signal in the dash and by an audible tone.

Furthermore, there are guidelines in place for professional drivers as to how often they should take a break from driving and what type of break this should be. This is again solely from a safety perspective and no reference to improving discomfort is included in the guidelines.

2.6.1.1 Guidelines for Commercial Vehicle Drivers

In the EU and AETR, commercial vehicle drivers are required by law to have breaks and rest periods throughout their journey duration. These break and rest periods are described in the EU & AETR rules on drivers’ hours. A ‘break’ is defined by Gov.uk as “any period during which a driver may not carry out any driving or any other work and which is used exclusively for recuperation. A break may be taken in a moving vehicle, provided no work is undertaken.

After a driving period of no more than 4.5 hours, a driver must immediately take a break of at least 45 minutes unless he takes a rest period. A break taken in this way must not be interrupted. For example (Figure 22):
Figure 22: Guidelines for continuous driving (or with other work)

Alternatively, a full 45 minute break can be replaced by one break of at least 15 minutes followed by a break of at least 30 minutes. These breaks must be distributed over the 4.5 hour period. Breaks of less than 15 minutes will not contribute towards a qualifying break, but neither will they be counted as duty or driving time. The EU rules will only allow a split-break pattern that shows the second period of the break being at least 30 minutes, such as the following examples (Figure 23):

Figure 23: Guidelines for split breaks from driving

The maximum daily driving time described by the guidelines is 9 hours; for example (Figure 24):

Figure 24: Guidelines for maximum daily driving

However, this can be increased to 10 hours, twice a week. The maximum weekly driving limit therefore is 56 hours and each 9 hour driving period must be separated by a daily rest period of 11 hours or more. The guidelines for commercial vehicle drivers are currently one of the only forms of reference for drivers regarding correct breaks from driving implementation and solely focus on safety. However, these guidelines vary across different countries and there are some interesting contrasts between regulations for different countries with the EU guidelines providing the most restrictive regulations in terms of driving hours (9 hours) while Canada has the least restrictive (13 hours). Furthermore, there is a large variation in break duration and break frequency with the US guidelines providing no mandatory break duration (Table 5).
<table>
<thead>
<tr>
<th>Regulation</th>
<th>European Union</th>
<th>United States</th>
<th>Canada</th>
<th>Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum On-Duty Time</td>
<td>9 hours (10 hours max, 2 times weekly)</td>
<td>11 hours in a 14 hour period</td>
<td>13 hours in a 24 hour period</td>
<td>12 hours in a 24 hour period</td>
</tr>
<tr>
<td>Maximum Daily Driving Time</td>
<td>4.5 hours</td>
<td>11 hours</td>
<td>Not specified</td>
<td>5 hours</td>
</tr>
<tr>
<td>Minimum Mandatory Break Time</td>
<td>0.75 hours (can be split into 15 and 30 min breaks)</td>
<td>None specified</td>
<td>2 breaks consisting of 15 min</td>
<td>0.5 hours for every 5 hours driving time</td>
</tr>
<tr>
<td>Minimum Daily Continuous Rest</td>
<td>11 hours (9 hours max. 3 times weekly)</td>
<td>10 hours, or 8 hours and 2 hours using the sleeper berth provision</td>
<td>10 hours, or 8 hours and 2 hours using the sleeper berth provision</td>
<td>6 hours</td>
</tr>
<tr>
<td>Daily Cycle</td>
<td>20.75 hours (min. 18.75 hours, max 21.75 hours)</td>
<td>24 hour goal (14 hours during driving duty and 10 hours rest: including meals and fuel stops)</td>
<td>24 hours</td>
<td>24 hours</td>
</tr>
<tr>
<td>Time Off After Days of Driving</td>
<td>45 hours after 6 days of driving</td>
<td>10 hours off, provided the 60/70 hours in 7/8 day schedule is met, or a 34 hour reset</td>
<td>24 hours every 14 days</td>
<td>24 hours after 72 hours working</td>
</tr>
<tr>
<td>Total Driving Time per Period</td>
<td>56 hours in 7 days</td>
<td>60/70 hours in 7/8 days moving window</td>
<td>70/120 hours in 7/14 days</td>
<td>72 hours in 7 days</td>
</tr>
</tbody>
</table>
These guidelines are not a requirement for non-commercial drivers. It could be assumed that, although performance of a private driver is important, comfort is an equally important factor for private drivers undertaking long journeys. With this in mind, one question is to ask how successful these guidelines might be from a comfort perspective. The EU guidelines suggest a duration of 4.5 hours driving before requiring a break from driving; however this is unrealistic in terms of driver discomfort for both private and commercial drivers. Discomfort increases with time (Mansfield et al., 2015) and previous literature suggests that drivers undertaking a journey of 4.5 hours continuous driving will experience high levels of discomfort (El Falou et al., 2003). Possibly, in terms of reducing discomfort, it is more sensible to split this 4.5 hour drive into 2 shorter drives as described in Figure 23. Therefore the driving duration would be reduced to a drive of 2 hours and a drive of 2.5 hours for example. Gyi & Porter (1999) determined that drivers would be reporting high levels of discomfort after 2 hours of driving and suggests that there would be a need for discomfort reduction after this time period.

As private drivers have few factors controlling the frequency at which they are able to take breaks from driving, unlike professional drivers, the time at which a driver can take a break is not specified and quite flexible. Therefore, breaks from driving could be planned into a long term journey prior to the trip or during the journey itself. Due to this flexibility there may be a temptation for drivers to wait until they consciously feel the need for a break due to high levels of discomfort; however this may not be successful in minimising discomfort. Rest breaks taken after the point at which performance has begun to decline are likely to be less effective in promoting recovery, with only temporary respite from the decline in performance being achieved (Murrel, 1962). The same could be assumed for discomfort; however there is no evidence to support this theory.

Another issue, from a discomfort perspective, is the definition of a break suggested by the guidelines. The guidelines report that a break may be taken ‘in a moving vehicle, provided no work is undertaken’. The fact that the main factors contributing to automotive seat discomfort highlighted by the literature are long term sitting, a restricted posture and long term exposure to vibration suggests that
remaining seated in a moving vehicle will not be effective in reducing car seat discomfort rendering this break from driving almost irrelevant. Therefore, research should be conducted that investigates the effect of breaks from driving on driver discomfort and furthermore to investigate the benefits of leaving the vehicle when taking a break in comparison with remaining seated in the vehicle. In order to fully understand the factors surrounding driver discomfort, the effect of breaks from driving should be further investigated as this may have a large impact on future guidelines for drivers but also how discomfort is perceived and modelled.

2.7 Summary
The literature review conducted in this chapter has highlighted some major gaps in knowledge within the current field of driver discomfort and the potential benefits of further research into these areas has been discussed. Driver discomfort during long duration driving is not yet fully understood and in order for vehicle seat designers to effectively design comfortable seats for the future that minimise the effects of long duration driving and vibration exposure it is crucial that further research aims to determine the effects. The majority of research conducted until now has failed to encompass all of the factors that influence driver discomfort and a multifactorial approach is necessary.

Improvements in seat design are useless if successful evaluation of the designs is not achieved. Many issues have been highlighted with the current methods of discomfort evaluation in place across the industry and major benefits have been highlighted with the standardisation of discomfort measurement. If this can be achieved, this may not only have an impact on the automotive industry as there is the potential for any successful method to be implemented into any form of seating evaluation from office chairs to aircraft seats. Standardised measurement may also impact the current standards concerned with measurement and assessment of whole-body vibration (ISO2631-1 (1997)).

There becomes a point where improvements in seat design become ineffective as prolonged sitting and vibration exposure will lead to increases in discomfort regardless of how well the seat is designed. The onus is then on the driver to
manage their discomfort and there is the potential breaks from driving to positively impact driver discomfort. However the effects of breaks from driving on driver discomfort are not well defined and further research is needed to establish what happens to driver discomfort following cessation of vibration exposure. The literature review has highlighted these areas as opportunities for future research and helped in developing the aims for this research.
CHAPTER 3

Experimental Methodologies

This chapter describes the experimental design, use of equipment, the test configurations, calibration and validation methods implemented in this research. The analysis methods are described and include a newly developed method to objectively measure overall car seat discomfort. Table 6 provides an introduction to the studies that have been conducted in the thesis and includes a report of the equipment used and methods of data collection and analysis employed.

3.1 Experimental Overview

As described by Reynolds (1993), to solve problems encountered during the development of a new automotive product, ergonomists rely on a number of different approaches. Figure 25 describes three basic approaches to solve a problem. This research intends to utilise the ‘hypothesis and experiment’ approach and the experimental chapters in this thesis will follow this structure.

Figure 25: Problem-solving approaches (adapted from Reynolds (1993))
Three laboratory studies and one observation study were conducted for this thesis and 4 Chapters are dedicated to reporting the findings of these studies. The experimental laboratory work in the UK was carried out in the Environmental Ergonomics Research Centre at Loughborough University and the laboratory work in Japan was conducted at Kinki University. The laboratory studies investigated the subjective responses and behavioural responses of subjects to the required driving conditions and whether a newly developed objective measure of discomfort is sufficient in predicting subjective responses. This was tested across largely differing laboratory conditions. The observation study acts as a real world analysis to ensure that the conditions and behaviour required of the participants during the final study can be regarded as replicating real world situations.

3.2 Experimental Development

3.2.1 Developing the Knowledge of Driver Discomfort in Long Duration Driving and Combatting the Effects

The first aim of this research was to further the knowledge of driver discomfort during long term driving and how these effects can be combatted. The studies were designed to tackle issues surrounding discomfort in long term driving. The studies in this thesis were designed so that, where possible, the results and conclusions drawn from one study could inform the design of the next. The research conducted in Chapter 4 was developed from the analysis of the literature during the literature review in Chapter 2 and also continued the research conducted by the experimenter in Mansfield et al. (2015). The results of this study were then used to determine the aims for Chapter 5 as the study in Chapter 5 intended to validate the findings of Chapter 4 with largely different conditions and sample.

The observation study in Chapter 6 was then conducted to gain a real world understanding of the behaviour of drivers during long duration driving and inspired and informed the design of the experiment conducted in Chapter 7. The results and conclusions obtained during Chapters 4, 5 and 6 provided the basis for the research questions to be addressed in Chapter 7, in addition to the knowledge and gaps in knowledge exposed by the literature review in Chapter 2.
Table 6: Outline of the laboratory and observation studies’ main objectives and measurement conditions

<table>
<thead>
<tr>
<th>Study</th>
<th>Objectives</th>
<th>Equipment</th>
<th>Measurements</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjective and Objective Discomfort during Long Duration Driving Trials (Chapter 4)</td>
<td><strong>Driver Discomfort:</strong> Conduct extended duration driving trial, determine effects on discomfort. <strong>SFM Method:</strong> Determine the success of method</td>
<td>LABORATORY Biometrics data logger, MAVIS platform, XPI driving simulator, driving rig, digital video recorder, discomfort rating scale</td>
<td>Acceleration at seat surface, subjective discomfort ratings, video analysis of seat fidgets and movements</td>
<td>Continuous driving for 140 minutes</td>
</tr>
<tr>
<td>Subjective and Objective Discomfort during Long Duration Driving Trials with Japanese Participants (Chapter 5)</td>
<td><strong>Driver Discomfort:</strong> Determine effects of long term driving with a different sample in different driving conditions. <strong>SFM Method:</strong> Validate findings with different sample in different lab conditions.</td>
<td>LABORATORY Stewart platform, Brüel &amp; Kjær (Type 4515-B) accelerometer, Rion VM-54 Meter, driving simulator with seat and controls, subjective rating scale, GoPro</td>
<td>Acceleration at the seat surface, subjective discomfort ratings, video analysis of seat fidgets and movements</td>
<td>Continuous driving for 60 minutes</td>
</tr>
<tr>
<td>Field Observation of Typical Driver Behaviour during Breaks from Long Duration Driving (Chapter 6)</td>
<td><strong>Driver Discomfort:</strong> Determine duration of breaks and behaviour during breaks. <strong>Inform Design of Chapter 7</strong></td>
<td>OBSERVATION Stopwatch, pen, paper</td>
<td>Duration of break, type of vehicle, number of passengers</td>
<td>n/a</td>
</tr>
<tr>
<td>Subjective and Objective Discomfort when Taking Breaks during Long Duration Driving (Chapter 7)</td>
<td><strong>Driver Discomfort:</strong> Determine effects of breaks from driving and type of activity on discomfort. <strong>SFM Method:</strong> Determine accuracy of the method with acute changes in discomfort</td>
<td>LABORATORY Biometrics data logger, MAVIS platform, XPI driving simulator, driving rig, Microsoft HD webcam, discomfort rating scale, treadmill, chair</td>
<td>Acceleration at seat surface, subjective discomfort ratings, video analysis of SFMs</td>
<td>3 trials: (1) 60 minutes driving – Walk – 60 minutes driving. (2) 60 minutes driving – Sit – 60 minutes driving. (3) 60 minutes driving – Walk &amp; Sit – 60 minutes driving.</td>
</tr>
</tbody>
</table>
3.2.2 Developing an Objective Measure of Driver Discomfort

In conjunction with furthering the knowledge of long term driver discomfort, the ultimate aim of this thesis was to determine the success of a novel objective measure of overall car seat discomfort and assess its ability to be implemented into the automotive industry. Therefore each laboratory study aimed to test the methodology and each study aimed to investigate a different aspect of the method whilst validating its success.

The first in the series of laboratory studies implemented the novel method and determined the success of the method. The subsequent laboratory studies aimed to validate the findings by applying the method in varying laboratory conditions with varied samples and aimed to assess the robustness of the method by altering the driving conditions under which it was tested. The final laboratory study aimed to test the method with much the same sample under multiple conditions to determine the methods’ ability to detect acute changes in discomfort across multiple conditions, as such:

- Chapter 4: Determine the success of novel method
- Chapter 5: Validate findings with altered sample and laboratory conditions
- Chapter 7: Determine the accuracy of the method in detecting acute differences by testing under the multiple conditions with largely the same sample

A diagram describing the experimental conditions and interactions between the different experimental chapters can be seen in Figure 26.
3.3 UK Laboratory Studies

This section will outline any methods and equipment used common to all UK laboratory studies whilst discussing any pilot studies conducted in order to make improvements to the methods (Figure 27). This section will be relevant for research conducted in Chapter 4 and Chapter 7.
3.3.1 Motion Simulation

Both UK laboratory studies (Chapter 4 & Chapter 7) utilised the Rexroth Hydraulyne B.V Micro Motion 600-6DOF-200-MK5 multi-axis vibration simulator (MAViS) housed in the Loughborough University Environmental Ergonomics Laboratories (Figure 28). All vibration conditions were simulated using MAViS. The simulator is capable of producing motion in the range of 1-25Hz and the vertical, lateral and fore-aft peak to peak displacement is 180mm and roll, pitch and yaw peak to peak angles are 20 degrees. The distortion for single axis sinusoidal motion is specified at <10% displacement and cross talk between axis <10%. The maximum payload for the system is 600kg. An outline of the system can be seen in Figure 29.

Figure 28: Multi-axis vibration simulator (Loughborough University, UK)
Normal operation of the system would be as follows:

- Subject seated on seat fixed to a rig on top of the platform with safety belt fastened
- Area around the platform would be cleared and cordoned off with a safety barrier
- The vibrator would then be pressurised and set to the neutral position (from -0.15m to 0.0m)
- The required vibration exposure would then be specified by the operator
- Subject then exposed to vibration for required duration
- The vibrator would then be set to settled position and depressurised
- Subject then asked to disembark the platform
This operation follows a standardised process as reported by other research that employed the same system. Much of the research in the field of vibration utilises a similar system on varying scales, ranging from very large platforms to smaller platforms, however the procedure of operation remains relatively constant between different laboratories.

### 3.3.1.1 Safety Aspects when Using the Vibration Platform

All experiments conducted using the MAViS platform were in accordance with ISO 13090-1 (1998) ‘Mechanical Vibration and Shock – Guidance on safety aspects of tests and experiments with people’. Safety barriers are installed around the platform to outline a ‘safety zone’. This is employed to ensure that there is no possible contact between personnel and the motion platform, or any parts fixed to it. No entry into the safety zone is permitted whilst MAViS is pressurised. An emergency stop button was in reach of the experimenter at all times, although stopping the system was also possible without the use of the emergency button to avoid the shock exposure caused by an abrupt stop in the case of a non-emergency stop request, for example a participant request.

The platform is controlled by one dedicated computer that has no general purpose software or networking capabilities to ensure sole control of the platform. A mechanical end-stop cushioning system is included in the system’s actuators to avoid end-stop shocks. Furthermore there are additional accumulators added to the hydraulic system to dampen motion during depressurisation in the event of a power or mechanical failure.

In order to monitor the exposure and modify this if necessary, eight accelerometers are mounted on the MAViS platform and real time acceleration data can be observed via the use of laboratory PCs throughout the experiments. These accelerometers can be used to confirm whether the exposures of the participant are below the thresholds of risk outlined in the international standards and also to ensure that the motion platform is calibrated correctly.
3.3.1.2 Simulating Vibration Exposure

The vibration stimuli implemented in the experiments was designed to best replicate real world driving conditions. This was obtained by utilising vibration recordings of real road driving. The recording implemented in this research was a recording of a rough city road in Finland which was then inputted into the computer controlling the MAViS platform and recreated to the desired magnitude. This recording was conducted during research by Marjanen (2010). As to which vibration exposure to use in these experiments was determined during a pilot study conducted prior to commencing this research and will be discussed in Section 3.3.2.1.

3.3.1.3 Measuring Vibration Exposure

In order to measure the vibration exposure relevant to the driver, or subject, a tri-axial accelerometer contained inside a flexible disc, or SAE pad, was used to record the vibration at the seat surface. This accelerometer (S2-10G-MF, Biometrics Ltd, UK) weighs 15g. The sensitivity of the accelerometer is ±1V and the operating range is ±16g.

This accelerometer was calibrated using a simple inversion test. For accelerometers that are capable of measuring continuous acceleration, the acceleration due to gravity is a convenient and cheap known acceleration source (Mansfield, 2005). This means that when an accelerometer is aligned so that it is sensitive in the vertical direction, it outputs +1g (9.81 m/s²), reflecting the presence of gravity. Therefore, any horizontal surface can be used to calibrate the accelerometer by implementing an inversion test whereby the accelerometer is initially placed on a horizontal surface, then flipped upside down, then returned to its original position. It is, however, usually convenient to use an offset to set the vertically aligned output to zero, meaning that when the accelerometer is inverted it measures -2g (-19.62m/s²). The typical output for an offset inversion test (Figure 30) is well documented and was used to test the calibration of the accelerometer prior to its use in each experiment.
Figure 30: Typical signal from a piezoresistive accelerometer undergoing an inversion test (taken from Mansfield (2005))

As measurements of vehicle vibration are made using accelerometers mounted to the vehicle as close to the contact point as possible (Mansfield, 2014), when measuring vibration on a vehicle seat, accelerometers are mounted in a flexible disc which is then placed on the seat cushion (Figure 31 and Figure 32).

This procedure was conducted in compliance with ISO 10326 (1992) that specifies: “basic requirements for the laboratory testing of vibration transmission through a vehicle seat to the occupant”. The standard has a description for a 3-axis seat pad (Figure 31) and installation locations for floor, backrest and seat surface used in whole-body vibration measurements.

Figure 31: Cross section of design of flexible disc for mounting seat accelerometers as defined in ISO 10326-1 (ISO, 1992)
Care must be taken when recording to ensure that no unwanted signals are recorded due to ‘seat motion artefacts’ caused by the occupant rather than the motion of vehicle such as ingress and egress and fidgeting in the seat. However it is crucial this data be recorded with a human occupant as body dynamics will change the vibration data at the seat surface (Mansfield, 2013).

Figure 32: Flexible disc containing accelerometer mounted on an automobile seat

Data from the accelerometers was collected using data acquisition hardware, the Biometrics DataLOG MWX8, which allowed the experimenter to record frequency weighted r.m.s acceleration data. The acceleration data recorded was the A-weighted equivalent; specifically WdX, WdY and WkZ as defined previously in Chapter 2 via the summary by Rimmel & Mansfield (2007).

Vibration data was collected over a 1 minute period, using this method for each subject prior to participation in the study for a number of reasons. Firstly, to ensure that the vibration exposure recorded at the seat surface was as expected and in the desired range for that experiment. Secondly, as a method of system characterisation to certify that each subject was exposed to similar levels of vibration by ensuring that each subject was exposed to levels of vibration that
varied by <10% of the desired magnitude. Seat dynamics can be slightly different for different subjects, due to differential driving point mechanical impedance (Mansfield et al., 2014) and therefore the system was checked before each trial. If the vibration exposure measured at the seat surface was not in the appropriate range, the input stimuli were adjusted and the process was repeated until the desired magnitude of vibration was obtained. Finally, to ensure that the experiment could be repeated and to use as a reference to any unexpected results, the vibration exposure for each subject was recorded and documented for future use.

3.3.2 Driving Simulator

The use of a driving simulator was crucial throughout the duration of this research, as highlighted by the literature review, as guaranteeing that participants maintained a natural driving position throughout the study was fundamental in ensuring valid results. As discussed previously in Chapter 2, the driving position differs vastly in comparison with a seated position (Gyi, 2013) and the driving simulator not only provided a realistic experience, following the findings of Pilot Study 1, but ensured that participants maintained a realistic and natural driving posture, as a production vehicle seat was used. As highlighted by Reed & Green (1999) there are three primary justifications for using driving simulation rather than in vehicle testing. Firstly, safety, as some research is too hazardous to conduct in vehicles on the road. Secondly, cost, as simulators allow for changes in the vehicle without having to construct a vehicle with those features and thirdly, perhaps most importantly, experimental control, as a wider variety of test conditions can be prescribed and consistently applied in a simulator than on the road, increasing experimental reliability and validity.

All UK laboratory studies utilised the XP300 driving simulator developed by XPI Simulation, the UK’s most popular road safety education simulator. In order to ensure that the optimum methodology would be utilised in the studies that form the basis of this thesis, a pilot study was conducted to investigate how realistic an experience could be created using the aforementioned MAViS platform and the driving simulator. This will be briefly explained before outlining the details of the driving simulator design implemented in the UK laboratory studies.
3.3.2.1 Pilot Study 1: Investigating Realism when Exposed to a Motion Platform and Driving Simulator

3.3.2.1.1 Introduction

Following the lead set by the aviation industry, simulators have become increasingly developed for both research and training of road vehicle users (Carsten & Jamson, 2011). Driving simulators now have a range of uses and there have been many technical innovations including; video of real scenes and more recently, computer generated environments that have led to immersive experiences that can be very similar to the sensations of driving a real vehicle (Parkes, 2013).

The degree of realism has become an increasingly important issue and the question of how realistic and complete an experience needs to be in order for it to be useful from either a training or more importantly, a research perspective underlines current debate. Some have argued that from a training perspective, high realism is not crucial; however the simple view from a research perspective is that the experience should be of optimum realism (Parkes, 2013).

3.3.2.1.2 Aims and Objectives

Therefore the purpose of this pilot study was therefore to determine the realism of the motion platform and driving simulator to be used for the duration of this research, with the aim of creating the optimum experience in terms of realism. The XP300 driving simulator is able to produce a number of different virtual environments or ‘scenarios’ for the user, ranging from motorway, to city, to rural environments. Furthermore, the MAViS platform is also capable of producing a wide range of dynamic conditions and it was crucial to understand which combination of motion and visual cues best represented a realistic drive.

Therefore the main objectives were to establish the extent to which:

• The motion is perceived to be realistic
• The visual cues are perceived to be realistic
• The motion relates to the visual cues
• The overall experience feels realistic
3.3.2.1.3 Methodology

Due to the nature of the study, Subject Matter Experts were recruited to participate in the study. These participants all had previous experience with the driving simulator and motion platform, or had a background in vibration and vehicle motion. The sample consisted of 4 participants from the staff and student population of Loughborough University. Participants were aged between 18 and 65 and all held a full UK driving licence.

A repeated measures design was used such that each participant took part in 1 trial where they were exposed to 9 conditions. Participants were required to sit on a driving rig mounted on top of the motion platform and undertook 3 different tasks on the driving simulator whilst being exposed to 3 different motion files. Participant were exposed to each condition for 1 minute and were required to report their perception of realism after each condition in the form of a 4 part subjective questionnaire (Figure 33).

![Figure 33: Subjective questionnaire design for realism](image)

The questionnaire is designed to have 4 parts that address different aspects of the system as a whole. As questions 3 and 4 were designed to be more important, these
questions are weighted higher when taking the average of the item ratings; 1.5 and 2 respectively.

All vibration exposure was maintained at 0.3m/s$^2$ weighted r.m.s. and during the trial participants were exposed to three different motion types produced by the MAViS platform:

1. File 1 – 6 axis replay of a recording of a rough city road.
2. File 2 – tri axial random vibration.
3. File 3 – 6 axis replay of a recording of a bumpy dirt road.

During the trial participants were also exposed to 3 different ‘scenarios’ provided by the driving simulator. These scenarios were named:

1. Town
2. Free
3. Motorway

Therefore participants took part in a total of 9 conditions. It is important to note that as each participant would be exposed to all 9 conditions it was crucial to randomise the order of conditions to ensure there were no order effects; this was implemented using a Latin Square.

3.3.2.1.4 Results and Discussion

The key figures from the results are displayed below with a brief discussion. The results in Figure 34 display that File 1 – Motorway was the most successful combination of motion type and simulator scenario; suggesting that participants perceived this condition to be the condition that represented the most realistic driving experience.

File 1 is shown to be the most successful in providing a realistic experience as it scores highest for both combinations with the town and motorway simulator scenarios. Figure 35 shows the average score each motion file received when combined with all three simulator scenarios and demonstrates that File 1 was
considered to be the most realistic when combined with all three simulator scenarios.

Figure 34: Weighted rating of realism for all participants

Figure 35: Mean realism rating for each motion file
3.3.2.1.5 Conclusions and Recommendations

Ultimately, the results of this pilot study show that File 1 was perceived to be the most realistic motion type when combined with the scenarios provided by the driving simulator. It was reported that the motion presented by File 1 had a high correlation with the visual cues provided by the driving simulator and that it represented the most realistic driving experience in terms of motion. Motion was found to play a more important role in influencing the participants’ perception of realism which is why File 1 scored highest in terms of realism.

With respect to the scenarios provided by the driving simulator, ‘Motorway’ was reported as the most realistic experience, closely followed by ‘Town’. The reasons for these findings were qualitatively reported as being a result of these particular scenarios having minimal stoppages and traffic to engage with. Therefore the motion from File 1 should be used in combination with these simulator scenarios to produce the most realistic experience. However, the highest mean score for either of these scenarios was still only slightly more than 2.5 out of 6. This implies that improvements may be necessary to obtain a sufficiently realistic experience.

Qualitative recommendations from participants to improve the experience included:

- Improved scenarios for the driving simulator that combine both town and motorway driving
- Reduced contact with the experimenter

The findings of this pilot study determined the motion simulation implemented in the UK laboratory studies and provided the basis for the design of the driving simulator.

3.3.2.2 Virtual Reality Software

Following the findings of Pilot Study 1, the software for the driving simulator was updated in order to obtain a more realistic virtual environment as determined by the recommendations made by subjects. A newly developed simulator scenario was provided by XPI simulation that incorporates town, rural and motorway driving as a continuous experience and all future research includes the new scenario to ensure a
highly realistic experience for participants. It includes interaction with traffic, various different road types with varying speed limits and requires drivers to perform a range of different manoeuvres and driving tasks, as well as displaying a speed dial and full set of mirrors. This scenario was developed in association with Road Safety Professionals and was based on UK driving, in a UK city and town environment and follows standard UK road rules (Figure 36).

A number of standardised routes were designed that navigated drivers through the virtual environment and incorporated the various different road conditions. These routes were designed in order to control the workload of the task so that when driving on the simulator, subjects were exposed to the same driving conditions and had a similar experience, in terms of workload. This was crucial as workload may affect perceptions of discomfort and in order to accurately assess discomfort all participants must experience as similar a task as possible.

As proposed by Pilot Study 1, another improvement to be made was to reduce the contact with the experimenter. Therefore, in order to do this, increase realism and ensure that all participants completed the same pre-determined routes when driving on the simulator, a GPS style navigation soundboard was developed that allows the experimenter to provide the participants with audio cues to successfully direct them around the different pre-determined routes during the experiments. The soundboard was controlled by the experimenter and this soundboard along with one of the predetermined routes can be seen in Figure 37.
Each icon on the soundboard would produce a different instruction audibly to the subject driving. These instructions were adapted from a standard commercially available GPS navigation system for drivers and the different instructions are as follows:

- Ahead, turn left: Turn left at the roundabout, first exit
- Turn left: Go straight at the roundabout, first exit
- Ahead, turn right: Go straight at the roundabout, second exit
- Turn right: Turn right at the roundabout, second exit
- Please pull over to the left: Turn right at the roundabout, third exit
- Turn right at the roundabout, fourth exit
3.3.2.3 Equipment

The equipment required for the driving simulator consisted of 4 screens, 2 speakers, the computer required to run the XP300 XPI simulator software and the controls required to drive the simulator including the steering wheel mount and pedal mount. The system consists of 3 screens to provide a wide angle field of view for the driver and 1 smaller screen for the use of the experimenter. The wider viewing angles gives a more realistic feel to the driver and better peripheral vision for assessing speed and approaching hazards. The screens used to display the visual aspect of the simulation to the driver were 3 Toshiba 47VL963 TVs and were situated in front of the motion platform. The precise design of the set up can be seen in Figure 38. The angle of the screens adjacent to the centre screen was defined via the specifications of provided by the manufacturer as was the viewing distance. The viewing distance is described when the seat was set in the fully back position. This distance was approximately 2.5m and varied slightly with the preferences of each individual participant.

![Figure 38: Simulator screen set up with viewing distance and angles defined](image-url)
The computer used for the driving simulator software was solely used for this purpose and was only controlled by the experimenter during the experiment. The speakers used to provide the audio for the simulator and the GPS navigation system were 2 Mackie Thump TH-15A two-way powered loudspeakers and the volume was controlled so that it was the same for each participant.

The controls such as the steering wheel mount and pedal mount were included in the driving rigs designed to host the driver, these will be outlined in Section 3.3.3. It is important to note that the driving simulator was set to automatic transmission as issues have been highlighted with using manual transmission when using driving simulators.

**3.3.2.4 Blackout Environment**

In order to further reduce contact with the experimenter and further enhance the realism of the driving experience, a ‘blackout’ environment was installed surrounding the driving rig, MAViS platform and driving simulator screens. This consisted of blackout sheets positioned around the sides, front and as a roof for the testing area.

![Figure 39: Blackout environment surrounding the test area](image-url)
This ensures that the only focal point for the driver is the 3 screen system positioned in front of the driving rig. This helped to ensure a sense of presence and immersion in the virtual environment as it allowed the subject very few visual cues relating to the real world surrounding them (Figure 39).

3.3.2.5 Crashing

Due to the design of the software used for the driving simulator, it was possible for participants to crash during the drive on the simulator. This posed no risk in terms of safety, however it was crucial that this was addressed as it was inevitable that some participants would crash during the experiments. In the case of a crash the simulation would stop; the experimenter was then required to restart the simulation immediately as to not allow the participant any opportunity to pause from the driving task. This was done very simply by clicking one button and the participant would then immediately return to the driving task. Upon returning to the driving task, participants would be directed via the fastest route back to the location of the crash in order to continue with the predetermined route that they were following.

It was important that participants were not allowed any opportunity to break from the driving task, as breaks from the task would provide the subject with the opportunity to alter their posture and therefore potentially relieve some of the discomfort they may be experiencing (Herman & Bubb, 2007). As the focus of this research was to accurately measure discomfort, it was crucial that no negative aspects of the driving simulator, such as crashing, had adverse implications on the results.

Subjects were informed prior to participation in the experiments that care should be taken when driving and that performance, in terms of number of crashes, was being monitored, encouraging subjects to minimise the number of crashes during their drive. A mock competition was proposed to subjects whereby the ‘winner’ would be the subject with the least number of crashes. This method proved to be extremely successful as the majority of subjects recorded zero crashes during the trials.
3.3.2.6 Safety Aspects when Using the Driving Simulator

One safety aspect that had to be considered when exposing participants to the driving simulator was the possibility of the subject experiencing motion sickness. Motion sickness by definition occurs when an individual is exposed to real or apparent motion. In some situations, such as in some driving simulators, the motion sensing signals being interpreted by the brain are inconsistent with each other (Mansfield, 2005). The basis for the cause of motion sickness is that if there is a conflict between the expected sensory signals and the sensory signals actually experienced, an imbalance can result in sickness, known as sensory conflict. As the motion produced by the motion platform and the visual cues provided by the driving simulator are not completely linked then the chance of a participant experiencing motion sickness must be accounted for.

One weakness of the driving simulator system implemented in these trials was that the visual cues provided by the driving simulator did not directly influence the motion output of the MAViS platform, for example when breaking, accelerating or manoeuvring around corners. This posed the potential for sensory conflict due to the mismatch between driving simulator and motion experienced.

Therefore, participants were informed of their right to quit the trial at any point if they began to experience symptoms of motion sickness and furthermore participants were required to undertake a brief motion sickness susceptibility questionnaire (MSSQ) prior to participation in the experiments. This questionnaire will be discussed later in this chapter.

3.3.3 Driving Rigs

Two rigs were developed that housed a car seat along with the steering wheel and pedals used to control the driving simulator and could be installed on top of the MAViS platform. These rigs were designed using dimensions taken from current production vehicles and were fully adjustable to ensure that there are no adverse effects due to an unrealistic or unnatural driving position.

The seats included on both rigs were current production seats provided by the manufacturers. The seat included on Rig A was a Toyota Rav4 seat and the seat
included on Rig B was a Nissan NV200 seat. It was important to use real seats currently in production in the industry in order for the objective measure of discomfort to be tested reliably.

Furthermore, both steering wheels used are current performance steering wheels to ensure that there were no detrimental effects to the ecological validity of the research due to the look and/or feel or the steering wheel. Similarly, the pedals used to control the driving simulator were current production pedals and replicated the dimensions that particular rig had been based on.

This was to ensure that a realistic environment was created with the aim of ensuring a high level of control and eliminating any factors that could have a detrimental effect on the data collection. The dimensions for these rigs can be seen in Figure 40 and Figure 41 and images of the rigs used can be seen in Figure 42 and Figure 43.

**Figure 40: Dimensions for Rig A**
Rig B Dimensions

Seat Fully Back
Seat Fully Raised
Units = mm

Steering Wheel Angle = 39°
Steering Wheel Diameter = 369 mm

Figure 41: Dimensions for Rig B

Figure 42: Image of Rig A installed on MAViS
3.3.4 Thermal Environment

Another aspect of the laboratory set up that was designed to be controlled was the thermal environment of the laboratory. As the thermal environment has been shown to affect ratings of discomfort in vehicle drivers (Brooks & Parsons, 1999; Hodder, 2013) it was crucial that this factor was controlled in order to obtain ratings of discomfort that were comparable between subjects. Furthermore, the thermal environment has been shown to affect the performance of the foam used in vehicle seating in terms of vibration damping performance (as recommended by the manufacturer) and materials used for the seat may elicit different ratings of discomfort under different thermal conditions (Fung & Parsons, 1993; Fung, 1997).

As a result, the temperature and humidity in the laboratory was controlled and measured during each trial. Temperature (°C) and humidity (%RH) were measured prior to each trial and recorded using a Solex SE126 Digital Humidity / Temperature Meter. This was to ensure that each participant was exposed to similar thermal conditions and ensure there were no adverse effects due to the design of the
thermal environment. Measurements were taken in the space directly where the subject would be sitting in the vehicle seat.

Furthermore, as discussed in Chapter 2 the thermal environment in a vehicle can mostly be controlled via air velocity as this is the parameter that occupants have the greatest control over via the ventilation system in the vehicle (Hodder, 2013). Therefore, in order to replicate this factor, 2 small electric fans were installed facing the seat that were set to their lowest setting to produce some air circulation as would be experienced in a vehicle. These fans were not in view of the participant and the velocity of the fans remained constant for each trial.

3.3.5 Subjects

3.3.5.1 Ethical Approval

The methods for all laboratory experiments conducted for this research conform to the conditions expressed by the generic experimental protocols approved by Loughborough University’s ethical committee: G05-P1, use of multi-axis vibration simulator; G04-P3, subjective and objective measures of human response to whole-body vibration; G02-P1 quantification of vibration exposure of vehicle occupants’ vibration collection.

The greatest magnitudes of vibration to which participants were exposed were designed to be similar to those experienced in normal road driving, with the total vibration dose not exceeding the lowest criteria for risk specified in the EU physical agents (vibration) directive $0.5m/s^2$ r.m.s A(8). The risks from vibration exposure were controlled by monitoring the vibration dose. Some of the vibration stimuli may cause discomfort to participants; this was a requirement for the research.

Participants were always referred to by number. Records of vibration exposure were kept and archived; any collection and storage of data complied with the Data Protection Act, this included any subjective data and video recordings of participants during the studies.

Participants were informed of their right to withdraw from the experiments at any time on the instruction sheet provided prior to completion of the experiment,
informed by the experimenter verbally and posters were displayed around the laboratory to the same effect. Written consent was obtained from participants prior to participation in the experiments and exclusion criteria was determined by a health screening questionnaire. Participants were chaperoned at all times during the experiments and all studies took place during office hours whilst the laboratories and facilities are occupied.

3.3.5.2 Informed Consent and Health Screening Questionnaire

All participants were provided with a ‘Participant Information Sheet’ upon arrival to the laboratories that informed them of the aims and procedure of the experiment. Participants were encouraged to familiarise themselves with the format of the experiment, the environment and asked to clarify any queries they may have before signing the informed consent form. Furthermore, participants were required to complete an informed consent and health screening questionnaire before participation in the studies. An example of these can be found in Appendix A1 and participants were unable to partake if they did not satisfy the criteria outlined in the ‘Guidance for experimenter (from ISO 13090-1)’ section on page 4 of Appendix A1.

3.3.5.3 Motion Sickness Susceptibility Questionnaire (MSSQ)

In addition to the health screening questionnaire, participants were also required to complete a brief motion sickness susceptibility questionnaire to ensure that any participants who were extremely vulnerable to the effects of motion sickness were not exposed to the driving simulator and therefore not permitted to partake in the experiment, as was the case with one participant.

The questionnaire used was the Reason & Brand MSSQ (Short) (1975). This is a simple motion sickness susceptibility questionnaire that quickly allows the experimenter to calculate a score for each subject, depending on the results of the questionnaire, and establish how susceptible that subject may be to experiencing motion sickness whilst using the driving simulator. Any participants that scored high levels of motion sickness susceptibility were informed of the results of the questionnaire and told that they could withdraw from the study immediately if they felt it necessary. A copy of the MSSQ (Short) can be found in Appendix A1.
3.3.5.4 Recruitment

As the sampling strategy adopted is associated with the external validity of research findings, or the success at which results can be generalised from the sample to the population (Robson, 2002) it was crucial that an appropriate strategy was implemented. There are a number of various sampling strategies in place across all research, each with their own benefits and limitations (Table 7).

Table 7: Summary of sampling strategies used in research (adapted from Allison et al., 1996)

<table>
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<th>Strategy</th>
<th>Summary</th>
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</table>
| Simple random sampling | • Obtain a sample frame, number each subject in the frame and choose numbers at random  
• Every subject has an equal chance of being selected  
• Good chance of obtaining a representative sample                                                                 |
| Systematic sampling    | • 1st subject selected at random; further subjects selected at equal intervals thereafter e.g. every tenth subject                          |
| Stratified sampling    | • Used to split the population into a number of smaller sub-groups e.g. male / female  
• Used when it is thought that the characteristics of the sub-groups will have an effect on the data being collected  
• Once strata identified, a simple random sample is taken from each sub-group                                             |
| Quota sampling         | • Similar to stratified sampling but accepting subjects that are available from sub-groups                                               |
| Cluster sampling       | • Splitting the population in to sub-groups called clusters  
• Each cluster represents the various characteristics that the population might contain                                         |
| Judgement sampling     | • Subjects included that are thought to be representative of the population                                                                    |
| Convenience sampling   | • Includes subjects that are immediately to hand                                                                                               |

This research used a combination of both stratified sampling and quota sampling as these strategies represented the most successful and logical methods to obtain a sample that reflected the desired population but also allowed for a quick and simple
recruitment process. It was important to use a strategy that allowed the investigator to aim to recruit a sample that contained a range of age groups and also an even distribution of males and females, but that also allowed for some further criteria to be included in the selection process.

Participants were primarily recruited from the staff and student population of Loughborough University and from the surrounding area of Loughborough and Leicester. Recruitment methods mainly consisted of email advertisement, posters around the university and via word of mouth. A wide range of anthropometric data was desired and in the case of over recruitment, decisions were made in relation to anthropometry. Participants were not paid for their time. Furthermore, participants were only allowed to participate in the research if they held a full UK drivers licence and had been driving regularly in the year prior to the study to ensure that posture and task required would be familiar.

3.3.5.5 Participant Data

Participants’ date of birth, gender, stature and weight were all collected prior to participation in the study. Stature was recorded in cm using a free standing stadiometer and weight was recorded in kilograms (kg) using an electronic scale (Mettler Toledo kcc150). This allowed body mass index to be calculated if necessary using the standard formula:

\[ BMI = \frac{h^2}{m} \]

Where: \( h \) = height (m) and \( m \) = mass (kg).

3.3.6 Subjective Methods

All laboratory studies asked participants to rate their perceived discomfort subjectively at clearly defined time periods. These responses were reported verbally and participants were asked to provide ratings of discomfort firstly regarding their local discomfort, or body part discomfort, and secondly regarding their overall discomfort, or overall level of perceived discomfort. Subjective methods of discomfort analysis were included due to the range of factors that influence driver
discomfort and due to the issues related with objective assessment. It has been reported that the perception of discomfort is not only affected by physiological factors but is also influenced by mental fatigue and monotony (Ravnik, 2011). This suggests that many of the objective measures previously investigated are not sufficient in describing a driver’s true discomfort level and that, although there are many issues with subjective assessment, subjective methods are crucial until a successful objective measure has been determined and in order to determine the success of an objective measure, the findings must be first compared with subjective responses.

The research in this thesis is mainly concerned with the drivers’ perception of overall discomfort however local discomfort responses were collected for a number of reasons. As local discomfort responses were designed to be collected prior to responses for overall discomfort, participants were required to consciously reflect on the discomfort they were experiencing at that moment in each part of their body. Previous research by Mansfield et al. (2015) found that asking participants to consciously reflect on their local discomfort improved the quality of the responses provided for overall discomfort.

In addition to this, collecting data for local discomfort also provides the researcher with the ability to assess whether the responses collected for overall discomfort are in fact an accurate representation of the driver’s perceived overall discomfort level or whether one particular body part is extremely uncomfortable and therefore contributing a significant proportion of the overall discomfort, dominating the results. As reported by Morgan & Mansfield (2014) the most commonly reported side effect of whole body vibration is lower back pain, therefore it is expected that the greatest increase in local discomfort may be observed in the lower back, however a steady increase is expected across all body regions.

### 3.3.6.1 Local Discomfort

As discussed in Section 2.2.4, Porter & Gyi’s (1999) body map was developed at Loughborough University for assessing automobile discomfort. The design was based upon an original by Corlett & Bishop (1976) where instead of assessing
overall discomfort, as was the norm, body parts could be assessed in isolation allowing the identification of problem body areas. The original design was based on a standing individual; however it was developed to represent the seated individual in an effort to reduce subject effort and therefore error and become more relevant to the automotive industry. Porter & Gyi’s experience in this evaluation technique exceeded 20 years and the method was found to be simple to administer and required very little training before use (Porter et al., 2003). The design is simple, with responses ranging from extremely comfortable to extremely uncomfortable (Figure 44).

Figure 44: Porter & Gyi’s body map (1999): 1. very comfortable; 2. moderately comfortable; 3. fairly comfortable; 4. neutral; 5. slightly uncomfortable; 6. moderately uncomfortable; 7. very uncomfortable. Reproduced from Gyi & Porter (1999)

However, following the discussion regarding comfort and discomfort previously in Chapter 2, it was concluded that comfort and discomfort are based on different variables (Zhang et al., 1996) and should therefore be treated as different entities (De Looze et al., 2003). As this research decided to focus solely on discomfort it was crucial that, in order to implement Porter & Gyi’s (1999) body map, the descriptors and design were adapted.
ISO 2631-1 (1997) provides descriptors of the levels of discomfort that can be expected from exposure to vibration. Therefore the design of Porter & Gyi’s (1999) body map was altered to include the descriptors suggested by ISO 2631-1 (1997) (Figure 45). This design is illustrated in Figure 46 and was implemented in all laboratory studies reported in this research as a measure of local discomfort.

<table>
<thead>
<tr>
<th></th>
<th>Not Uncomfortable</th>
<th>A Little Uncomfortable</th>
<th>Fairly Uncomfortable</th>
<th>Uncomfortable</th>
<th>Very Uncomfortable</th>
<th>Extremely Uncomfortable</th>
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**Figure 45**: 6 point discomfort rating scale proposed by ISO 2631-1 (1997)

As the focus of this research is on overall discomfort not all of the body regions outlined in Porter & Gyi’s (1999) body map were included in the design of this local discomfort questionnaire. Only body regions that were highlighted during piloting as largely affected by long term driving were included in order to reduce the amount of time needed to provide these discomfort ratings. These body regions were determined as sufficient in inducing the desired priming affect.

Participants were trained in the use of the local discomfort questionnaire prior to commencing the experiment as sufficient information on the ratings should be provided to the subject so that learning the scale is not an additional effort required
by the subject during the experiment (Shen & Parsons, 1997). Furthermore, a copy of the 6 point rating scale proposed by ISO 2631-1 (1997) was positioned in full view of the participant at all times whilst driving on the simulator to facilitate the subject in rating their discomfort when requested (Figure 47). As to which body part a rating was required for was communicated verbally by the experimenter before collecting the rating.

3.3.6.2 Overall Discomfort

As mentioned previously, local discomfort was mainly used as a tool to prepare participants for the responses for overall car seat discomfort. Therefore, responses for overall car seat discomfort were collected following the responses for local discomfort. The design of the discomfort rating scale to be used to record responses for perceived overall discomfort was discussed earlier in Section 2.2.4. This discomfort scale was implemented previously in a study by Mansfield et al. (2015) and was shown to be very successful in detecting acute changes in discomfort and differences in seat design and vibration conditions. This scale was also in view of the participants at all times whilst driving (Figure 47) and although this may have had negative implications on the ecological validity of the study, not positioning the scales in the participants’ view would have required participants to remember the scales from memory, increasing the demand and workload placed upon subjects and the chance for errors. As discussed in Chapter 2 this may negatively impact discomfort ratings and is one of the major issues with subjective assessment.

3.3.6.3 Continuous Driving

It is also important to note that all discomfort responses during laboratory trials were recorded verbally whilst the participant was still performing the driving task on the simulator. Previous laboratory research into the field of driver discomfort up until this date has implemented a protocol of halting the driving task in order for participants to provide discomfort responses. This can have negative implications on the validity of the responses.

As discussed in Chapter 2, one of the main contributory factors to overall car seat discomfort are temporal factors and the discomfort associated with fatigue from
long term sitting and maintaining a driving posture (Mansfield et al., 2014). If participants are given the opportunity to have a break from the driving task in order to provide discomfort responses, they are also presented with the opportunity to relieve some of their discomfort by altering their posture and relieving the pressure on compressed body parts with impeded blood flow (Herman & Bubb, 2007, Odell, 1978). This can therefore have a negative impact on the validity of the responses provided at that time interval and also the validity of the responses provided at the end of the trial. For example, many researchers (Smith et al., 2015) have implemented the method of collecting discomfort responses every 10 minutes across the duration of an hour drive. If drivers pause the driving task to provide responses, this effectively alters the experiment from representing a 60 minute drive to six 10 minute drives with brief rest periods in between.

This was highlighted in a brief pilot study conducted prior to commencement of this research as upon analysis of driver behaviour during driving trials it was determined that as participants paused the driving task to provide discomfort responses they recorded high numbers of fidgets and movements in the seat and very few movements whilst driving. Another trial was conducted where participants were required to drive continuously and analysis determined that fidgets and movements recorded had no correlation with the times at which discomfort responses were collected. As one of the main aims of this research is to accurately measure and determine the effects of long term driving on driver discomfort it is crucial that participants drive continuously whilst providing discomfort responses in order to ensure high validity in the results.

Therefore, participants were asked to provide discomfort ratings whilst driving and this required some brief interaction with the experimenter. Reporting of subjective discomfort data was designed so that at the appropriate time interval the experimenter would ask the subject if they were ready, then proceed to state the different body locations required for local discomfort using the 6 point discomfort scale (ISO 2631-1(1997)) followed by asking the participant to provide one rating for overall discomfort using the adapted Borg CR100 scale.
3.3.4 Analysis of Subjective Measures

The analysis method implemented for each set of subjective data depended on which scale was used to collect that data. With respect to the overall discomfort ratings collected, due to the special construction, data obtained with the Borg CR scales can be interpreted as ratio data (Borg & Kaijser, 2006) and therefore fulfil the assumptions required for parametric tests. As a result, parametric tests were employed when analysing data for overall discomfort.

3.3.7 Objective Measures

The main aim of this research was to investigate the success of an objective measure of overall car seat discomfort that could be implemented into the automotive industry. As discussed in Chapter 2, one promising method that warranted further exploration was a measure of ICM or in the case of automobile seating; posture changes or fidgets and movements in the seat.

This method is based on the theory that over duration of sitting, occupants’ frequency of movements will increase as subjective discomfort increases. If a measure of drivers’ fidgets and movements can be correlated with subjective
ratings of overall car seat discomfort this opens the door for measurements to be made by remote monitoring and therefore removing the need for subjective responses. Research has shown success in the past with ICM related to sitting discomfort in chairs (Fenety et al., 2000) and posture changes related to driver discomfort (Adler, 2007).

In the case of this research, the term ‘in-chair movement’ was dismissed as automobile seating is referred to as ‘seats’ rather than chairs. The phrase ‘seat fidgets and movements’ was coined as it was deemed more appropriate for the automotive industry and therefore this research will refer to the measure of driver movements as ‘seat fidgets and movements’ or SFMs.

3.3.7.1 Seat Fidgets and Movements

As discussed in Chapter 2, a measure of driver movements was deemed to be successful in accurately predicting overall car seat discomfort; however some issues were highlighted with the current methods employed. Many researchers have previously assessed driver movements by using pressure mats to monitor the drivers’ centre of pressure and recording changes (Na et al., 2005). Issues with pressure mats have been highlighted (Gyi & Porter, 1999) and furthermore this method may encounter difficulties due to the dynamic environment to be investigated during this research, as vibration exposure may negatively affect the quality of the data recorded by the pressure mat.

Adler’s (2007) method of recording posture changes was deemed to be more appropriate and a method to measure SFMs was developed in order to be implemented during this research using Adler (2007) as a reference but aimed to be a less invasive method than Adler’s (2007). Therefore, in addition to recording subjective measures of discomfort, participants were video recorded to allow the investigator to analyse SFMs post trial. As previous research has suggested that not only the frequency of SFMs but also the magnitude of SFMs increase with driver discomfort (Adler, 2007) it was crucial to develop a method that was capable of determining both variables.
The method developed required the experimenter to review the video recording of the participant after the trial and record each time at which the participant recorded an SFM. A framework was developed using the previous research into driver posture changes and ICMs that outlined the definition of an SFM, which movements qualify as an SFM and which type of SFM movements should be recorded as in terms of magnitude. SFM types were defined as:

- Type 1 – any movement of the limbs not related to the driving task
  (excluding transition from two hands to one on the steering wheel, and vice versa, or any scratching/itching of the head and body)
- Type 2 – any movement of the torso not related to the driving task
- Type 3 – any movement of the whole body not related to the driving task

A pilot study was conducted to test this method and the results of this pilot study are briefly discussed in the next section.

**3.3.7.2 Pilot Study 2: The Effect of Long Term Driving and Vibration Exposure on Frequency and Magnitude of Seat Fidgets and Movements (SFM)**

**3.3.7.2.1 Introduction**

Discomfort assessment is a difficult task due to its multidimensional nature and the many different modalities in the perception of discomfort (Zhang et al., 1996). Subjective methods of evaluating perceptions of discomfort are common place throughout the research into the field of driver discomfort, however there are issues related with subjective evaluations as Griffin (2007) highlights that the difference threshold for the detection of change is often less than the change that can be quantified by using subjective evaluation methods. There is the need in the automotive industry for a successful standardised objective measure of overall car seat discomfort to remove the issues related with subjective assessments of discomfort.

**3.3.7.2.2 Aims and Objectives**

The aim of this pilot study was therefore to investigate the effect that duration of driving and vibration exposure has on driver discomfort and how subjective ratings
of discomfort correlate with observed seat fidgets and movements of the participant; with ultimate aim of developing a successful objective measure of overall car seat discomfort. This study aims to investigate both the frequency and magnitude of SFM and the relationship with time and subjective discomfort.

Therefore the research hypotheses (and null hypotheses (nH)) for this study are:

nH1: No correlation will be observed between subjective discomfort and SFMs

H1: A correlation will be observed between subjective discomfort and SFMs

nH2: The frequency of SFMs will not increase

H2: As discomfort increases over time, the frequency of SFMs will increase

nH3: The magnitude of SFMs will not increase

H3: As discomfort increases over time, the magnitude of SFMs will increase

3.3.7.2.3 Methodology

This study consisted of 2 participants from the staff of Loughborough University and participants were asked to complete 60 minutes of driving on the simulator whilst exposed to constant vibration maintained at 0.3m/s² weighted r.m.s. Participants were asked to provide subjective discomfort responses for both local and overall discomfort every 10 minutes and participants SFM data was analysed post trial using the methodology developed previously.

3.3.7.2.4 Results and Discussion

The results obtained in this study can be seen below. In order to correlate subjective overall discomfort and SFM frequency and magnitude; the number of SFMs recorded during the 10 minutes prior to the subjective discomfort responses were totalled and displayed at the same time interval. For example, the number of SFMs displayed corresponding with the overall discomfort rating recorded at 10 minutes describes the number of SFMs recorded between 0-10 minutes.

The results displayed in Figure 48 and Figure 49 show both the subjective overall discomfort ratings recorded and the number of SFMs per 10 minutes observed
against time. Subjective ratings of overall discomfort are shown to increase over the 60 minutes of driving for both participants suggesting that a combination of both dynamic and temporal factors lead to an increase in discomfort, supporting previous literature.

**Figure 48**: Overall discomfort and SFM observations for participant 1

**Figure 49**: Overall discomfort and SFM observations for participant 2
More importantly, there does appear to be some correlation between overall discomfort ratings and the number of SFMs observed as the frequency of SFMs is shown to increase with duration and discomfort increase. Participant 1 shows a steady increase in SFM frequency over 60 minutes and a clear increase can be observed when comparing 0 – 10 minutes and 50 – 60 minutes for participant 2. This evidence suggests that a correlation could be found between overall car seat discomfort and frequency of SFMs, again supporting the previous literature.

Furthermore, a trend can be observed between the type of SFM and time in Figure 48. For participant 1, 33.3% of SFMs from 0 – 20 minutes were Type 1 SFMs, whereas this percentage drops to 21% for 40 – 60 minutes; with Type 3 SFMs increasing from 33% to 42% over the same time period. A similar trend can be observed in the results for participant 2 as Type 3 and Type 2 SFMs become more frequent over time and with increased discomfort, shown in Figure 49.

The type of SFM relates to the magnitude of the movement as explained previously. The literature suggests that the magnitude of SFMs may increase with discomfort increase as the subject must more greatly alter their posture to relieve the onset of discomfort (Adler, 2007). The results obtained during this study provide a suggestion that a correlation could be determined between increased discomfort and increased magnitude and frequency of SFMs. Although this evidence is far from conclusive, the results of this pilot imply that further research could provide a greater insight into this relationship.

3.3.7.2.5 Conclusions and Recommendations

Ultimately, the results of this pilot study suggest that a correlation between overall car seat discomfort and drivers’ seat fidgets and movements (SFMs) may be found with further research and suggests that this method may be applicable to the automotive industry. Therefore future work should aim to investigate the relationships proposed by this pilot study and in the literature with the aim of developing an objective method for evaluating overall car seat discomfort. Future work should also aim to develop and improve the method itself, however initial suggestions are positive.
3.4 Japan Laboratory Study

This section will outline any methods and equipment used in the Japan laboratory study. This section will be relevant for research conducted in Chapter 5 and a brief outline of this section can be seen in Figure 50. The laboratory set up used in the Japan laboratory study was designed such that it best replicated the equipment and experimental design implemented in the UK study in Chapter 4.

**Figure 50:** Diagram outlining Section 3.4

### 3.4.1 Motion Simulation

The Japan laboratory study (Chapter 5) utilised the Stewart platform at Kinki University that has six prismatic joints driven by a DC motor. This platform allows for movement in 6 degrees of freedom (x, y, z, roll, pitch, yaw), as does the MAViS platform used in the UK laboratory studies. Table 8 shows the performance for this platform. Although there are many similarities between this platform and the MAViS platform utilised in the UK studies, there are also some differences. As the main objective of the Japan study was to evaluate if the studies conducted in the UK could be replicated in a different laboratory with different equipment, the differences between the motion platforms should only enhance the success of the results if similar results are observed.

**Table 8:** Japan motion platform performance by axis

<table>
<thead>
<tr>
<th>Moveable Axis</th>
<th>Moveable Scope</th>
<th>Peak Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-axis</td>
<td>-120 to 120 mm</td>
<td>0.4G</td>
</tr>
<tr>
<td>y-axis</td>
<td>-135 to 135 mm</td>
<td>0.4G</td>
</tr>
<tr>
<td>z-axis</td>
<td>-30 to 30 mm</td>
<td>0.1G</td>
</tr>
<tr>
<td>Roll (x-axis roll)</td>
<td>-0.192 to 0.192 rad (-11° to 11°)</td>
<td>---</td>
</tr>
<tr>
<td>Pitch (y-axis roll)</td>
<td>-0.175 to 0.175 (-10° to 10°)</td>
<td>---</td>
</tr>
<tr>
<td>Yaw (z-axis roll)</td>
<td>-0.297 to 0.297 (-17° to 17°)</td>
<td>---</td>
</tr>
</tbody>
</table>
Normal operation of the system would be as follows:

- Subject seated on seat fixed to a rig on top of the platform with safety belt fastened
- Area around the platform would be cleared and cordoned off with a safety barrier
- The vibrator would then be pressurised and set to the neutral position (from -0.1m to 0.0m)
- Subject then exposed to vibration for required duration
- The vibrator would then be set to settled position and depressurised
- Subject then asked to disembark the platform

This operation follows a standardised process as reported by other research that employed the same system and follows a similar procedure to that for the MAViS platform used in the UK laboratory studies. As comparisons will be made between studies conducted in different laboratory conditions it was important to keep the procedures and experimental design as similar to the UK studies as possible.

**Figure 51**: Multi-Axis Vibration Simulator (Kinki University, Japan) with driving rig installed
3.4.1.1 Safety Aspects when Using the Vibration Platform

The safety aspects and procedures when using the vibration platform in Japan followed a similar structure to those adhered to in the UK studies. The experiment conducted using the Stewart platform was in accordance with ISO 13090-1 (1998) ‘Mechanical Vibration and Shock – Guidance on safety aspects of tests and experiments with people’. Safety barriers are installed around the platform to outline a ‘safety zone’. This is implemented to ensure that there is no possible contact between personnel and the motion platform, or any parts fixed to it. No entry into the safety zone is permitted whilst the platform is pressurised. An emergency stop button was in reach of the experimenter at all times, although stopping the system was also possible without the use of the emergency button to avoid the shock exposure caused by an abrupt stop in the case of a non-emergency stop request, for example a participant request.

The platform is controlled by one dedicated computer that has no general purpose software or networking capabilities to ensure sole control of the platform. A mechanical end-stop cushioning system is included in the system’s actuators to avoid end-stop shocks. Furthermore there are additional accumulators added to the system to dampen motion during depressurisation in the event of a power or mechanical failure.

3.4.1.2 Simulating Vibration Exposure

In order to produce a dynamic environment, speed bumps were implemented into the design of the route on the driving simulator at specific intervals (the route and driving simulator will be discussed in the next section). As the simulator itself was not able to produce a constant set level of vibration exposure, as in the UK laboratory studies, these speedbumps were required in order to expose the subjects to a controlled magnitude of vibration.

The height of the speedbumps was determined in piloting prior to the experiment using data presented in Tatsuno et al. (2011) and a diagram representing the design of these speedbumps can be seen in Figure 52. The height of the speedbumps determined the magnitude of vibration exposure and was set at 4cm. Additionally,
so that each participant experienced similar vibration exposure, it was important that each subject drove at the same speed over the speed bumps. This was enforced by adding speed indication alerts to the virtual environment generated by the driving simulator that indicated to the subject which speed they should be driving at specific points during the route. Subjects were informed prior to participation in the study that they must best keep to the speed indicated.

Figure 52: Outline of dynamic environment design (Tatsuno et al., 2011)

Furthermore, in this system, simulator control software (CarSim Ver.8, Mechanical Simulation Corporation) is also used to calculate the vehicle dynamics. The behaviour of the motion platform depends on the setting of the road shape (including speed bumps) and vehicle model. When a subject begins driving, information about the road condition and driving parameters such as the amount of break/accelerator depression and steering angle are also transmitted to CarSim from the UC-win/Road. In CarSim the dynamic behaviour of the vehicle is calculated based on the information transferred from UC-win/Road and returned to the driving simulator to create representative dynamic conditions. This system is outlined in Figure 53.
3.4.1.3 Measuring Vibration Exposure

In order to determine the degree of whole-body vibration generated by the motion platform in relevance to each participant, simple driving experiments were again conducted prior to beginning the full experiment, in accordance with the UK laboratory experiments. A tri-axial accelerometer contained inside a flexible disc, or SAE pad, was again used to record the vibration at the seat surface. This accelerometer (Brüel & Kjær, Type 4515-B) and a vibration meter (Rion, VM-54) were used to measure the weighted r.m.s. accelerations for each subject. The sensitivity of the accelerometer is 100 mV/g and the operating range is ±10g. This accelerometer was again calibrated using a simple inversion test as described previously in section 3.3.1.3 (Figure 30).

This measurement was taken for each subject prior to participation in the experiment and was recorded during a 1 minute practice drive allocated in which participants drove on a practice route that replicated the route and dynamic environment of the full experiment. This directly replicated the procedure implemented in the UK laboratory studies in order to; firstly, ensure that the vibration exposure recorded at the seat surface was as expected and in the desired range for that experiment. Secondly, as a method of system characterisation to
certify that each subject was exposed to similar levels of vibration by ensuring that each subject was exposed to levels of vibration that varied by <10% of the desired magnitude. If the vibration exposure measured at the seat surface was not in the appropriate range, the input stimuli were adjusted and the process was repeated until the desired magnitude of vibration was obtained. Finally, to ensure that the experiment could be repeated and to use as a reference to any unexpected results, the vibration exposure for each subject was recorded and documented for future use.

3.4.2 Driving Simulator

A driving simulator body that housed the seat, controls and virtual environment used in the Japan experiment was mounted on top of the Stewart platform used to simulate the dynamic environment. The simulator was developed by merging flight simulation technologies from the aerospace division of Fuji Heavy Industries and automotive technologies from Subaru automobiles. The driving simulator was used to create a virtual reality driving environment for the subjects. As defined by the pilot study outlined previously (Section 3.3.2.1), a system with a high degree of realism is crucial for performing psychometric experiments and it was important that the system used for the experiment in Japan replicated the experience of the simulator at Loughborough University. This simulator design varied from the UK studies as the virtual environment equipment, controls and seat were all housed in the same driving rig in comparison with being separate components in the UK laboratory. Ultimately this may benefit the research as if the methodologies proposed by this research are to be implemented in the automotive industry it is important that they are compatible with any simulator design.

3.4.2.1 Virtual Reality Software

The software used in the Japan laboratory study to create a virtual reality environment for the drivers was UC-win/Road Ver.5 developed by Forum8 Co., Ltd. Using this software, a 3D virtual reality space can be easily created and modified. The procedure to create a VR simulation with this software is defined in Tastuno et al. (2011) and is described as follows:
1. Contour Mapping: An imaginary contour map is prepared as a sample. In addition, actual contour map data can be used.

2. Road design: Road parameters – vertical alignment, horizontal alignment, road profile and landscape are defined.

3. Simulation conditions: The simulation is designed by setting traffic flow and intersection signal parameters as well as the scenario function.

4. Virtual driving: Subjects can execute the virtual driving task under the conditions set by the experimenter.

Using this method, a virtual reality environment was created for use in this research. So that there were no adverse effects due to the design of the simulator task, the workload and task required by the driving simulator were designed to best replicate the conditions produced by the UK driving simulator. Therefore, the route and road design for this virtual simulation was created using the maps implemented in the UK research.

As the driving simulator used in the Japan laboratory study was less advanced than the UK driving simulator, a simple simulation was designed whereby there was no
other traffic on the road and subjects had a clearly defined route to follow as they were unable to make any wrong turns. The route was designed so that it best replicated the route taken in the UK research and followed a similar pattern in terms of number of right and left turns, the severity of the turns included and the distance between turns. This route can be seen in Figure 54 and is labelled A. The route took roughly 10 minutes and when drivers reached the end of the route they were automatically seamlessly transported to the start of the route again to continue driving.

There was no need for any interaction with the experimenter in order to provide navigation instructions and the route was designed to be one continuous road. This differed slightly from the design of the UK studies; however, the crucial aspect was that there was no interaction with the experimenter during the drive. Furthermore, the design of the simulation was such that it was impossible for subjects to crash during the drive. This removed any need for the experimenter to restart the simulation and removed any possible negative implications due to crashing and therefore altering posture. As mentioned previously, the virtual reality environment would also provide subjects with speed indications that they were required to adhere to.

Figure 55: Rear view of the simulator displaying the VR environment
3.4.2.2 Equipment

The equipment used in this simulation included 3 screens, 4 audio speakers, the computer required to run the simulation software and the controls necessary to control the simulator.

The display configuration used for this driving simulator (Figure 55) was set to 1 x 3 in order to provide a wide viewing angle, as to replicate that of the UK laboratory studies. Each display was a 26 inch colour-LCD. The audio information was provided by a 4.1 surround sound system installed into the driving rig. Furthermore, the controls used to control the simulator were also included in the driving rig design as the rig is designed to replicate a realistic vehicle environment (Figure 56). It is important to note that, as with the UK laboratory studies, the simulator was set to automatic transmission to best replicate a similar experience.

![Diagram of driving simulator equipment]

**Figure 56**: Driving simulator, driving rig and all components (Kinki University, Japan) (taken from Tatsuno et al., 2011)
It was important that both laboratory designs implemented an automatic transmission. Firstly to ensure that participants were exposed to a similar experience but perhaps more importantly, the use of manual transmission in driving simulators is inherently flawed, as such configurations typically provide an unrealistic experience for the user. As a result, only automatic transmission was implemented during this research however further work should aim to determine the impact of manual transmission on driver discomfort as the added workload caused by the use of the clutch may potentially affect drivers’ comfort perception.

3.4.3 Driving Rig

The driving rig implemented in the Japan study is designed to replicate the dimensions another current production vehicle (Figure 56) to ensure a high sense of realism and valid results. The vehicle seat used was a Subaru Impreza seat. The instrument panel is identical to that of a Subaru automobile along with the steering wheel, pedals and vehicle packaging dimensions. The instrument panel is constructed according to Japanese specifications and the design of this rig varied largely from those tested in the UK laboratory studies.

<table>
<thead>
<tr>
<th>Japan Rig Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat Fully Back</td>
</tr>
<tr>
<td>Seat Fully Raised</td>
</tr>
<tr>
<td>Units = mm</td>
</tr>
<tr>
<td>Steering Wheel Angle  = 18.5°</td>
</tr>
<tr>
<td>Steering Wheel Diameter = 372</td>
</tr>
</tbody>
</table>

Figure 57: Japan driving rig dimensions
The steering wheel uses force feedback to give the subjects a feeling of manoeuvring a real vehicle and the design of the rig has a high sense of realism for participants. Furthermore, the seat was again fully adjustable to ensure that there are no adverse effects due to an unrealistic or unnatural driving position. The dimensions for this rig design can be seen in Figure 57.

### 3.4.4 Subjects

#### 3.4.4.1 Ethical Approval

All of the research carried out in the Japan laboratory study adhered to the ethical requirements defined in the UK Laboratory studies (Section 3.3.4.1) but furthermore, adhered to the requirements determined by Kinki University. Written consent was obtained from each participant via the use of a different consent form, which can be seen in Appendix A2. This was provided by Kinki University, in Japanese, and followed the standard procedure for laboratory experiments as outlined by Kinki University.

#### 3.4.4.2 Recruitment

As with the recruitment of subjects in the UK, the recruitment strategy implemented for the Japan study needed to be as rigorous. A combination of both stratified sampling and quota sampling as were therefore implemented again, however due to the time constraints and the location of the study, colleagues in Japan were responsible for applying these methods and recruiting the desired participants prior to the experiment. Again it was important to use a strategy that allowed the investigator to recruit a sample containing a range of age groups and an even distribution between the sexes of the participants, but that also allowed for some further criteria to be included in the selection process.

Participants were primarily recruited from the staff and student population of Kinki University, Japan, and from the surrounding area of Hiroshima. Recruitment methods mainly consisted of email advertisement and via word of mouth. A wide range of anthropometric data was desired and in the case of over recruitment, decisions were made in relation to anthropometry. Participants were reimbursed for their expenses. Furthermore, as with the UK studies participants were only
allowed to participate in the research if they held a full Japanese drivers licence and had been driving regularly in the year prior to the study to ensure that posture and task required would be familiar.

This method of recruitment was fundamentally very similar to that employed for the UK studies. It was important that participant recruitment followed a similar strategy to ensure that a sample was attained that was comparative with the UK sample. If the results of the studies are to be compared it is important that a similar demographic be recruited so that any conclusions made are not simply a product of vastly differing samples.

3.4.4.3 Participant Data

Participants’ date of birth, gender, stature and weight were all collected prior to participation in the study. This data was self-reported. This allowed body mass index to be calculated if necessary using the standard formula, described in Section 3.3.5.5.

3.4.5 Subjective Measures

The design of the study in Japan best replicated the design of the studies conducted in the UK, therefore the collection of subjective responses was implemented in an identical way to that detailed in Section 3.3.6. However, due to the use of Japanese subjects, the discomfort rating scales needed to be adapted to be suitable for Japanese speakers.

3.4.5.1 Local Discomfort

Therefore, the local discomfort scale used in the UK experiments was adapted to include Japanese translations. As the 6 point rating scale utilised in the local discomfort questionnaire design was the 6 point scale proposed by ISO 2631-1 (1997), the Japanese translation was available in the Japanese version of the standard and was therefore directly implemented into the design (Figure 58).
Figure 58: Local discomfort questionnaire design including Japanese translations

The translations used can be regarded as the best possible translations for this purpose due to their inclusion in ISO 2631-1 (1997), however due to the nature of the language some of the phrases are not literal translations. The literal translations are as follows:

<table>
<thead>
<tr>
<th>Japanese</th>
<th>English</th>
</tr>
</thead>
<tbody>
<tr>
<td>不快 で ない</td>
<td>Not Uncomfortable</td>
</tr>
<tr>
<td>少し 不快</td>
<td>A little Uncomfortable</td>
</tr>
<tr>
<td>やや 不快</td>
<td>Slightly Unpleasant</td>
</tr>
<tr>
<td>不快</td>
<td>Discomfort</td>
</tr>
<tr>
<td>かなり 不快</td>
<td>Pretty Unpleasant</td>
</tr>
<tr>
<td>極度 に 不快</td>
<td>Extremely Uncomfortable</td>
</tr>
</tbody>
</table>

As outlined previously in Section 3.3.6 the main purpose of asking subjects to report their local discomfort was to improve the responses for overall discomfort by acting as a primer that required subjects to consciously reflect on their perceived discomfort in each body area.

3.4.5.2 Overall Discomfort

Additionally, the overall discomfort rating scale used in the UK experiments also had to be adapted to include Japanese translations (Figure 59). The translations were obtained from the Japanese translation of ISO 2631-1 (1997) and a Japanese
colleague was responsible for applying the appropriate translation to the equivalent English discomfort descriptor.

As the Japan study followed the same design as the UK studies, overall discomfort responses were collected after recording responses for local discomfort. Subjects provided their discomfort ratings verbally whilst driving and were asked to respond in Japanese to ensure no incorrect responses were given due to misinterpretation.

Figure 59: Overall discomfort rating scale with Japanese translations
3.4.6 Objective Measures

Due to the aims of the research the objective measure implemented in the Japan study was designed to be identical to that in the UK studies. The process of recording and evaluating SFMs remained the same as determined in Section 3.3.7. However, as a result of the equipment available some of the equipment used in the method was altered. The study in Japan utilised a GoPro Hero 3 in order to video record participants during the trials and was again positioned with a similar view of the driver that encapsulated the whole body of the subject.

3.5 Field Observation Study

This section will outline the general methodologies adhered to during the field observation study detailed in Chapter 6.

3.5.1 Ethical Approval

Ethic approval for this study was obtained from Loughborough University Ethical Advisory Committee prior to conducting the study. This field observation adhered to generic protocols G07-P3 (Discrete observation of members of the general public whilst in public spaces in order to identify real design needs). In addition, whilst conducting the study, the experimenter carried an information sheet detailing the design and purpose of the study upon their person at all times during the experiment in the event of any questions from members of the general public. This document can be seen in Appendix A3.
CHAPTER 4

Subjective and Objective Discomfort during Long Duration Driving Trials

This chapter discusses the first in the series of laboratory studies conducted during this research designed to determine the effects of long duration driving on overall car seat discomfort and how this knowledge can be correlated with the behaviour of drivers whilst undertaking a long term drive. This study aimed to continue the work by the author reported in Mansfield et al. (2015) as some of the initial thoughts and ideas were a product of this work.

The study was designed to replicate a realistic long term driving scenario to investigate how driver discomfort is affected when undertaking journeys of extended durations and aims to tackle some of the issues highlighted in Chapter 2. Furthermore an analysis of a novel objective measure of overall discomfort was explored and evaluated. The hypotheses and design of the objective evaluation technique were informed by the findings of Pilot Study 2 discussed previously in Section 3.3.7.2. This study combines long term driving with exposure to normal road level vibration and is the longest known multifactorial trial of its kind in the literature.

4.1 Introduction

Consumers of automobiles not only consider comfort as a luxury, it is now a requirement and consumers often base their perception of a vehicle’s quality on overall comfort. However many consumers still purchase vehicles based on the comfort in the showroom (Mansfield, 2005). It has been well documented in the field of driver discomfort that a showroom analysis, or short term analysis, can be extremely misleading as it fails to encompass many of the factors affecting overall car seat discomfort, such as dynamic and temporal factors.

Porter et al. (2003) demonstrated that short term evaluations of discomfort are inadequate as the effects of fatigue and long term sitting have not been accounted
for. Previous research has recommended that driving trials have a duration of at least 2 hours to accurately determine the performance of a seat (Gyi & Porter, 1999). However, research into non-commercial vehicle driver discomfort has typically implemented trial durations ranging from 60 seconds to 135 minutes (Kolich, 2003a; Gyi & Porter, 1999). This study intends to investigate a longer duration than previously studied and aims to encompass vibration; another important factor affecting driver discomfort as described by Mansfield et al.’s (2014) model. Many studies that aimed to evaluate long term driver discomfort failed to include vibration in the experimental design and therefore this study intends to expose participants to vibration levels typically experienced during normal road driving and will be the longest trial of its kind.

Another issue that currently surrounds the automotive industry is how to accurately quantify overall car seat discomfort. Many objective measures have been employed with varying levels of success, further complicating understanding of the concept (De Looze et al., 2003). Subjective measures of discomfort have been questioned as the validity of subjective measures relies on the ability of the subject to accurately describe their perceived discomfort level and a variety of extraneous factors can influence the subject’s choice (Hermann & Bubb, 2007). This suggests that an effective objective measure may hold some advantages over subjective measures. Previous research proposed that a measure of driver movement or Seat Fidgets and Movements (SFM) may be successful in accurately predicting subjective discomfort (Adler, 2007) and if a measure of SFM can be implemented into the automotive industry, such a finding creates the opportunity to less subjectively measure a subject’s perceived discomfort and opens the door for measurements to be made remotely.

4.2 Aims and Objectives

Therefore this study has two main objectives. Firstly to evaluate the influence of temporal and dynamic factors across a long term drive and determine the rate of discomfort increase with greatly extended driving duration. This study aims to validate the knowledge proposed by the previous literature in the field of driver
discomfort and determine the success of the models proposed. Secondly, to investigate an objective measure of driver discomfort via the analysis of Seat Fidgets and Movements (SFM) and to draw a comparison with subjective discomfort ratings, with the ultimate aim of producing an objective measure to predict subjective assessment. Therefore the aims of this study are;

Long term driver discomfort:

• To determine the effect of extended exposure times on local and overall car seat discomfort
• To analyse the rate of change in discomfort as duration of driving increases

Seat fidgets and movements:

• To determine whether SFM frequency increases with duration of driving
• To determine whether SFM magnitude increases with duration of driving
• To compare the SFM observations with the subjective discomfort ratings reported

The main hypotheses (and null hypotheses (nH)) of this study were:

nH4.1: Driver discomfort will not increase with duration of driving

H4.1: Driver discomfort will increase with duration of driving

nH4.2: SFM frequency will not increase with duration of driving

H4.2: SFM frequency will increase with duration of driving

nH4.3: SFM magnitude will not increase with duration of driving

H4.3: SFM magnitude will increase with duration of driving

nH4.4: No relationship will be observed between subjective discomfort ratings and SFMs

H4.4: A relationship will be observed between subjective discomfort ratings and SFMs
4.3 Method

The study reported in this chapter was conducted at Loughborough University, UK, and as a result utilises the methods determined previously regarding the UK Laboratory studies (Section 3.3) to be reported in this thesis. The equipment and procedures used in this study that were common to all UK laboratory studies have been detailed previously and this section will outline the methodologies implemented that were specific to this study. Firstly, details regarding the sample recruited to take part in the study will be defined followed by outlining how the study aimed to determine the hypothesis for the study stated previously. The independent and dependant variables for the study will be defined and the section will conclude with a detailed description of the experimental protocol undertaken during this study, with specific regards to the design and equipment used.

4.3.1 Sample

The participants recruited for this study were sampled from the local, staff and student population of Loughborough University. All participants were subjected to the inclusion criteria outlined previously in Section 3.3.5 and all participants completed the various health screening, ethical clearance and consent forms. Participant characteristics are defined in Table 9.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>10</td>
</tr>
<tr>
<td>Gender</td>
<td>6 male; 4 female</td>
</tr>
<tr>
<td>Age</td>
<td>22 – 34 years (mean ± sd: 26 ± 4.3 years)</td>
</tr>
<tr>
<td>Stature</td>
<td>163 – 184 cm (mean ± sd: 173.9 ± 7.2 cm)</td>
</tr>
<tr>
<td>Mass</td>
<td>56.4 – 93.1 kg (mean ± sd: 69.9 ± 10.6 kg)</td>
</tr>
</tbody>
</table>

Participants were provided detailed information regarding the purpose of the study, experimental protocol and possible risks associated with participation in the study. Anthropometric data was collected prior to participation in the study.
4.3.2 Independent Variables

4.3.2.1 Driving Task and Duration

All participants were required to drive continuously for a set duration on the driving simulator housed at Loughborough University, detailed in Section 3.3.2. This duration was 140 minutes and all participants completed the same duration of driving with no breaks from the driving task. Participants all completed the same task on the driving simulator as subjects were required to follow pre-determined routes commanded to the subject via the use of GPS navigation style instructions as described by Section 3.3.2.

Subjects completed the driving task whilst seated on a driving rig that had been installed on top of the MAViS platform and all participants used the same driving rig. This rig was Rig A as described by Section 3.3.3 and all participants were allocated time prior to the start of the experiment to adjust the seat as to best replicate their normal driving position.

4.3.2.2 Vibration Exposure

All participants were exposed to 6-axis vibration throughout the duration of the drive on the simulator. Vibration exposure was simulated by the MAViS platform housed at Loughborough University with a mean total magnitude of $0.246 \text{m/s}^2$ weighted r.m.s. System characterisation ensured that all participants were exposed to a vibration magnitude of within 10% of the desired exposure. Details regarding the simulation, measurement and system characterisation of the vibration exposure were detailed previously in Section 3.3.1.

4.3.2.3 Thermal Environment

Measurements of temperature ($^\circ C$) and humidity (%RH) were collected prior to commencing the trial for each participant (Figure 60). As detailed in Chapter 3 (Section 3.3.4), it was useful that this data was recorded in the event of any abnormal results, as these may be explained by extreme thermal conditions. The mean temperature ($^\circ C$) recorded for the study was $25.69^\circ C$ and the mean humidity (%RH) was 44.18%. The values for individual participants can be seen in Figure 60.
4.3.3 Dependant Variables

4.3.3.1 Subjective Discomfort Assessment

Throughout the duration of the study participants were required to provide subjective discomfort ratings verbally via the use of 2 part discomfort questionnaire (local and overall discomfort) discussed previously in Section 3.3.6.

4.3.3.2 Objective Discomfort Assessment

Participants were also video recorded in order to conduct the analysis of subjects’ SFMs post trial. This was conducted in accordance to the methodology stated in Section 3.3.7.

4.3.4 Experimental Protocol

Each trial was conducted in one laboratory session at Loughborough University and had a duration of approximately 160 minutes using equipment and methodologies discussed in Section 3.3. Upon arrival to the laboratory the participants were asked to complete the health screening, Motion Sickness Susceptibility Questionnaire (MSSQ), ethical clearance and consent forms before collecting the relevant
anthropometric data (age, stature, mass). Measurements of thermal conditions were also collected at this point.

Participants were then asked to embark the driving rig, adjust the seat as required, apply the safety harness and perform 1 minute of driving on the simulator in order to familiarise themselves with the task. This was conducted with no exposure to vibration. Participants were then asked to assist the experimenter in conducting the vibration exposure system characterisation by remaining seated in the car seat whilst exposed to vibration for a further minute. Vibration exposure was recorded using the Biometrics DataLOG MWX8 and accompanying accelerometer and the input to the MAViS platform was then adjusted if necessary. Participants were then trained in the use of the subjective ratings scales and details regarding the collection of subjective data were explained. When confident the participants were ready to begin the trial they were asked if they had any questions before starting and were asked to provide the first set of subjective discomfort ratings. Once these had been collected the trial began and the video recording was started.

The trial consisted of 140 minutes continuous driving on the driving simulator housed at Loughborough University with exposure to vibration at an average of 0.246m/s² weighted r.m.s. Participants were required to provide subjective ratings of discomfort verbally every 10 minutes (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130 and 140 minutes) throughout the duration of the drive via the use of the 2 part discomfort questionnaire.

Upon completion of the 140 minute drive, participants were asked for any qualitative feedback they may have and asked to wait until the MAViS system had depressurised before disembarking and ending the trial.

4.4 Results

The results section will first consider the subjective discomfort data to address the original hypotheses. Firstly the results will address the influence of extended duration driving on overall discomfort, corresponding to part two of the discomfort rating scale. Secondly, the influence on local discomfort, part one of the discomfort rating scale. Lastly, the results will address the influence on the corresponding
discomfort descriptors that correlate to the numeric data provided as response to part two of the discomfort rating scale in order to provide a descriptive analysis of long term driver discomfort.

Furthermore, this results section will consider the objective discomfort data in the form of Seat Fidgets and Movements (SFM) analysis and describe the relationship observed between the subjective and the objective discomfort responses (Section 4.4.3).

4.4.1 Subjective Overall Discomfort

The first hypothesis (H4.1) is that subjective driver discomfort will increase with duration as proposed by previous studies (e.g. El Falou et al., 2003; Porter et al., 2003; De Carvalho and Callaghan, 2011; Smith et al., 2015).

![Figure 61: Mean overall discomfort ratings for all participants against time](image)

The results (Figure 61) show that the mean overall discomfort ratings (part two of the rating scale) increased with duration of driving; supporting the findings of the previous literature (Mansfield et al., 2015; Gyi & Porter, 1998) and Mansfield et al.’s (2014) model of overall car seat discomfort.
Participants’ mean overall discomfort rating increased from 2.35 after the first 10 minutes of driving to 29.8 upon completion of the trial. Participants’ mean overall discomfort rating did not decrease at any time interval during the trial, showing that on average, overall discomfort increases with driving duration.

However, data collected shows that overall discomfort increases at a steady rate until approximately 80 minutes of continuous driving where a change is observed in the rate of discomfort onset until completion of the trial.

![Individual overall discomfort ratings for all participants](image)

**Figure 62:** Individual overall discomfort ratings for all participants

Individual subject data (Figure 62) appears to follow a similar trend as each participant recorded greater discomfort ratings upon completion of the 140 minute drive when compared to the start of the trial. There is some variation in responses for individuals, as to be expected, where some individuals recorded discomfort ratings of as low as 12 at the end of the trial, whereas others recorded discomfort ratings of as much as 47 at the end of the trial. This variation in responses is most likely due to individual differences and interpretation of the discomfort rating scale but should be examined further.

The time interval at which each participant began to experience levels of discomfort over 5 (Very Little Discomfort) on the discomfort scale varied largely, suggesting
that some participants coped better with their discomfort during the early stages of the drive, whereas some participants experienced higher levels of discomfort immediately after beginning the drive.

The differences observed in individual data may be due to interpretation of the discomfort rating scale and personal preferences of each participant. In order to account for individual differences and to make a comparison between individual discomfort ratings the data can be standardised by performing a Z transformation. The following equation (Equation 4.1) was used to convert the overall discomfort ratings collected during the study into Z scores that represent deviations from the mean rather than specific discomfort ratings:

\[ Z_i = \frac{x_i - \bar{x}}{S} \]

Where: \( Z_i \) = Z-transformed sample observations, \( x_i \) = original values of sample, \( \bar{x} \) = sample mean and \( S \) = standard deviation of sample.

![Figure 63: Individual overall discomfort rating Z-scores for all participants](image)

When analysing the overall discomfort rating Z-scores for each individual participant (Figure 63) it is clear from the results that there is closer relationship between the
participants than observed in Figure 62. These results show a very different perspective of the individual results collected and highlights that all participants report a similar increase in overall discomfort across the duration of the trial despite the discomfort ratings collected the end of the trial being largely varied.

4.4.2 Subjective Local Discomfort

The mean local discomfort ratings (Figure 64), part one of the discomfort rating scale, follow a similar trend to that observed for overall discomfort. The results show that the accumulative total discomfort rating for all body parts increases with duration of driving, supporting the findings for overall discomfort. Furthermore, the rate of discomfort increase appears to decrease at approximately 80 minutes of continuous driving, following a similar trend to that observed in the data collected for overall discomfort. It is important to note that no particular body part dominates the local discomfort responses. It is important to mention that due to the design of the local discomfort rating scale, the minimum score that could be recorded on this graph is a cumulative score of 5, as the minimum rating for each body part was 1. Therefore, the results show that at the start of the trial participants recorded, on average, almost no discomfort at all in each of the body regions investigated.
This can be observed in further detail when analysing each body part individually (Figure 65). Participants were asked to provide discomfort ratings for 5 body regions and this data can be useful when highlighting any body parts with particularly high discomfort. The largest increase in local discomfort can be seen in the lower back region, as expected due to the most commonly reported side effect of long term exposure to vibration is lower back pain (Morgan & Mansfield, 2014).

Another benefit of local discomfort analysis is that, due to the fact that participants reported their local discomfort prior to providing overall discomfort ratings, it led participants to consciously reflect on their perceived discomfort and helped participants to accurately determine their responses for part 2 of the questionnaire, improving the quality of the overall discomfort responses.
Figure 65: Mean local discomfort for each body party at each time interval
4.4.3 Objective Seat Fidgets and Movements

Figure 66: Mean overall discomfort ratings and number of SFMs against time for all participants

SFM s are described by type to coincide with the definitions stated previously (Section 3.3.7). Both overall discomfort and SFM frequency, the number of SFMs per 10 minutes, are shown to increase with duration of driving and a close relationship is observed between total SFM frequency and overall discomfort ratings.

Participants’ SFM frequency is shown to increase across the duration of the trial, reflecting the responses recorded for subjective overall discomfort. Participants recorded, on average, 0.3 SFMs during the first 10 minutes of the trial, in comparison with 6.1 SFMs during the last 10 minutes of the trial. The results follow a similar trend to those observed for the participants’ mean overall discomfort ratings (Figure 66).

When comparing the results for overall discomfort and the SFM data recorded, it is clear that a close relationship exists. There is a positive relationship between the mean overall discomfort rating at each time interval and the number of SFMs recorded in the 10 minutes that preceded it; therefore it can be concluded that as overall discomfort increases, the frequency of SFMs also increases (Figure 67).
4.5 Discussion

This section will firstly discuss the subjective discomfort ratings observed during the study to address the first hypothesis of this study and then analyse the objective SFM data recorded in order to satisfy the remaining hypotheses. Comparisons will then be drawn between the subjective discomfort data and the objective SFM data in order to determine the outcome of H4.4.

4.5.1 Analysing the Rate of Discomfort Onset over Time

As discomfort is shown to increase with duration of driving in much of the literature (Mansfield et al., 2014; Gyi & Porter, 1999) the first hypothesis (H4.1) of this study was that discomfort would increase with duration of driving. As driver discomfort is clearly shown to increase with driving duration in the results, it is important to investigate this finding further and analyse whether discomfort increases in a linear fashion, as suggested by much of the literature (Mansfield et al., 2014). Therefore it was crucial to analyse the rate of change in discomfort and determine whether this changes with duration of driving. Much of the literature suggests that overall car seat discomfort increases in a linear fashion; however few studies of this kind have observed a duration of over 2 hours.
In order to analyse the rate of discomfort onset, this analysis will focus solely on subjective discomfort ratings and make a comparison between the first half of the trial (first 70 minutes) and the second half (last 70 minutes). Furthermore, as the responses for local discomfort were used as a primer for the responses for overall discomfort and the local discomfort responses are shown to follow a similar trend to that observed for overall discomfort, this section will mainly focus on overall discomfort. As shown in Figure 61, when comparing the gradients of the mean subjective overall discomfort ratings for the first 70 minutes with the last 70 minutes of the trial, it is clear that there is a change in gradient. The last 70 minutes show a less steep incline in comparison to the first 70 minutes with regression line gradients of 0.27 and 0.16 respectively. This suggests that discomfort does not increase linearly throughout the duration of the trial, as previously suggested (Mansfield et al., 2014), implying that at some time interval the rate of change in discomfort decreases.

This can easily be observed when comparing the discomfort/time ratio for each half of the trial. This was calculated by dividing the mean overall discomfort score by the time at which it was recorded and a table outlining these ratios can be seen in Table 10.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Discomfort / Time Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 70 minutes</td>
<td>18.85 / 70 = 0.269</td>
</tr>
<tr>
<td>Last 70 minutes</td>
<td>29.8 – 18.85 / 70 = 0.156</td>
</tr>
<tr>
<td>140 minutes</td>
<td>29.8 / 140 = 0.213</td>
</tr>
</tbody>
</table>

Overall discomfort is shown to increase at a rate of 2.69 on the discomfort rating scale per 10 minutes of driving across the first 70 minutes of a long term drive; however this rate decreases after 70 minutes of driving to 1.56 per 10 minutes for the next 70 minutes, implying a decline in the rate of discomfort onset. When the discomfort/time ratio is observed across every time interval (Figure 68), a steady decline is observed after 80 minutes of driving and suggests that a change in perceived overall discomfort occurs at this time interval.
If overall discomfort increased in a linear fashion, as previously suggested by much of the literature, the discomfort/time ratio would remain constant throughout the duration of the trial. However the results observed in this study provide evidence to the contrary and suggest that at around 80 minutes of driving there is a change in drivers’ perceived overall discomfort that leads to a decrease in the rate of overall discomfort onset.

The quantitative model proposed by Mansfield et al. (2014) can be used to predict overall car seat discomfort and has been successful in predicting overall car seat discomfort for trials with a duration of less than an hour. It can be seen that this model would be extremely successful in predicting overall car seat discomfort for this study up until 60 – 80 minutes. However this model employs the theory that discomfort increases in a linear fashion. Therefore the results of this study suggest that some adaptations may need to be made to the model in order to incorporate changes in the rate of discomfort increase observed at around 80 minutes and to accurately predict overall car seat discomfort for driving trials that have a duration greater than 80 minutes.
Figure 69: Comparison between mean overall discomfort ratings observed for the first 70 minutes and last 70 minutes relative to scores at $t = 0$ and $t = 70$ for all participants

Figure 69 shows a comparison between the mean overall discomfort ratings recorded during the first 70 minutes and the last 70 minutes of the trial. In order to observe a comparison, individual discomfort ratings for the last 70 minutes of the trial were transformed so that both sets of data had an origin of zero. This was produced by subtracting the average overall discomfort rating recorded at 70 minutes from the following discomfort ratings recorded at each time interval after 70 minutes. Therefore; Adjusted Discomfort Rating = Overall Discomfort Rating – 18.85. This can be seen in Table 11.

Table 11: Adjusted mean overall discomfort ratings for last 70 minutes

<table>
<thead>
<tr>
<th>Time</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted Mean Discomfort Rating</td>
<td>0.00</td>
<td>2.65</td>
<td>4.45</td>
<td>5.45</td>
<td>6.85</td>
<td>9.60</td>
<td>10.45</td>
<td>10.95</td>
</tr>
</tbody>
</table>

This allows for a comparison to be made between the mean discomfort ratings recorded for the first and second half of the trial. T-tests were performed in order to establish whether a significant difference can be observed ($\alpha = 0.05$):
• $t = 40$ vs $t = 110$ adjusted, one tailed $P = 0.05635$
• $t = 50$ vs $t = 120$ adjusted, one tailed $P = 0.04262$
• $t = 60$ vs $t = 130$ adjusted, one tailed $P = 0.00615$
• $t = 70$ vs $t = 140$ adjusted, one tailed $P = 0.03538$

A significant difference is observed after 50 minutes and implies that after 120 minutes of driving the overall discomfort ratings recorded follow a significantly different trend to those obtained before 120 minutes. Therefore it can be concluded that the rate of discomfort onset significantly decreases after 120 minutes of driving.

The results obtained in this study suggest that a change in perceived overall discomfort occurs at around 80 minutes of driving and this change becomes significant at around 120 minutes of driving. This raises the question as to why this decrease in rate of overall car seat discomfort onset occurs and why discomfort does not increase linearly with greatly extended exposure times as previously suggested.

4.5.1.1 Ceiling Effect due to Extreme Discomfort or Rating Scale Design

One cause for the change in discomfort onset may be that participants are experiencing a ceiling effect, whereby as they reach high levels of discomfort they simply cannot become more uncomfortable and therefore plateau at an extremely high level of discomfort. As the discomfort rating scale employed in the study uses a range from 0 – 120, with 0 being no discomfort and 120 being the absolute maximum, it would be expected for participants to experience this ceiling effect towards the upper limit of the scale.

The highest mean overall discomfort rating recorded during this study is 29.8 which is described as ‘Moderate-High Discomfort’. Therefore, on average, participants are yet to experience even ‘High Discomfort’ and when analysing individual responses, rarely do participants record responses of ‘High Discomfort’ as the maximum value recorded for an individual is 50. Therefore as the upper limits of the scale have not
been reached it can be concluded that this ceiling effect is unlikely to be a product of the participants reaching the upper limit of discomfort.

Additionally, this ceiling effect may be observed due to the design of the scale, as participants may reach the upper limit of the scale and would therefore be unable to provide higher ratings of discomfort. This may be a problem with scales designed with a small range of responses however, due to the fact that this scale has a wide range of possible responses and that the upper limit of the scale has not been reached it can be concluded that this ceiling effect is not a product of the design of the scale.

4.5.1.2 Behaviour Adaptation

Another theory regarding the decrease in the rate of discomfort onset is that participants may be becoming ‘used to their discomfort’ or are coping with the discomfort they are experiencing more effectively. After 80 minutes one participant stated when asked about their perception of discomfort:

“I feel like I am getting used to it. I became more uncomfortable really quickly but now I don't feel so bad” (Participant 8, Male, 23).

This could possibly be purely psychological and participants really are becoming used to their discomfort, however it is more likely that participants are coping with their discomfort more effectively. Another participant stated after providing a discomfort rating lower than the previous rating given that:

“(My rating) went down because I shifted my weight” (Participant 2, Male, 33).

This suggests that this participant adapted their behaviour to better cope with the higher levels of discomfort they were experiencing and this theory could be based on the fact that when people first sit down, they move little but over extended periods of sitting, increased discomfort has been shown to lead to significant increases in movement, as stated by much of the literature (Bendix et al., 1985; Jenson & Bendix, 1992). It has been shown that people move unconsciously when seated, even when driving with the purpose of relieving discomfort in compressed
body parts (Hermann & Bubb, 2007) and therefore a decrease in the rate of discomfort onset could be a product of the participant altering their behaviour as discomfort increases and therefore coping more effectively with the increasing discomfort, by moving more frequently in the seat. SFM analysis should provide a better insight into this phenomenon.

4.5.2 Seat Fidgets and Movements

The second and main objective of this study was to investigate the success of an objective measure of discomfort that analyses drivers’ Seat Fidgets and Movements in relation to subjective ratings of overall discomfort. This section will firstly address SFM frequency, then SFM magnitude and then draw conclusions on the relationship between SFMs and subjective overall discomfort.

4.5.2.1 SFM Frequency

The second hypothesis (H4.2) of this study was that SFM frequency would increase with duration of driving. The results (Figure 66) show that the frequency of SFM increased with time, supporting the studies by Bendix et al. (1985), Jensen & Bendix (1992), Fenety et al. (2000) and Adler (2007). This implies that as the duration of driving increased, drivers moved more frequently in the seat, possibly as a method to better cope with increased levels of overall discomfort. This supports the theoretical model of sitting condition and discomfort proposed by Fujimaki & Noro (2005) and this theory can be implemented to describe the effect and purpose of driver SFMs. The statement made by Hermann & Bubb (2007) that drivers move unconsciously in order to relieve pressure on compressed body parts suggests that drivers move in the seat when discomfort reaches a detection threshold that is unconsciously perceived. As the frequency of SFMs increased with time, this implies that as the duration of driving increased drivers reached this detection threshold faster (Figure 70).
A driver’s detection threshold can be described as a driver’s acceptable comfort level. As discomfort reaches the threshold and becomes detectable to the driver, the driver moves in the seat in order to relieve themselves of discomfort; therefore an SFM occurs. With extended duration driving, the driver’s acceptable comfort level, or detection threshold decreases throughout the duration of the drive. Therefore discomfort reaches this detection threshold with increasing frequency and drivers record more frequent SFMs as time increases.

This phenomenon may provide some insight into the theory that drivers were better coping with their discomfort towards the end of the 140 trial, as described by the decrease in the rate of change in discomfort. As SFM frequency increases, this suggests that subjects were moving more often to cope with higher levels of discomfort (Hermann & Bubb, 2007) and perhaps this process affected their subjective discomfort responses. However, if a strong correlation is observed between SFM frequency and subjective overall discomfort ratings at the end of the trial this will suggest that this is not the case as the rate of increase in SFM frequency will also decrease following the trend of the subjective overall discomfort ratings.
4.5.2.2 SFM Magnitude

The third hypothesis (H4.3) for this study was that SFM magnitude would increase with duration of driving as proposed by (Adler, 2007). Each SFM type, defined in Section 3.3.7, was related to a different type, or different magnitude of movement; type 1 being small movement and type 3 being large movement. In order to assess how magnitude changes over duration of driving, a comparison of SFM type percentage across the duration of trial was made (Figure 71).

If magnitude of SFMs did increase with duration of driving, it would be expected that the percentage of Type 2 and Type 3 SFMs would increase with time and the percentage of Type 1 movements would decrease. Two-way ANOVAs (α = 0.05) were conducted on the mean data that compared the percentage of each SFM type at each time interval. It was shown that the percentage of Type 2 and Type 3 does not increase with time as no significant difference was found between percentage of Type 2 or Type 3 SFMs at the beginning of the trial and at the end. Furthermore, when analysing individual subject data collected for SFMs, no participant is shown to fit the hypothesis. No participant records an increase in Type 2 or Type 3 movements as time increases. Therefore the conclusion can be drawn that in the
case of this experiment, SFM magnitude has not been shown to increase with duration of driving.

This does not comply with the findings of the previous research (Adler, 2007) however this may be due to the design of the SFM method. The method used to analyse SFM only determines type of movement in regards to magnitude and does not analyse magnitude changes of each type. For example, although Type 1 movements all consist of the same postural change, some changes may be greater in terms of magnitude than others. Improvements to the methodology may need to be made in order to investigate magnitude of SFMs in more detail.

4.5.3 Relationship between Subjective Overall Discomfort Ratings and SFMs

It is clear from the results (Figure 66 & Figure 67) that both overall discomfort and SFM frequency increase with time, however the final and most important aim of this study was to investigate the relationship between subjective ratings of overall discomfort and driver SFMs in order to determine the success of the SFM method in accurately predicting subjective overall discomfort. Hypothesis 4 (H7.4) suggested that there will be a relationship observed between subjective discomfort ratings and SFMs. As a close relationship is observed between overall discomfort ratings and SFM frequency in the results, this relationship will be investigated.

4.5.3.1 Observed Data

In order to assess this relationship further, a Pearson Correlation and regression analysis were performed on the data that compared overall discomfort ratings and the number of SFMs recorded per 10 minutes. Relating to the guidelines proposed by Cohen (1988), a large positive correlation was found with an r value of 0.963, with 93% shared variance and was statistically significant (r = 0.963, n = 14, P < 0.05). This suggests that as drivers’ overall car seat discomfort increases the frequency of SFMs increases and supports the findings of Adler (2007).

As one of the overall aims of the study was to develop an objective measure that can be used to predict discomfort it was crucial to analyse whether SFM data could be used to predict subjective discomfort. Because of their special construction, data
obtained with the Borg CR scales can be interpreted as ratio data (Borg & Kaijser, 2006) and therefore a linear regression was performed to produce the equation:

\[ \Psi = 3.002 + 48.68sfm \]  
(4.2)

Where: \( \Psi \) is the rating of overall discomfort and \( sfm \) is the number of SFMs per minute.

This equation (Equation 4.2) was then used to produce predicted values of overall discomfort using only SFM data, a comparison between the observed subjective overall discomfort ratings and the predicted overall discomfort ratings can be seen in Figure 72.

Figure 72: Observed vs predicted overall discomfort ratings using regression equation (non-weighted)

As shown in Figure 72, the predicted values of discomfort are closely related to the observed values suggesting that for the data in this experiment, SFM observations can be used to accurately predict subjective overall discomfort ratings.
4.5.3.2 SFM Weighting Factors

In order to examine whether this relationship could be improved further, weightings were applied to the different SFM types and further analysis was conducted to determine whether this improves or reduces the correlation ($r^2$ value). Weightings ranging from 0 to 2.5 were applied to each SFM type in order to determine exactly where the strongest correlation could be observed (Figure 73).

![Figure 73: Correlation strength ($r^2$ value) when applying weighting factors to each SFM type](image)

As described by Figure 73, the relationship can be improved by applying a weighting factor to each Type 2 and Type 3 movement recorded. When applying weightings of 1:1:1 the $r^2$ value was shown to be 0.927. However, after applying a weighting of 1 to Type 1 movements, 0.2 to Type 2 movements and 0.7 to Type 3 movements the correlation can be improved to correspond with an $r^2$ value of 0.957. Represented by:
\[
\text{Total } sfm_w = Type1 + (Type2 \times 0.2) + (Type3 \times 0.7) 
\] (4.3)

As a result of the improved relationship, another regression was conducted in order to produce another equation that included the weightings proposed for each SFM type:

\[
\Psi = 1.960 + 92.77sfm_w 
\] (4.4)

Where: \( \Psi \) is the rating of overall discomfort and \( sfm_w \) is the weighted number of SFMs per min.

This equation (Equation 4.4) was then used to produce predicted values of overall discomfort using only the weighted SFM data, a comparison of the observed overall discomfort ratings and the weighted predicted discomfort ratings can be seen in Figure 74.

![Figure 74: Observed vs. weighted predicted overall discomfort using regression equation](image)

As described by the Pearson Correlation, a closer relationship is observed when using the weighted SFM data as a predictor for overall discomfort. There is need for this weighting to be validated during future research to ensure that this weighting is not only fitting for data in this experiment, however, if this weighting is successful in future research, there is the potential for the method to be improved by adding
weighting factors to each SFM type. Conversely, the improvement in correlation strength observed is only slight. Therefore, if these weighting factors are shown to be unsuccessful during further research, this does not diminish the success of the method. The analysis until this point has shown that although weighting factors may be implemented to enhance the method, the relationship between observed SFM frequency and overall discomfort is still proved to be successful.

4.5.3.3 Interpolated Data

Perhaps one issue with the assessment of the data is that the ratings reported for overall discomfort were collected at the beginning and end of the 10 minute time intervals, 10 and 20 minutes for example. However, the total number of SFMs that corresponded to this discomfort rating was collected throughout the duration of that time interval, for example; the number of SFMs between 10 and 20 minutes. Therefore, in order to accurately make a comparison between the two variables and determine the strength of the correlation, mean overall discomfort ratings should be interpolated between both time intervals to establish an average of that time interval with which to compare the number of SFMs, for example; the total number of SFMs recorded between 10 and 20 minutes should be compared with the interpolated overall discomfort rating for 15 minutes. As a result, the overall discomfort data was interpolated in order to make a new comparison (Figure 75).

The interpolated ratings for overall discomfort (Figure 75) represent mean discomfort ratings collected at 5, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115, 125 and 135 minutes. When comparing these results to those displayed previously in Figure 66, a marginally stronger relationship is observed after interpolating the overall discomfort ratings. This may be expected due to the averaging of the data however this should improve the ability to accurately analyse the correlation as a more precise representation of time is being utilised.
This is again reflected by the strength of the correlation. A Pearson Correlation and regression analysis were again performed on the data that compared the interpolated mean overall discomfort ratings and the number of SFMs recorded per 10 minutes. A large positive correlation was found again with an r value of 0.966, with 93% shared variance and was statistically significant (r = 0.966, n = 14, P < 0.05). This displays an improvement in terms of correlation strength, albeit very slight, when compared to the observed data, suggesting that by interpolating the data to reflect a more true time interval a more accurate representation of the correlation strength can be obtained.

As with the observed data, weighting factors can now be applied to the SFM data then correlated with the interpolated overall discomfort data in order to evaluate whether this relationship (r² value) can be improved further (Figure 76).
Figure 76: Correlation strength ($r^2$ value) when applying weighting factors to each SFM type using interpolated discomfort data

As shown in Figure 76, correlation strength can again be increased by applying weighting factors to each SFM type when comparing the frequency of SFMs and the interpolated mean overall discomfort ratings. By applying the same weighting factors as with the observed data (1:0.2:0.7) the correlation can be improved to correspond with an $r^2$ value of 0.968.

These findings suggest that when using SFM data to predict overall discomfort the most successful approach, in terms of correlation strength, is to apply the weighting factors determined to the SFM data in order to produce predicted overall discomfort ratings. Due to the interpolated data showing a stronger correlation, this suggests that these predictions will more accurately represent discomfort ratings at an average of the time interval. For example, when collecting SFM data between 50 and 60 minutes of a driving trial, the recorded SFM data should be weighted as appropriate and then used to predict an overall discomfort rating that represents
discomfort at 55 minutes or as an average of the discomfort experienced between 50 and 60 minutes.

However, it is important to mention that although improvements in correlation strength can be obtained via this method of analysis, these improvements are very slight and need to be tested against a wider range of data. The correlation between the number of SFMs and overall discomfort is shown to be a strong positive correlation regardless of how the data is manipulated and suggests that both weighted and un-weighted SFMs can useful for predicting values of overall discomfort that represent both the discomfort at the end of the time interval throughout which they were collected and as an average of that time interval.

4.5.4 Relationship between SFMs and Verbal Discomfort Descriptors

The overall aim of this research is to provide an objective measure of overall car seat discomfort that could be implemented into the automotive industry, with the aim of replacing subjective methods of discomfort assessment. Therefore, it was vital to understand how SFM data relates to verbal discomfort descriptors as ultimately this is the goal when assessing a driver’s discomfort. For the purpose of this analysis, only the observed SFM and overall discomfort data will be considered as although weighting and interpolation of the data has shown some minor improvements in correlation strength, these improvements were not deemed large enough to be necessary when conducting this analysis.

For each time interval a verbal descriptor was chosen, using the discomfort rating scale, that related to the subjective ratings of overall discomfort and this in turn, was matched with the number of SFMs per minute for that time interval. The ultimate goal was to determine which verbal discomfort descriptor best correlates to the number of SFMs (per min). A table outlining this can be seen in Table 12.
Table 12: Comparison of number of SFMs per minute with overall discomfort rating and verbal discomfort descriptors

<table>
<thead>
<tr>
<th>Time</th>
<th>Overall Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.35</td>
<td>0.03</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>20</td>
<td>5.60</td>
<td>0.10</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>30</td>
<td>9.23</td>
<td>0.15</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>40</td>
<td>10.45</td>
<td>0.18</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>50</td>
<td>14.45</td>
<td>0.20</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>60</td>
<td>16.35</td>
<td>0.24</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>70</td>
<td>18.85</td>
<td>0.34</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>80</td>
<td>21.50</td>
<td>0.27</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>90</td>
<td>23.30</td>
<td>0.46</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>100</td>
<td>24.30</td>
<td>0.45</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>110</td>
<td>25.70</td>
<td>0.39</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>120</td>
<td>28.45</td>
<td>0.54</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>130</td>
<td>29.30</td>
<td>0.51</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>140</td>
<td>29.80</td>
<td>0.61</td>
<td>Moderate-High Discomfort</td>
</tr>
</tbody>
</table>

Table 12 was produced using the observed data obtained in this experiment. Using the equation produced by the regression analysis (Equation 4.2) another table was produced that determines the range of number of SFMs (per min) and overall discomfort rating against the verbal discomfort descriptors. This table was developed by rearranging the regression equation (Equation 4.2), as such:

1) $\Psi = 3.002 + (48.68sfm)$

2) $sfm = (3.002 - \Psi) / -48.68$  \hspace{1cm} (4.5)

Then, using the boundaries for overall discomfort ratings, ranges for SFM frequency were calculated that relate to the equivalent verbal discomfort descriptor. This can be seen in Table 13.
Table 13: Number of SFMs (per min) and the relationship with overall discomfort ratings and verbal discomfort descriptors

<table>
<thead>
<tr>
<th>Overall Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No Discomfort at all</td>
</tr>
<tr>
<td>0 – 4</td>
<td>0 – 0.021</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>4 – 10</td>
<td>0.021 – 0.144</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>10 – 17</td>
<td>0.144 – 0.288</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>17 – 23</td>
<td>0.288 – 0.411</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>23 – 28</td>
<td>0.411 – 0.514</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>28 – 33</td>
<td>0.514 – 0.616</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>33 +</td>
<td>0.616 +</td>
<td>High Discomfort</td>
</tr>
</tbody>
</table>

Table 13 provides the basis for discomfort assessment to be made using only SFM data, bypassing any need to predict overall discomfort and providing a simplistic approach. The table suggests that a driver experiencing ‘Very Little Discomfort’ would record an SFM less than once every 7 minutes whereas a driver experiencing ‘Moderate-High Discomfort’ would record an SFM roughly once every 2 minutes. There is a need for this method to be tested against new data, however when fitting to the mean data collected in this experiment, the SFM method serves to successfully replace subjective ratings of overall discomfort and can be utilised to provide a verbal description of the discomfort experienced by recording drivers’ seat fidgets and movements.

4.6 Conclusions

The study presented in this chapter was designed to investigate the effect of long duration driving on subjective driver discomfort and determine the success of an objective measure of discomfort in accurately predicting subjective responses. This section will draw conclusions with reference to the research hypotheses for the chapter.

**H4.1: Driver discomfort will increase with duration of driving**

The results of the laboratory study showed that driver discomfort increased across the duration of the 140 minute driving trial. All subjects recorded an increase in discomfort upon completion of the trial and distinct similarities were observed
between the responses recorded for overall discomfort and local discomfort. The rate of change in discomfort was shown to decrease over the last 70 minutes of the trial as drivers may alter their behaviour to cope with increased levels of discomfort. As discomfort is not shown to increase at a linear rate, future research in the area should aim to investigate this finding further and determine the success of the quantitative model proposed by Mansfield et al. (2014), discussed in Chapter 2, by testing this model against greatly extended driving durations. The model is shown to be very successful when predicting discomfort for journeys up to an hour in duration, however in order to predict discomfort for long duration driving (>1 hour) the model will need to account for the change in rate of change in discomfort observed in this study.

**H4.2: SFM frequency will increase with duration of driving**

SFM frequency was shown to increase with duration of driving as participants recorded significantly more Seat Fidgets and Movements in the last 10 minutes of the trial when compared to the first 10 minutes. This finding supports the previous literature in the area and suggests that as discomfort increases across the duration of a long term drive, drivers move in the vehicle seat in order to relieve themselves from the discomfort experienced. This was defined by the conceptual model proposed in Section 4.5.2.1. The model describes that drivers move when their discomfort reaches a ‘detection threshold’, as the frequency of SFMs increases over time spent driving, this suggests that this detection threshold decreases with driving duration and therefore discomfort reaches this detection threshold with increased frequency as the duration of driving duration increases.

**H4.3: SFM magnitude will increase with duration of driving**

The relationship between SFM magnitude and driving duration should be further investigated as no correlation was observed during this experiment. However, this may be due to the design of the method as magnitude was defined by the type of movement. If a method of measuring the magnitude of every movement in terms of distance and duration, regardless of type, could be implemented there is a chance
that very different results may be observed and a relationship may be seen between SFM magnitude and driving duration, as proposed by Adler (2007).

**H4.4: A relationship will be observed between subjective discomfort ratings and SFM**

Ultimately, the results of the laboratory study show that a measure of SFMs can successfully be used to predict subjective car seat discomfort. Fitting to the data in this experiment, a strong correlation was found between predictions of discomfort made using SFM data and observed subjective overall discomfort. It was shown that this correlation can be improved by weighting each SFM type and analysis suggested that an understanding of the time intervals used when measuring SFMs is crucial. Future studies will need to validate the method further however there is the potential for driver discomfort analysis to be made by remote monitoring as SFM measurements have been found to successfully replicate subjective discomfort analysis. It has been shown that it is possible to gain qualitative ratings of discomfort using only observed SFM data, bypassing the need for subjective assessment.

Future work should aim to validate the methodology and further determine the relationship between overall driver discomfort and driver seat fidgets and movements. The method should be tested in different laboratory conditions with different vibration stimuli to determine whether the same correlation is observed with a different discomfort gradient and a vastly different sample. This may yield different results, however it is crucial to understand how the method applies to any population. If similarities are observed this will have positive implications on the success of the method in fitting any sample, however if differences are observed this may suggest that the method need to be refined to fit the larger data set.
CHAPTER 5

Subjective and Objective Discomfort during Long Duration Driving Trials with Japanese Participants

This chapter reports the findings of the second in the series of laboratory studies, conducted in collaboration with Kinki University, Japan, and carried out with Japanese subjects in the laboratory at Kinki University. The study was designed to further the research conducted in Chapter 4 and develop upon the successes of the previous study. Subjective overall car seat discomfort was shown to increase across the duration of a long term drive when drivers were exposed to normal driving conditions with typical road vibration experienced in every day driving (Chapter 4). This study investigates different road conditions and seat design and the effect on overall car seat discomfort, drawing comparisons with the previous findings.

In Chapter 4, a strong correlation was observed between subjective ratings of overall discomfort and Seat Fidget and Movement frequency suggesting that there is potential for this objective method of driver discomfort to be implemented successfully, reducing the need for subjective assessment. However, in order to test the validity, reliability and repeatability of the method further, the method must be tested against a largely different sample, with different laboratory conditions, driving duration and vibration exposure.

Therefore, this study aimed to best replicate the study conducted in Chapter 4 in a different laboratory with some alterations to the requirements placed upon the subjects. As the main aim of this research was to determine the success of an objective measure of discomfort, if similarities can be found with Chapter 4 with respect to the comparison between subjective discomfort ratings and Seat Fidgets and Movements, this will provide a strong indication as to the success of the method.
5.1 Introduction

Many different objective methods of measuring driver discomfort have previously been implemented into the automotive industry, all with varying levels of success. However, no sole objective measure has been deemed successful enough to be implemented throughout the industry and successful objective measures of driver discomfort are difficult to find in both literature and practice (Zenk et al., 2012).

One method that has shown some promise in the previous literature was a measure of a driver’s frequency of movements (Adler, 2007) and the research conducted in Chapter 4 determined that a method of monitoring drivers’ Seat Fidgets and Movements (SFM) could be implemented successfully. A strong positive correlation was observed between subjective overall driver discomfort and the frequency of SFMs and it has been proposed that remote measurements of SFMs could be used to accurately predict driver discomfort, removing the need for subjective assessment in future research.

However, in order for any method to be deemed successful in predicting overall car seat discomfort, said method must be applicable for any individual. Therefore it must be tested against a wide range of anthropometric data and should be able to account for any individual differences that drivers being assessed may possess. It is well documented throughout the research into automotive seat design that anthropometry varies between countries (Peebles & Norris, 1998) and there are vast differences between a Japanese female (5th%tile) and a Dutch male (95th%tile). When designing a vehicle seat these differences must be accounted for, therefore any method to assess the success of seat in terms of comfort must also be able to account for these differences.

As anthropometry varies been countries, cultural differences can elicit similar differences in terms of discomfort perception and therefore could be deemed equally important. Kolich (2008) explains that Western Europeans are generally thought to prefer firmer seats as compared to North Americans. Seats are required to satisfy culture-based preferences and expectations of seat comfort, therefore any method implemented to determine the comfort or performance of a seat must
also be able to account for these cultural differences. As a result, if the success of
the SFM method is to be further evaluated, the method must be tested using a
vastly different sample to that tested in the previous study.

During the previous research detailed in Chapter 4, the experiment was conducted
in the Laboratory at Loughborough University using familiar equipment and a
European sample. The average age, 26 years old, average weight, 69.9kg, and
average height, 173.9cm, all represented a moderately typical UK sample from
Loughborough University. Furthermore, the vast majority of participants recruited
for the experiment were of British nationality (9 of 10 subjects) and were all from
Western European countries.

If the method is to be successfully implemented across the automotive industry and
seating research, it is crucial that the method can be repeated using any type of
sample and also be implemented into any laboratory conditions. The SFM method
has previously only been investigated under one set of laboratory conditions,
therefore, it is essential that the method be tested in conditions where the
equipment used is altered and subjects are exposed to different road conditions,
different vibration exposure and different seat and vehicle packaging factors.

5.2 Aims and Objectives

The aim of this study was to determine the success of the Seat Fidgets and
Movements method under different conditions to those previously tested in
Chapter 4. Although the design of the study will be largely similar due to the nature
of the method, many of the parameters that can potentially affect the success of
the method will be altered in order to examine how applicable the method is to any
population and driving conditions. The first objective was to determine the success
of the Seat Fidgets and Movements method in accurately predicting overall car seat
discomfort when using Japanese participants whose anthropometric data and
cultural preferences differed from the sample of European participants used
previously.

The next objective of the study was to determine the success of the SFM method
when conducted in differing laboratory conditions. If the method is to be used
across the field of automotive seating research, it is important that the method can be recreated and implemented in any laboratory conditions and the reliability of the SFM method in a different laboratory must be tested. Therefore this study was conducted at Kinki University, Japan, where the laboratory conditions were designed to be as similar as possible to those previously tested. However, the experimental conditions differed largely from the conditions at Loughborough University, UK, in Chapter 4.

Furthermore, the conditions of the dynamic environment will be greatly altered in comparison with those previously tested. As described by Mansfield et al. (2015) and Mansfield et al. (2014) vibration magnitude has been shown to effect the rate of discomfort increase whilst driving and therefore differing dynamic conditions will be implemented to determine the success of the SFM method in coping with these differences.

Additionally, this study will also investigate driver discomfort using the subjective discomfort ratings to build upon the knowledge and findings of Chapter 4 with regards to driver discomfort over long duration driving with vibration exposure.

Therefore the aims of this study are;

Long duration driver discomfort:

• To determine the effect of long duration driving on local and overall car seat discomfort

Seat fidgets and movements:

• To determine whether SFM frequency increases with duration of driving
• To determine whether SFM magnitude increases with duration of driving
• To compare the SFM observations with the subjective discomfort ratings reported
• To further validate the success of the SFM method using a different sample and conditions
Comparison with different sample:

- To determine whether differences are observed between the subjective discomfort ratings recorded for a Japanese sample and the British sample used in Chapter 4
- To determine whether differences are observed between the SFM data recorded for a Japanese sample and the British sample used in previous experiments

The main hypotheses (and null hypotheses (nH)) of this study were:

**nH5.1**: Subjective discomfort ratings observed for the Japanese sample will show no comparison with the European sample in Chapter 4

**H5.1**: Similar subjective discomfort ratings will be observed for the Japanese sample when compared to the European sample in Chapter 4

**nH5.2**: SFM frequency will not increase with duration of driving

**H5.2**: SFM frequency will increase with duration of driving

**nH5.3**: SFM magnitude will not increase with duration of driving

**H5.3**: SFM magnitude will increase with duration of driving

**nH5.4**: No relationship will be observed between subjective discomfort ratings and SFMs

**H5.4**: A relationship will be observed between subjective discomfort ratings and SFMs

**nH5.5**: No similarities in SFM data will be observed between this study and the study in Chapter 4

**H5.5**: Similarities in SFM data will be observed between this study and the study in Chapter 4
5.3 Method

The study reported in this chapter was conducted at Kinki University, Japan, and as a result utilises the methodologies determined previously regarding the Japan Laboratory study (Section 3.4) to be reported in this thesis. The equipment and procedures used in this study have been detailed previously and this section will outline any further methodologies implemented that were specific to this study. Firstly the details regarding the sample recruited to take part in the study will be defined followed by an outline of how the study aimed to tackle the hypothesis for the study stated previously. The independent and dependant variables for the study will be defined and the section will conclude with a detailed description of the experimental protocol undertaken during this study, with specific regards to the design and equipment used.

5.3.1 Sample

The participants recruited for this study were sampled from the local, staff and student population of Kinki University, Japan, and were all Japanese. All participants were subjected to the inclusion criteria outlined previously in Chapter 3 (Section 3.4.4) and all participants completed the various health screening, ethical clearance and consent forms. Participant characteristics are defined in Table 14.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>14</td>
</tr>
<tr>
<td>Gender</td>
<td>8 male; 6 female</td>
</tr>
<tr>
<td>Age</td>
<td>20 – 42 years (mean ± sd: 26.7 ± 7.3 years)</td>
</tr>
<tr>
<td>Stature</td>
<td>155 – 183 cm (mean ± sd: 168.2 ± 8.4 cm)</td>
</tr>
<tr>
<td>Mass</td>
<td>43 – 70.5 kg (mean ± sd: 58 ± 7.6 kg)</td>
</tr>
</tbody>
</table>

Participants were provided detailed information regarding the purpose of the study, experimental protocol and possible risks associated with participation in the study. Anthropometric data was collected prior to participation in the study.
5.3.2 Independent Variables

5.3.2.1 Driving Task and Duration

All participants that took part in the study were required to drive continuously for a set duration on the driving simulator housed at Kinki University, Japan. This duration was 60 minutes and all participants completed the duration on the driving simulator with no breaks from driving. 60 minutes was decided as an appropriate duration for the trial for a number of reasons. Firstly due to the time constraints of the study and the demands placed upon participants. Secondly, after 60 minutes of driving during the study in Chapter 4, participants had reached a discomfort rating that represented ‘Little Discomfort’, as the vibration exposure was intended to be greater in this experiment it was decided that a shorter duration would still produce the desired discomfort levels. Furthermore, as the aim of the study was to test the method in vastly differing experimental conditions, the effect of duration of driving on the success of the method was a useful variable to investigate.

All participants completed the same task on the driving simulator as drivers were required to follow the predetermined route defined by the driving simulator, this route and use of the driving simulator was defined in Chapter 3 (Section 3.4.2). Due to the design of the driving simulator at Kinki University, all participants completed the driving task while sat on the same driving rig using the same seat and controls as outlined previously in Chapter 3 (Section 3.4.3). The dimensions of this seat and vehicle controls and packaging can be found in Section 3.4.3 and all participants were allocated time prior to the start of the experiment to adjust the seat as to best replicate their normal driving position.

5.3.2.2 Vibration Exposure

All participants were exposed to 6-axis vibration throughout the duration of the drive on the simulator. Vibration exposure was simulated by the Multi-Axis Vibration Simulator housed at Kinki University with a mean total magnitude of 0.405m/s² weighted r.m.s. System characterisation ensured that all participants were exposed to a vibration magnitude of within 10% of the desired exposure. This vibration exposure was designed to be of a higher magnitude than previously tested
in Chapter 4 and the characteristics of the vibration were very different to those previously tested due to the design of the simulation, outlined in Section 3.4.1.

5.3.2.3 Thermal Environment

Measurements of temperature (°C) and humidity (%RH) were collected prior to commencing the trial for each participant (Figure 77). As detailed in Chapter 3 (Section 3.4.4), it was important that the thermal conditions were recorded as to provide an insight into the cause of extreme discomfort ratings in the event of any abnormal results. The mean temperature (°C) recorded was 21.7°C and the mean humidity (%RH) recorded was 36.3%.

Table 15: Experimental Conditions for Chapter 4 and Chapter 5

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Driving Duration</th>
<th>Vibration Exposure</th>
<th>Thermal Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 4</td>
<td>140 minutes</td>
<td>0.405m/s² weighted r.m.s.</td>
<td>21.7°C / 36.3% RH</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>60 minutes</td>
<td>0.246m/s² weighted r.m.s.</td>
<td>25.7°C / 44.2% RH</td>
</tr>
</tbody>
</table>

Figure 77: Laboratory thermal conditions
5.3.3 Dependant Variables

5.3.3.1 Subjective Discomfort Assessment
Throughout the duration of the study participants were required to provide subjective discomfort ratings via the use of 2 part discomfort questionnaire (Local and Overall discomfort) discussed previously in Section 3.4.5. This followed the same format as the study conducted in Chapter 4, however the verbal descriptors that accompany the discomfort rating scales had been translated in Japanese and participants responded in Japanese.

5.3.3.2 Objective Discomfort Assessment
Participants were also video recorded in order to conduct the analysis of subjects’ SFMs post trial. This was conducted in accordance to the methodology stated in Chapter 3 (Section 3.4.6). The methodology employed for analysing participants’ SFMs was identical to that in the previous UK laboratory study, however the equipment used varied.

5.3.3 Experimental Protocol
Each trial was conducted in one laboratory session at Kinki University, Japan, and had a duration of approximately 80 minutes using equipment and methods discussed in Section 3.4. Upon arrival to the laboratory the participants were asked to complete the health screening, ethical clearance and consent forms before collecting the relevant anthropometric data (age, stature, mass). Measurements of thermal conditions were also collected at this point.

Participants were then asked to embark the driving rig, adjust the seat as required, apply the safety harness and perform 1 minute of driving on the simulator in order to familiarise themselves with the task. This was conducted with exposure to vibration. Vibration exposure was recorded using the Rion VM-54 and accompanying accelerometer (discussed in Section 3.4.1) and the input to the motion platform was then adjusted if necessary. Participants were then trained in the use of the subjective ratings scales and details regarding the collection of subjective data were explained. When confident the participants were ready to begin the trial they were asked if they had any questions before starting and were
asked to provide the first set of subjective discomfort ratings. Once these had been collected the trial began and the video recording was started.

The trial consisted of 60 minutes continuous driving on the driving simulator housed at Kinki University with exposure to vibration at an average of $0.405m/s^2$ weighted r.m.s. Participants were required to provide subjective ratings of discomfort verbally every 10 minutes (0, 10, 20, 30, 40, 50 and 60 minutes) throughout the duration of the drive via the use of the 2 part discomfort questionnaire.

Upon completion of the 60 minute drive, participants were asked for any qualitative feedback they may have and asked to wait until it was safe to disembark the motion platform and end the trial.

5.4 Results

This results section will outline the results obtained in this study in order to address the hypotheses described previously. Initially this section will consider the effects of long duration driving on the subjective discomfort data collected during the experiment and will consist of two parts. Firstly, part two of the discomfort questionnaire, overall discomfort, and secondly, part one of the discomfort questionnaire, local discomfort. The effect of long term driving on drivers’ subjective discomfort will be determined and comparisons will be drawn with the data obtained in Chapter 4.

Furthermore, to develop on the findings of Chapter 4, this section will also consider the objective discomfort data collected in the form of Seat Fidgets and Movements (SFM) and describe the relationship observed between the subjective and objective discomfort responses. If the SFM method is to be successful, it is crucial that comparisons are made with the findings of Chapter 4 and similarities are observed.

5.4.1 Subjective Overall Discomfort

The first hypothesis for this study was that the overall discomfort ratings reported in this study would follow a similar trend to those obtained in the study reported in Chapter 4. Previous studies (e.g. El Falou et al., 2003; Porter et al., 2003; De carvalho and Callaghan, 2011; Smith et al., 2015) reported that driver discomfort
increases with driving duration and the study in Chapter 4 supported these findings as mean overall discomfort was shown to increase across the duration of the 140 minute drive.

![Graph](image)

**Figure 78**: Mean overall discomfort ratings over time

When analysing the data collected for overall discomfort (Figure 78) it is clear that the mean overall discomfort ratings (part two of the subjective rating scale) increased with duration of driving; supporting the findings of the previous literature (Mansfield et al., 2015; Gyi & Porter, 1998), Mansfield et al.’s (2014) model of overall car seat discomfort and supports the findings of Chapter 4.

Participants mean overall discomfort rating increased from 8.71 after the first 10 minutes of driving to 47.71 upon completion of the trial. Participants’ mean overall discomfort rating did not decrease at any time interval during the trial, showing that on average, overall discomfort increases with driving duration.

The individual subject data (Figure 79) appears to follow a similar trend as each participant recorded greater discomfort ratings upon completion of the 60 minute drive when compared to the start of the trial. There is some variation in responses for individuals, as to be expected and as observed in Chapter 4, where some
individuals recorded discomfort ratings of as low as 10 at the end of the trial, whereas others recorded discomfort ratings of as much as 80 at the end of the trial. This variation in responses is most likely due to individual differences and interpretation of the discomfort rating scale but should be examined further, in correspondence with Chapter 4.

![Figure 79: Individual overall discomfort ratings for all participants](image)

In order to account for individual differences and to make a comparison between individual discomfort ratings the data can be standardised by performing a Z transformation. As discussed previously in Chapter 4, the following equation (Equation 5.1) was used to convert the overall discomfort ratings collected during the study into Z scores that represent deviations from the mean rather than specific discomfort ratings:

\[
Z_i = \frac{x_i - \bar{x}}{S}
\]  

(5.1)

Where: \(Z_i\) = Z-transformed sample observations, \(x_i\) = original values of sample, \(\bar{x}\) = sample mean and \(S\) = standard deviation of sample.
Figure 80: Individual overall discomfort rating Z-scores for all participants

When analysing the overall discomfort rating Z scores for each participant (Figure 80), a much closer relationship can be observed between participants. All participants appear to follow a similar trend and although there is some variation at around 30 minutes of the trial, the data recorded at 50 and 60 minutes shows more uniformity.

5.4.2 Subjective Local Discomfort

In addition to overall discomfort, this study also required participants to provide ratings of local discomfort for specific body parts, as was the procedure in Chapter 4. These body regions were the Upper Back, Lower Back, Sitting Bones, Buttock Area and Contact with the Edge of the Seat and discomfort ratings collected were in accordance with ISO 2631-1 (1999) as discussed in Chapter 3 (Section 3.4.5).
As was expected due to the findings of Chapter 4, the accumulative mean local discomfort ratings (Figure 81) once again follow a similar trend to that observed for mean overall discomfort. The results show that the accumulative total discomfort rating for all body parts increases with duration of driving, supporting the findings for overall discomfort and the findings of Chapter 4. It is important to note that no particular body part dominates the local discomfort responses. This can be observed in further detail when analysing each body part individually (Figure 82). The largest increases in mean local discomfort can be seen in the lower back region and sitting bones region, as expected due to the most commonly reported side effect of long term exposure to vibration is lower back pain (Morgan & Mansfield, 2014) and due to prolonged sitting.
Figure 82: Mean local discomfort for each body party at each time interval.
5.4.3 Objective Seat Fidgets and Movements

The results for all participants (Figure 83) display subjects’ mean overall discomfort rating and mean number of SFMs per 10 minutes, or SFM frequency, against time.

Figure 83: Mean overall discomfort rating and number of SFMs against time for all participants

Figure 83 describes the mean number of SFMs, defined by type, recorded by all participants over each 10 minutes of the trial and displays the corresponding mean overall discomfort rating reported at the end of those 10 minutes. Both overall discomfort and SFM frequency, the number of SFMs per 10 minutes, increase with the duration of driving and a close relationship is observed between SFM frequency and overall discomfort ratings.

Participants’ mean Seat Fidget and Movement (SFM) frequency is shown to increase across each time interval throughout the duration of the trial. Participants recorded, on average, 1.64 SFMs during the first 10 minutes of the trial, in comparison with 7.86 SFMs during the last 10 minutes of the trial and the results are shown to be closely related to those reported for participants’ mean overall discomfort ratings. This increase in SFM frequency supports the findings of Chapter 4 and suggests that similarities are observed between the results of Chapter 4 and this study.
When analysing the data recorded for overall discomfort and the number of SFMs, a clear relationship is observed. Figure 84 describes a positive relationship between the mean overall discomfort rating at each time interval and the number of SFMs reported in the 10 minutes that preceded it and therefore the conclusion can be drawn that as overall discomfort increases, the frequency of seat fidgets and movements also increases. These results appear to follow a very similar trend to those obtained in Chapter 4 and further analysis will be conducted to determine the relationship with the data outlined in Chapter 4.

5.5 Discussion

This section will first discuss the subjective driver discomfort data recorded during the study with regards to the first hypothesis (H5.1) of this study and comparisons will be made between the findings of this study and the findings of Chapter 4. This section will then analyse the findings of the objective SFM data recorded during the study to further determine the success of the method and comparisons will be made with the subjective discomfort data in order to satisfy H5.2, H5.3 and H5.4. Furthermore this section will draw comparisons between the SFM data recorded in
this study to those reported in Chapter 4 to determine the success of implementing the SFM method with largely varying conditions and sample; as was the ultimate aim of the study.

5.5.1 Analysing the Rate of Discomfort Onset over Time

The first research hypothesis (H5.1) for this study was that similar subjective discomfort ratings will be observed for the Japanese sample when compared to the European sample used in Chapter 4. Much of the literature surrounding driver discomfort has reported that subjective discomfort increases with driving duration (Mansfield et al., 2014; Mansfield et al., 2015; Gyi & Porter, 1999) and the findings of Chapter 4 reinforced this theory as increases in overall car seat discomfort and local discomfort were observed over the duration of the trial. T-tests were conducted comparing the discomfort ratings recorded at 10 and 60 minutes of driving which determined that the results for this study show a similar trend as significant increases in mean overall discomfort (p < 0.05, two-tailed) (Figure 78) and mean local discomfort (p < 0.05, two-tailed) (Figure 81) were observed across the duration of the trial.

Therefore, it can be concluded that driver discomfort, both overall and local discomfort, increases with driving duration as both studies in this research have reported increases in subjective discomfort over time. However, in Chapter 4 it was determined that the mean rate of overall discomfort increase decreased with driving duration via the analysis of the discomfort/time ratio and the discomfort gradient. This decrease in the rate of discomfort onset was only observed after approximately 80 minutes and therefore it is unexpected that a similar decrease will be seen when analysing the results of this study.

This can be observed simply by analysing the discomfort/time ratio for the experiment (Table 16). Values for the discomfort over time ratio were produced for this study by dividing the mean overall discomfort rating by the time interval at which it was recorded. The discomfort over time ratio does not appear to decrease across the duration of the trial and in fact an increase is observed at the final time interval. This supports the findings of Chapter 4 as this study was only observed
across a duration of 60 minutes and significant changes in the discomfort over time ratio were observed after 120 minutes of driving during the study in Chapter 4.

Table 16: Discomfort over time ratio

<table>
<thead>
<tr>
<th>Time Period (Minutes)</th>
<th>Discomfort / Time Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>8.71 / 10 = 0.87</td>
</tr>
<tr>
<td>20</td>
<td>14.36 / 20 = 0.72</td>
</tr>
<tr>
<td>30</td>
<td>21.07 / 30 = 0.7</td>
</tr>
<tr>
<td>40</td>
<td>28.29 / 40 = 0.71</td>
</tr>
<tr>
<td>50</td>
<td>36.43 / 50 = 0.72</td>
</tr>
<tr>
<td>60</td>
<td>47.71 / 60 = 0.8</td>
</tr>
</tbody>
</table>

However, the interesting aspect of the subjective discomfort ratings is that discomfort is shown to increase a much quicker rate during this study in comparison to the first 60 minutes of the study in Chapter 4. When comparing the discomfort/time ratio at 60 minutes in this experiment to the equivalent ratio in Chapter 4 there is an increase from 0.27 in Chapter 4 to 0.8 in this study.

This is supported when analysing the gradient of the mean overall discomfort ratings recorded for each study over 60 minutes. A large increase is observed when comparing the data recorded for the first 60 minutes of the study reported in Chapter 4 and the findings of this study (Figure 85).

Although a reliable comparison between the two studies is difficult to obtain due to the differences in the design of the studies, analysis of the subjective ratings of overall discomfort recorded over 60 minutes displays that discomfort increases more rapidly in the results of this study. When analysing the mean overall discomfort gradient for the two studies, a large increase is observed in this study reinforcing the finding that discomfort increased at a quicker rate during this study in comparison to the study in Chapter 4. Furthermore, when comparing the mean overall discomfort ratings at 60 minutes to their equivalent verbal descriptors on the discomfort rating scale, participants mean discomfort increased to a value equating to ‘Little Discomfort’ during the study in Chapter 4, whereas in this study, participants mean discomfort increased to a value that equates to ‘High Discomfort’.
Figure 85: Comparison between the mean overall discomfort ratings recorded over the first 60 minutes during the study reported in Chapter 3 and the mean overall discomfort ratings recorded for this study.

This increase in the rate of discomfort onset may be caused by a number of factors. Firstly, the design of the seat, seating position and driving controls used in this study were very different to that implemented in the study in Chapter 4. As discussed in the literature (Mansfield et al., 2015; Kolich, 2008) different seat designs can elicit different ratings of discomfort when tested under the same driving conditions, i.e. driving duration and vibration exposure, depending on the static and dynamic performance of the seat (Ebe & Griffin, 2000). Furthermore, vehicle packaging has been described as one of the main contributors to comfort perception in drivers (Kolich, 2008) and as a result the increase in the rate of discomfort onset observed in this study in comparison to the results of Chapter 4 may be attributed to the combination of a different seat design and different vehicle packaging design for this experiment.

Another factor potentially affecting the discomfort ratings collected may be the cultural differences between the subjects recruited to participate in the study. Cultural differences have been described as eliciting large differences in comfort perception (Kolich, 2008). Therefore, as this study recruited a Japanese sample, in
comparison with the European sample recruited in Chapter 4, the increase in rate of discomfort onset may also be attributed to cultural differences between the samples.

However, the greatest difference between the studies was the vibration exposure. Vibration magnitude has been shown to greatly affect the rate of discomfort onset in drivers (Mansfield et al., 2014; Mansfield et al., 2015; Ebe & Griffin, 2000) described by Mansfield’s (2013) model of overall car seat discomfort. As this study exposed subjects to a much greater frequency weighted r.m.s. vibration magnitude than the previous study in Chapter 4, 0.405m/s² weighted r.m.s. as opposed to 0.246m/s² weighted r.m.s. in Chapter 4, it was expected that this increase in discomfort would be observed. The findings of this study therefore support the literature as a large increase in discomfort was observed in comparison with the findings of Chapter 4.

Additionally, the signal waveform of the vibration was vastly different in this study. In Chapter 4, the waveform of the vibration maintained a constant level and contained few shocks, whereas the vibration stimuli implemented in this study was made up of a number of shocks due to the design of the experiment and vibration conditions. As shocks have been shown to cause higher levels of discomfort than other stimulus types (Mansfield et al., 2000), the combination of a higher frequency weighted r.m.s. magnitude and the change in stimulus type may explain the increase in mean overall discomfort ratings reported for this study and provide an insight into why much greater discomfort ratings have been recorded over the same exposure duration.

The focal reason this comparison is essential is that the findings may have large implications on the success of the SFM method. As discomfort is shown to increase at a much quicker rate during this study, it is crucial to determine how this impacts on the success of the SFM method. If a strong correlation is observed between the data recorded for SFMs and the subjective ratings of overall discomfort in this study, it provides a strong indication that SFMs and subjective discomfort are in fact closely related, as it suggests that SFMs are able to predict overall discomfort
regardless of the driving and dynamic conditions and the resulting rate of change in discomfort.

5.5.2 Seat Fidgets and Movements

The main aim of this study was to further investigate the relationship between subjective ratings of overall discomfort and the objective measure of SFMs. As the focal objective of this research was to determine the success of the SFM method, it is crucial that the findings of Chapter 4 are further validated during this study. This section will firstly discuss SFM frequency, then SFM magnitude and then draw conclusions on the relationship between SFMs and subjective overall discomfort. Finally, comparisons will be made between the findings of this study and the findings of Chapter 4.

5.5.2.1 SFM Frequency

The second research hypothesis (H5.2) of this study was that SFM frequency would increase with duration of driving as Chapter 4 determined that the number of SFMs recorded by a driver increases over time. The results for this study support this principle as SFM frequency was reported to increase across the duration of the trial, with participants recording an average of 1.64 SFMs during the first 10 minutes of the trial, in comparison with 7.86 SFMs during the last 10 minutes of the trial. T-tests were conducted comparing the SFM data recorded at 0-10 minutes and 50-60 minutes. A significant difference is observed (p < 0.05, two-tailed) suggesting that SFM frequency increased significantly across the duration of the trial. This further supports previous studies by Bendix et al. (1985), Jensen and Bendix (1992), Fenety et al. (2000) and Adler (2007) and validates the findings of Chapter 4.

A conceptual model was proposed in Chapter 4 (Figure 70) that suggested that drivers move or fidget in the car seat as their perceived discomfort reaches a detection threshold and that with increased duration of driving; drivers will reach this detection threshold with increasing frequency. This study supports the model as drivers were observed to record SFMs more frequently after each time interval throughout the trial. As participants recorded higher numbers of SFMs during this study in comparison with the study in Chapter 4 with a higher frequency of SFMs
recorded across the same time intervals this may have some implications on the model. This finding suggests that although a driver’s detection threshold may remain constant, different driving conditions and increased vibration exposure may cause an increase in rate at which the instantaneous discomfort sensation reaches this detection threshold. Therefore if the instantaneous discomfort sensation is reaching the detection threshold more rapidly, the frequency at which the driver will record SFMs will increase.

5.5.2.2 SFM Magnitude

The third research hypothesis (H5.3) for this study was that SFM magnitude would increase with duration of driving. This hypothesis was proposed by Adler (2007) and investigated in the previous study in Chapter 4. As each SFM type relates to a different type of movement, it was proposed that each SFM type related to a different magnitude of movement, Type 1 being small and Type 3 being large movement. However, no correlation was observed in Chapter 4 between SFM type, or magnitude, and duration of driving. It was crucial to investigate whether any relationship was observed in this study therefore a description of the percentage of each SFM type at each time interval can be seen in Figure 86.

![Figure 86: Changes in SFM type percentage over time](image-url)
As with Chapter 4, no correlation was observed during this study between SFM magnitude and time as the percentage of Type 2 and Type 3 SFMs did not increase with time. If magnitude of SFMs did increase with duration of driving, it would be expected that the percentage of Type 2 and Type 3 SFMs would increase with time and the percentage of Type 1 movements would decrease. Two-way ANOVAs ($\alpha = 0.05$) were conducted that compared the percentage of each SFM type at each time interval. No significant difference was found between the percentage of Type 2 or Type 3 SFMs at the beginning of the trial and at the end. Furthermore, when analysing individual subject data for SFM magnitude, no participant was shown to fit the hypothesis. Therefore the conclusion can be drawn that in the case of this experiment, SFM magnitude has not been shown to increase with duration of driving.

As no correlation between SFM type percentage and duration of driving has been observed in the findings of Chapter 4 or in this study it is likely that the conclusion can be drawn that SFM magnitude does not change with duration of driving. This does not comply with the findings of the previous research (Adler, 2007) who determined that when analysing some types of postural movements in drivers, the magnitude of driver movements increased with driving duration. However the fact that no correlation is found in this research may be due to the design of the SFM method. The method used to analyse SFM only determines type of movement in regards to magnitude and does not analyse magnitude changes of each type. For example although Type 1 movements are all the same postural change, some changes may be of greater magnitude than others. Improvements to the methodology may need to be made in order to investigate magnitude of SFMs in more detail.

5.5.3 Relationship between Subjective Overall Discomfort Ratings and SFMs

It can clearly be seen from the results of this study that both subjective overall discomfort ratings and SFM frequency increased with time, supporting the results of Chapter 4. However, the most important objective of this study was to determine the relationship between overall discomfort ratings and SFM frequency (H5.4) and
establish whether a similar relationship is found to that described by the findings of Chapter 4. If a method of SFMs is to be implemented into the automotive industry it is crucial that a similar relationship is observed in this study to further validate the method implemented in Chapter 4 and test its repeatability in vastly differing conditions. The fifth hypothesis of this study (H5.5) states that similarities in SFM data will be observed between this study and the study reported in Chapter 4 and this section will also compare the two studies.

5.5.3.1 Observed Data

A Pearson Correlation was performed on the data that compared the mean overall discomfort ratings at each time interval and the mean number of SFMs per 10 minutes, or mean SFM frequency. A large positive correlation was found with an r value of 0.984, 96.8% shared variance and was statistically significant (r = 0.984, n = 6, p < 0.05) suggesting that a strong relationship is reported between overall discomfort and SFM frequency.

When comparing these results to those reported Chapter 4, the data recorded in this experiment shows a slightly stronger relationship between overall discomfort and SFM frequency ($r^2 = 0.968$ and $r^2 = 0.927$). This may potentially be due to the shorter duration than the previous study. However as a similar relationship is observed, the theory proposed by Chapter 4 that overall discomfort ratings and SFM frequency are closely related is supported. The findings of this study validate the SFM method as this study was conducted in altered laboratory conditions with a different sample yet still produced similar results.

Perhaps the most promising finding is that the results recorded in this study support the theory that overall discomfort and SFM frequency are closely related, despite the rate of discomfort increase, or discomfort gradient, being vastly increased as discussed previously in Section 5.5.1. After 60 minutes of driving, the average overall discomfort rating recorded in this study was 47.7. When comparing this with the average overall discomfort rating recorded in Chapter 4, 29.8, it is clear that subjects experienced higher levels of discomfort more rapidly in this study due to the change in seat design, vehicle packaging and increased vibration exposure.
Encouragingly a strong relationship is still observed between overall discomfort and SFM frequency. This suggests that SFM frequency does not only increase due to duration of sitting but in fact the rate of increase in SFM frequency is closely related to the rate of discomfort increase and the two variables are intrinsically linked.

The overall aim of this research and the SFM method is to develop an objective measure that can be implemented into the automotive industry and used to predict overall discomfort. Therefore, as with Chapter 4, another linear regression was conducted that compared the mean overall discomfort ratings with the mean number of SFMs to produce the equation:

\[ \Psi = -3.384 + 60.55sfm \]  

(5.2)

Where: \( \Psi \) is the rating of overall discomfort and \( sfm \) is the number of SFMs per min.

This equation (Equation 5.2) was then used to produce predicted values of overall discomfort using only SFM data, a comparison of the observed mean overall discomfort ratings and the predicted overall discomfort ratings can be seen in Figure 87.

![Figure 87: Observed vs Predicted overall discomfort using regression equation](image-url)
The predicted values of discomfort are closely related to the observed values \((r^2 = 0.968)\) suggesting that for the data obtained in this experiment, SFM observations can be used to accurately predict subjective overall discomfort ratings, supporting the findings of Chapter 4.

### 5.5.3.2 SFM Weighting Factors

In Chapter 4 it was determined that applying weightings to each SFM type improved the relationship \((r^2 \text{ value})\) between overall discomfort and number of SFMs. Therefore to explore the relationship observed in this study further, weighting factors were applied to each of the SFM types to establish whether this would improve or reduce the correlation \((r^2 \text{ value})\) for this study using the same procedure as implemented in Chapter 4.

![Figure 88: Correlation strength \((r^2 \text{ value})\) when applying weighting factors to each SFM type](image)
As described by Figure 88 the relationship can be improved by applying a weighting factor to each Type 2 and Type 3 movement recorded. As discussed previously, when applying weightings of 1:1:1, the $r^2$ value was shown to be 0.969. However, after analysing the data described by Figure 88, this value can be increased to 0.981 by applying a weighting of 1 to Type 1 movements, 0.1 to Type 2 movements and 0.4 to Type 3 movements, suggesting an improved relationship. Represented by:

$$Total \ sfm_w = Type1 + (Type2 \times 0.1) + (Type3 \times 0.4)$$  \hspace{1cm} (5.3)

Therefore, another regression was conducted in order to produce another equation that included the weighting factors proposed for each SFM type:

$$\Psi = 2.383 + 97.59sfm_w$$  \hspace{1cm} (5.4)

Where: $\Psi$ is the rating of overall discomfort and $sfm_w$ is the weighted number of SFMs per min.

This equation (Equation 5.4) was then used to produce predicted values of overall discomfort using only the weighted SFM data, a comparison of the observed overall discomfort ratings and the weighted predicted discomfort ratings can be seen in

**Figure 89:** Observed vs Predicted (w) overall discomfort using regression equation
Figure 89. When comparing the observed overall discomfort ratings and the predicted discomfort ratings using the weighted SFM data (Figure 89), an improved relationship is observed, represented by the $r^2$ value produced by the regression analysis ($r^2 = 0.981$).

5.5.3.2.1 Comparison with Previous Findings

In order to make a comparison with the findings of Chapter 4, the weighting factors determined by Chapter 4 needed to be applied to the data recorded in this study. Therefore the weighting factors proposed by Chapter 4 were applied to the SFM data collected in this experiment and predicted values of overall discomfort were produced using the regression equation (Equation 4.4) stated in Chapter 4. A comparison could then be made between the observed mean overall discomfort ratings reported in this study (Observed) with the weighted predicted overall discomfort values produced by the equation (Equation 5.4) developed in this study (Predicted (w)) and the weighted predicted overall discomfort values using the equation (Equation 4.4) proposed by the previous study in Chapter 4 (Predicted (C4w)) (Figure 90).

![Figure 90: Observed overall discomfort ratings vs Predicted (w) and Predicted (C4w) overall discomfort using regression equation](image-url)
A close relationship is observed between the observed mean values of overall discomfort and the predicted values when using the weighted SFM equation (Equation 4.4) produced by Chapter 4 \( (r^2 = 0.98) \). This implies that despite the fact that the weighting factors determined in this study are not identical to those determined in the previous study; the weightings and SFM equation (Equation 4.4) from the previous study are applicable to this data. This determines that there is a close relationship between the two studies and that using weighted SFM data to predict values of overall discomfort is a successful method to objectively evaluate driver overall discomfort in long duration driving.

These results are promising for the implementation of the SFM method across the field of driver discomfort and seating evaluation as the method has been shown to be applied successfully in very different conditions with a similar outcome. The weighting factors applied to each SFM type may need to be adjusted after further research with the aim of producing a definition for the SFM method that accurately represents any sample. However, the fact that the SFM method has been able to accurately produce predicted values of overall discomfort for the data recorded thus far suggests that the method has been successful.

5.5.3.4 Interpolated Data

As with the data in Chapter 4, an alternative way to analyse the data is to investigate the correlation between SFM frequency and interpolated mean overall discomfort ratings. It was highlighted in Chapter 4 that perhaps one issue with the analysis of the data is that the ratings reported for overall discomfort were collected at the beginning and end of the 10 minute time intervals, 10 and 20 minutes for example. However, the total number of SFMs correlated with this discomfort rating was collected throughout the duration of that time interval, for example; the number of SFMs between 10 and 20 minutes. Therefore it was established that in order to accurately make a comparison between the two variables, mean overall discomfort ratings should be interpolated between both time intervals to establish an average of that time interval with which to compare the number of SFMs, for example; the total number of SFMs recorded between 10 and 20 minutes should be compared with the interpolated mean overall discomfort
rating at 15 minutes. This process has been conducted again for the data recorded in this study in order to make a new comparison (Figure 91).

![Figure 91: Interpolated mean overall discomfort ratings and number of SFMs against time for all participants](image)

The interpolated ratings for overall discomfort displayed (Figure 91) represent mean discomfort ratings collected at 5, 15, 25, 35, 45, and 55 minutes. In comparison with the observed data recorded in this study (Figure 83), there is a slight improvement in correlation strength between the interpolated overall discomfort ratings and the number of SFMs recorded. Regression analysis and a Pearson correlation determined that the correlation strength between the interpolated data and the number of SFMs (per 10 minutes) is $r^2 = 0.98$. When compared with the correlation strength of $r^2 = 0.969$ for the observed data, a slight improvement is presented suggesting that by interpolating the data to represent a truer reflection of the time intervals used to record SFM data, a more accurate representation of the correlation can be established, supporting the findings of Chapter 4.

As with the observed data, weighting factors can now be applied to the SFM data then correlated with the interpolated overall discomfort data in order to evaluate whether this relationship ($r^2$ value) can be improved further (Figure 92).
As shown in Figure 92, correlation strength can again be increased by applying weighting factors to each SFM type when comparing the frequency of SFMs and the interpolated mean overall discomfort ratings. By applying weighting factors of 1 to Type 1 movements, 0.3 to Type 2 movements and 0.6 to Type 3 movements, the correlation can be improved to correspond with an $r^2$ value of 0.986.

These findings again suggest that when using SFM data to predict overall discomfort the most effective approach, in terms of correlation strength, is to apply the weighting factors determined to predict values of discomfort. Due to the relationship with interpolated discomfort data again showing a stronger correlation this suggests that SFM predictions will more accurately represent ratings of discomfort at an average of the time interval.
However, again, these improvements are minimal, gaining no statistical significance and need to be tested against a wider range of data. The correlation between the number of SFMs and overall discomfort is again shown to be a strong positive correlation regardless of how the data is manipulated and suggests that both weighted and un-weighted SFMs can useful for predicting values of overall discomfort that represent both the discomfort at the end of the time interval throughout which they were collected and as an average of that time interval, as shown with the data in Chapter 4.

5.5.4 Relationship between SFMs and Verbal Discomfort Descriptors

As the ultimate aim of this research is to establish an objective measure of driver discomfort to be implemented into the automotive industry, it is important to determine how a measure of SFM frequency translates to verbal discomfort descriptors.

Therefore, as with Chapter 4, at each time interval a verbal descriptor was selected that corresponded to the average overall discomfort rating recorded at that time using the verbal discomfort descriptors included on the overall discomfort scale described in Chapter 3 (Section 3.4.5). This verbal discomfort descriptor can then be matched with the SFM frequency recorded at that time interval to gain an understanding of how SFM frequency relates to a tangible description of discomfort. A table outlining this can be seen in Table 17.

<table>
<thead>
<tr>
<th>Time</th>
<th>Overall Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>8.71</td>
<td>0.16</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>20</td>
<td>14.36</td>
<td>0.31</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>30</td>
<td>21.07</td>
<td>0.41</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>40</td>
<td>28.29</td>
<td>0.59</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>50</td>
<td>36.43</td>
<td>0.67</td>
<td>High Discomfort</td>
</tr>
<tr>
<td>60</td>
<td>47.71</td>
<td>0.79</td>
<td>High Discomfort</td>
</tr>
</tbody>
</table>
The data in Table 17 was collected during this experiment. In order to explore the relationship with verbal discomfort descriptors further, another table was developed using the equation produced by the regression analysis that determines the range of number of SFMs (per min) and overall discomfort rating against the verbal discomfort descriptors. This table was developed by rearranging the regression equation (Equation 5.2), as such:

1) \( \Psi = -3.384 + 60.55sfm \)
2) \( \Psi sfm = \frac{(-3.384 - \Psi)}{-60.55} \)  

(5.5)

Then, using the boundaries for overall discomfort ratings, boundaries for SFM frequency were calculated that relate to the equivalent verbal discomfort descriptor. This can be seen in Table 18.

<table>
<thead>
<tr>
<th>Overall Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No Discomfort at all</td>
</tr>
<tr>
<td>0 – 4</td>
<td>0 – 0.122</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>4 – 10</td>
<td>0.122 – 0.221</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>10 – 17</td>
<td>0.221 – 0.337</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>17 – 23</td>
<td>0.337 – 0.436</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>23 – 28</td>
<td>0.436 – 0.518</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>28 – 33</td>
<td>0.518 – 0.601</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>33 – &gt; 47.71</td>
<td>0.601 – &gt; 0.844</td>
<td>High Discomfort</td>
</tr>
</tbody>
</table>

Table 18 provides the basis for discomfort assessment to be made using only SFM data. The table suggests that a driver experiencing ‘Very Little Discomfort’ would record an SFM less than once every 4.5 minutes whereas a driver experiencing ‘Moderate-High Discomfort’ would record an SFM roughly once every 2 minutes. This finding allows for measurements of SFM frequency to be associated with direct descriptions of discomfort and suggests that the SFM method can be implemented successfully into automotive seating assessment and evaluation.
Table 18 is a replica of Table 13 from Chapter 4 (Section 4.5.4) however the SFM ranges have been produced using the regression equation (Equation 5.5) produced by this data. A comparison between the SFM frequency ranges produced by this data and the SFM frequency ranges produced by the data in Chapter 4 is required to determine whether the ranges are similar and therefore applicable for both data sets (Table 19).

<table>
<thead>
<tr>
<th>Verbal Descriptor</th>
<th>SFMs/min (This Study)</th>
<th>SFMs/min (Chapter 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Discomfort at all</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Just Noticeable Discomfort</td>
<td>0 – 0.122</td>
<td>0 – 0.021</td>
</tr>
<tr>
<td>Very Little Discomfort</td>
<td>0.122 – 0.221</td>
<td>0.021 – 0.144</td>
</tr>
<tr>
<td>Little Discomfort</td>
<td>0.221 – 0.337</td>
<td>0.144 – 0.288</td>
</tr>
<tr>
<td>Little-Moderate Discomfort</td>
<td>0.337 – 0.436</td>
<td>0.288 – 0.411</td>
</tr>
<tr>
<td>Moderate Discomfort</td>
<td>0.436 – 0.518</td>
<td>0.411 – 0.514</td>
</tr>
<tr>
<td>Moderate-High Discomfort</td>
<td>0.518 – 0.601</td>
<td>0.514 – 0.616</td>
</tr>
<tr>
<td>High Discomfort</td>
<td>0.601 +</td>
<td>0.616 +</td>
</tr>
</tbody>
</table>

Table 19 describes that although the SFM frequency (SFMs/min) ranges produced by the two studies are not identical; similarities are observed when discomfort is greater than ‘Little Discomfort’. For example, when comparing the upper and lower boundaries for ‘Moderate Discomfort’, both studies define similar ranges for SFM frequency (SFMs/min). This suggests that the ranges proposed when discomfort is greater than ‘Little Discomfort’ are applicable for both groups of data and therefore will be very useful as a way of defining the SFM frequency associated with different verbal discomfort descriptors.

One cause for the differences observed between the two studies at the lower ranges is that for the data recorded in this study, the lowest mean overall discomfort rating recorded was 8.71 after 10 minutes. This equates to near the upper boundary for ‘Very Little Discomfort’ and therefore as no SFM data recorded correlates to less than ‘Very Little Discomfort’, the definitions for SFM frequency ranges less than this are only speculative due to the regression equation. This may
explain the differences observed between studies and suggests that further analysis is required to determine the SFM frequency ranges for low levels of discomfort (< Little Discomfort). If the SFM method is to be implemented into the automotive industry it is important that the SFM frequency ranges are well defined. In order to utilise the SFM method without subjective assessment, as is the ultimate aim, SFM frequency ranges must be appropriate for any sample and well defined against verbal discomfort descriptors.

5.6 Conclusions

The study presented in this chapter was designed to investigate the effect of long duration driving on subjective driver discomfort and further validate the success of a novel objective measure of discomfort, SFMs, in accurately predicting subjective responses with a greatly altered sample, different laboratory conditions and different driving conditions. This section will draw conclusions with reference to the research hypotheses for the chapter.

**H5.1: Similar subjective discomfort ratings will be observed for the Japanese sample when compared to the European sample in Chapter 4**

The results of the laboratory study showed that driver discomfort increased across the duration of the 60 minute driving trial. All subjects recorded an increase in subjective discomfort upon completion of the trial and distinct similarities were observed between the responses recorded for overall discomfort and local discomfort. These findings supported the findings of Chapter 4 as discomfort was shown to increase with driving duration and also supported the findings of the literature. However, discomfort was shown to increase at a much quicker rate during this study when compared to the study in Chapter 4. This increase in the rate of change in discomfort was determined to be a product of increased vibration magnitude, different waveform signal of vibration in the form of shocks and different seat and vehicle packaging designs in combination with the cultural differences observed due to the sample recruited.

Additionally, discomfort is shown to increase at a linear rate. This supports the findings of Chapter 4 as this study had trial duration of 60 minutes compared with
140 minutes and discomfort was shown to increase at a linear rate up until approximately 70 minutes in Chapter 4. Moreover, these findings appear to support the quantitative model proposed by Mansfield et al. (2014) as the model has been shown to be extremely successful when predicting discomfort for journeys up to an hour in duration.

**H5.2: SFM frequency will increase with duration of driving**

SFM frequency was again shown to increase with duration of driving as participants recorded significantly greater number of SFMs during the last 10 minutes of the trial in comparison with the first 10 minutes. This finding supports the results displayed in Chapter 4 and the previous literature, suggesting that as discomfort increases across the duration of a long term drive, drivers move more often in the vehicle seat in order to relieve some of the discomfort associated with long term driving and vibration exposure. These findings also support the conceptual model proposed in Section 4.5.2.1.

**H5.3: SFM magnitude will increase with duration of driving**

As with the results in Chapter 4, no relationship was observed between SFM magnitude and driving duration during this study. Increases in Type 1 movements were observed across the duration of the trial; however the results were not significant. Therefore, it is concluded that further research is required to investigate the effect of driving duration on SFM magnitude, or SFM type, and that this finding may be a result of the design of the method. Adler (2007) proposed that magnitude of driver posture changes would increase with driving duration and therefore the method may need to be improved in further study to account for the magnitude of individual movements rather than classifying movement magnitude by movement type.
**H5.4:** A relationship will be observed between subjective discomfort ratings and SFMs

This hypothesis can be accepted as a strong positive correlation between subjective overall discomfort ratings and SFM frequency is again observed in this study, supporting the findings of Chapter 4 and the previous literature. Drivers are shown to move more frequently in the vehicle seat as discomfort increases. SFM frequency is shown to accurately predict overall discomfort ratings and suggests that a measure of SFMs may be successful in replacing subjective assessment.

**H5.5:** Similarities in SFM data will be observed between this study and the study in Chapter 4

This hypothesis can also be accepted as when comparing the results for subjects’ SFMs during this study and the study conducted in Chapter 4, clear similarities are observed between the studies. The correlation between SFM frequency and subjective overall discomfort observed in both studies shows a strong positive correlation, however the most promising finding is that this correlation is still observed despite the differences between the two studies. Subjective discomfort is shown to increase at a quicker rate during this study and the SFM method is shown to cope with increase as SFM frequency also increases at a quicker rate. It is therefore concluded that SFM frequency is closely related to the rate of discomfort increase and the two variables are intrinsically linked.

As the SFM method has been shown to be applicable in varying laboratory conditions and validated with a varied sample, the next question to address is whether the SFM method can detect acute differences in discomfort when comparing the same sample under multiple conditions. If the method is to be implemented into the automotive industry, the SFM method must be useful when assessing the design of different seats with the same sample or the same seat under different conditions, with the same sample. Therefore the next laboratory study, discussed in Chapter 7, aimed to tackle this issue by testing the same sample under different conditions and aimed to determine whether the SFM method can be used to detect acute differences in discomfort.
This chapter discusses a field observation designed to determine the current typical behaviour of drivers when undertaking a break from a long term drive; with the primary aim of informing the design of the study conducted in Chapter 7. Research was carried out by discretely observing drivers under real world conditions to gain an insight into typical break duration and type of activity undertaken by drivers when visiting a service station during a break from a long term drive.

This study aimed to clarify the typical experience of a driver whilst undertaking a break from driving in order to inform the development of a laboratory study that recreated a normal experience for drivers and investigates the effect of breaks from driving on driver discomfort. As the study to be conducted in Chapter 7 aims to investigate the effect of breaks from a long term drive on driver discomfort it is crucial this observation was carried out prior to designing the experimental conditions and protocol for Chapter 7.

Furthermore, there are many recommendations available for drivers who are undertaking a long-term journey regarding breaks from driving, mostly concerned with safety and tiredness. In order to further the knowledge of driver discomfort in long term driving, this study aimed to simply evaluate typical behaviour of real drivers and will briefly discuss whether these recommendations were realistic and complied with. However, the primary purpose for this study was to inform the design of the study to be conducted in Chapter 7.

6.1 Introduction

During a long term drive it is common that drivers and passengers will take a break from driving, often in a service station. These breaks from driving may be taken for a number of different reasons and the prior motivation for breaks from driving is
difficult to define. There are a range of guidelines provided for drivers undertaking a long term drive that propose the optimum behaviour for breaks from driving, as discussed in Chapter 2. Many of these suggest that a break of 15 minutes should be planned into a long term journey roughly every 2 hours in order to minimise the safety risks associated with fatigue and drowsiness (Horne & Reyner, 1999: Ravnik et al., 2008). From a safety perspective, the benefits of a break from a long term drive have been clearly determined (Horne & Reyner, 1999) however, these guidelines fail to address discomfort and more importantly it has yet to be established whether drivers adhere to these guidelines in practice. For many drivers, minimising total journey duration is a priority and therefore drivers are willing to compromise safety as the benefits of taking a break from driving are underestimated or unknown.

It is important to evaluate whether drivers who do undertake a break from a long term drive comply with the guidelines provided and a more detailed analysis of driver behaviour during breaks may provide an insight into the motivation for drivers to have a break from driving. It is crucial to investigate whether these guidelines are successful in encouraging drivers to undertake a break, due to the safety benefits, or whether these guidelines are ignored and therefore unsuccessful.

The evaluation of drivers during breaks is crucial for the planning of the next laboratory study in Chapter 7 that aims to analyse the benefits of breaks from driving in terms of discomfort. Typical behaviour of drivers must be determined in order to accurately recreate a realistic experience with specific regards to activity and duration when implementing breaks into a laboratory study design. If the study proposed for Chapter 7 is to be successful, the data recorded during this observation must inform the design of the study and it is important that this study was conducted as a real world verification to ensure that the conditions to be implemented in Chapter 7 are appropriate.

6.2 Aims and Objectives

The aims of this study were to observe and evaluate the typical behaviour of drivers during a normal break from a long term drive at a service station, with specific
interest in break duration and type of activity undertaken during the break. The findings of this study will provide an insight into driver behaviour and aid in the design of the laboratory study conducted in Chapter 7.

The main hypotheses (and null hypotheses (nH)) of this study were:

**nH6.1**: The average break duration for subjects will not be similar to the duration recommended in the guidelines provided in the literature

**H6.1**: The average break duration for subjects will be similar to the duration recommended in the guidelines provided in the literature

**nH6.2**: There will not be large variation in the type of activity drivers undertake during breaks from driving

**H6.2**: There will be large variation in the type of activity drivers undertake during breaks from driving

### 6.3 Methods

The study reported in this chapter was conducted as a field observation at Leicester Forest East service station on the M1 motorway in the UK. The procedures and methodologies implemented were as defined in Section 3.5 and this section will determine any further methodologies utilised that were specific to the study. Firstly the details regarding the sample recruited to take part in the study will be defined followed by an outline of how the study aimed to tackle the hypotheses for the study stated previously. The section will conclude with a detailed description of the experimental protocol undertaken during this study, with specific regards to the design and equipment used. The data collection sheet used during this study can be seen in Appendix A4.

#### 6.3.1 Sample

Participants were not actively recruited for the study but were selected for inclusion by previously defined criteria. Participants were only selected if they were an occupant of a vehicle with a normal seating position, for example larger vans were excluded as they incorporate a bench seat / more upright posture that did not fit
with the design of this research. All participants were occupants of a vehicle that stopped at Leicester Forest East service station and no participants were aware they were being observed.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Vehicles</td>
<td>45</td>
</tr>
<tr>
<td>Number of Occupants</td>
<td>62</td>
</tr>
<tr>
<td>Number of Vehicle with Multiple Occupants</td>
<td>13</td>
</tr>
</tbody>
</table>

### Table 20: Characteristics of sample observed

**6.3.2 Independent Variables**

**6.3.2.1 Position**

The researcher worked individually so as not to attract attention and adopted a carefully chosen position at the service station that allowed a full view of the service station car park.

**6.3.2.2 Time Frame**

In order to observe a high number of participants in a short duration, the observation took place during a time at which it was assumed the service station would be at its busiest. Therefore, the observation took place on a Sunday evening between 17h00 – 20h00. At time at which it was assumed that, firstly, the service station would be busy and secondly, the participants observed would be undertaking a drive of a long duration due to the location and time frame. This assumption was important but not essential as ideally the observation would have only included vehicles undertaking a journey of more than 2 hours in duration however due to the discrete nature of the observation, definitive journey durations were difficult to obtain. If interviews had been possible this would have improved the information regarding the sample and reduced the need for such assumptions.

**6.3.2.3 Vehicle Type**

As briefly mentioned previously, participants were only selected for observation if they were an occupant of vehicle with a normal seating position. Therefore, large vans, motorbikes and trucks were excluded as they do not include a seating position determined by the experimenter as ‘normal’. Normal seating positions were defined
by the type of seating position tested in the previous laboratory studies described by Chapter 4 and Chapter 5. As this research focused on vehicles with this type of seating design, it was important that this study observed similar vehicle types as the study conducted in Chapter 7 also included a similar style of seating position. An even distribution of each vehicle type was targeted and the types of vehicle included in this observation were:

- 4x4
- Small Van
- Saloon
- Coupe
- Hatchback
- People Carrier

6.3.3 Dependant Variables

6.3.3.1 Break Duration

The first of the dependant variables to be recorded was the duration of the break from driving. This duration was defined as the time between the driver stopping the vehicle and switching off the engine to the moment at which the driver started the engine again and began driving the vehicle. This was observed by the experimenter and a stopwatch was used to record break duration. Break duration was recorded for each vehicle.

6.3.3.2 Type of Activity

The second of the dependant variables was the type of activity undertaken by vehicle occupants during the break from driving. Due to the design of the observation, detailed analysis of vehicle occupant activity was difficult to obtain without being too invasive on the subjects. Therefore it was decided that activity would be defined under 2 different categories:

1) Left the Vehicle
2) Sat in the Vehicle
Type of activity was recorded for each vehicle occupant as occupants of the same vehicle may undertake vastly different activities during the break. Therefore, the duration of which each participant spent partaking in each activity type was recorded in combination with the total break duration. For example, if a subject sat in the vehicle, then left the vehicle, then sat in the vehicle before ending the break, the duration of which the subject partook in both activities would be recorded.

6.4 Results

In total, 45 vehicles were observed with a total number of 62 subjects, as some vehicles contained more than 1 occupant. During the data collection, the two most important variables to be recorded were the duration of the break from driving and the activity undertaken during the break. The graph displayed in Figure 93 shows the frequency distribution of break duration for all of the subjects observed.

![Histogram of Break Duration](image)

**Figure 93:** Frequency distribution of break duration for the total sample (Minutes)
The vast majority of subjects observed recorded break duration of less than 25 minutes, with the mean break duration concluded as 11 minutes 48.6 seconds. Furthermore, the median break duration observed was calculated to be 11 minutes 9.6 seconds. If any break duration greater than 22 minutes is removed from the data set, due to these being uncommon and regarded as outliers, the mean break duration is shown to be 10 minutes 52.2 seconds.

6.5 Discussion

This section will firstly discuss the break duration observed in the data and compare this with recommendations of break duration proposed in the literature. This analysis will initially discuss how the number of occupants and vehicle type affect typical break duration to further the knowledge of driver behaviour in long term driving but most importantly the analysis will define average break duration in order to satisfy the first hypothesis (H6.1) and to be implemented in the design of the study in Chapter 7.

Secondly this section will discuss the typical type of activity undertaken during a break from a long term drive in order to satisfy the second hypothesis (H6.2) and provide an insight into driver behaviour during breaks from driving but more importantly to develop a set of common activities undertaken that can be implemented into the design of the study conducted in Chapter 7.

6.5.1 Break Duration

As shown by Figure 93 the mean break duration for the 62 subjects observed was defined as 11 minutes 48.6 seconds. This implies that on average, drivers do not tend to adhere to the guidelines provided (Department for Transport; Horne & Reyner, 1999) that propose a minimum of 15 minutes break should be implemented after every 2 hours of driving. Unfortunately, due to the nature of the study, the duration of which the driver has been driving for prior to the break observed was not recorded, therefore it cannot be concluded that the drivers had been driving for longer than 2 hours, as the guidelines suggest. However, the assumption can be made, due to the observation taking place at a typical motorway service station and at a time where drivers are usually undertaking extended duration journeys, that a
range of journey durations will be accounted for and that many of these will be durations of more than 2 hours.

Therefore, although some drivers may have adhered to the guidelines available, many drivers have taken a break of less than the 15 minutes suggested. In fact, 75.8% (n = 47) of the 62 subjects observed recorded break durations of less than 15 minutes implying that these subjects either have not been driving for more than 2 hours, do not know the guidelines that are available, or chose to ignore these guidelines. This will in turn affect their ability to recuperate from the negative effects of fatigue and tiredness as described by (Horne & Reyner, 1999), moreover this may also have a negative effect on the subjects’ ability to relieve the discomfort experienced in long term driving.

6.5.1.1 Number of Occupants

In order to gain a further insight into the behaviour of drivers during a break from driving, a comparison was made between vehicles observed that contained one occupant (n = 30), the driver, and vehicles that contained more than one occupant (n = 32). A T-test was conducted that determined that no significant difference (p > 0.05, two-tailed) in break duration is observed between vehicles with one occupant when compared to vehicles with multiple occupants. However, a significant difference is observed if subjects that recorded break durations of over 25 minutes are excluded (p < 0.05, two-tailed). If subjects with abnormal break durations, 25 minutes or more, are excluded from the calculations, subjects who were alone recorded a mean break duration of 9 minutes 32.4 seconds whereas subjects in groups recorded an average break duration of 12 minutes 9.6 seconds. This suggests that when taking a break from driving, drivers who are alone will take a shorter break than if they were accompanied by a passenger or passengers. Drivers who are alone will typically only take a break of slightly less than 10 minutes, more than 5 minutes less than the break duration proposed by the ‘THINK! Don’t Drive Tired’ campaign by the Department for Transport. As much of this research is focused on the driver, it is important to understand how drivers will behave whilst they are undertaking a long term drive both alone and with company. Furthermore, the research conducted previously has required drivers to drive alone and therefore
if breaks are to be implemented into future research; the fact that the subject is driving alone should be accounted for.

6.5.1.2 Vehicle Type

Figure 94 describes the type of vehicle observed and the percentage of the total number of vehicles represented by that type. The aim was to investigate an even distribution of vehicle type in order to incorporate a range of different drivers and therefore different professions and reasons for travel, although this was very difficult to obtain without the use of interviews. The distribution of vehicle type shows that a relatively even distribution was attained with the most popular vehicle types being ‘Hatchbacks’ and ‘Saloons’ both at 22% of the total population. These are followed by ‘Coupes’ and ‘4x4s’ at 16% and then ‘Small Vans’ and ‘People Carriers’ at 13% and 11% respectively.

These vehicle types were chosen as they are all designed to have a normal driving position, or a typical seat that would be found in the majority of road vehicles. In addition to ensuring that an even distribution of the chosen vehicles was achieved, this data is also useful in determining whether any differences in break duration were observed between vehicle types (Figure 95). This information may be useful in designing future studies that aim to investigate breaks from driving.

The data shows that Hatchbacks recorded the shortest mean break duration of 9 minutes 25 seconds, followed by 9 minutes 36 seconds for Small Vans. Coupe’s recorded a mean duration of 10 minutes 29 seconds and People Carriers recorded a mean of 11 minutes 49 seconds. The longest mean break duration was recorded by Saloons at 14 minutes 48 seconds.

6.5.2 Type of Activity

In addition to recording the duration of the break and perhaps more importantly, the study aimed to provide an insight into the typical behaviour of vehicle occupants during a break from a long term drive. In order to do so, the duration of which a subject sat in the vehicle after stopping the driving task was recorded, the duration of which the subject was away from the vehicle (left the vehicle) was recorded and the duration of which the subject sat in the vehicle again before
commencing the driving task was recorded. Due to the method used, the minimum duration that a subject could be sat for was 60 seconds as any duration less than 60 seconds was regarded as immediately leaving the vehicle.

![Figure 94: Vehicle types and percentage of total sample](image)

![Figure 95: Mean break duration for each vehicle type](image)
Using the results displayed in Figure 96, the type of activity undertaken by subjects observed can be characterised under one of the following categories:

1) Left the Vehicle – subjects left the vehicle immediately after stopping the driving task and immediately commenced the driving task upon returning to the vehicle.

2) Sat in the Vehicle – subjects remained seated in the vehicle after stopping the driving task until returning to the driving task.

3) Sat in the Vehicle, Left the Vehicle – subjects remained seated in the vehicle after stopping the driving task, then left the vehicle and immediately commenced the driving task upon returning to the vehicle.

4) Left the Vehicle, Sat in the Vehicle - subjects left the vehicle immediately after stopping the driving task, then sat in the vehicle until returning to the driving task.

5) Sat in the Vehicle, Left the Vehicle, Sat in the Vehicle - subjects remained seated in the vehicle after stopping the driving task, then left the vehicle, then sat in the vehicle until returning to the driving task.

This can be seen in Figure 96 and the type of activity undertaken by subjects was largely varied in the sample observed. Furthermore, the importance of recording individual subject data in comparison with recording data just for each particular vehicle became apparent as subjects from the same vehicle often undertook very different activities during the break. For example, the total break duration for one particular vehicle observed with 3 occupants was 550 seconds; however the activity undertaken by the occupants varied as 2 occupants immediately left the vehicle for the duration of the break and one occupant remained seated in the vehicle for the duration of the break. This implies that subjects from the same vehicle may not perform the same activity during a break from a long term drive and therefore may not experience the same benefits from the break.
Figure 96: Type of activity undertaken and duration
As the varying types of activity undertaken have been defined using the data observed in this study, the remaining factor to be determined is the type of activity that subjects undertake upon leaving the vehicle. During the observation in this study, it was noted that almost all subjects that left the vehicle walked from their vehicle into the service station, except 2 subjects that ran. It can be assumed that the normal activity is to walk rather than run and the assumption can be made, due to experience and the design of a service station in the UK, that there are only 3 main activities that subjects could have undertaken whilst away from the vehicle:

1) Walked to the service station from their vehicle, walked inside the service station and then walked back to their vehicle from the service station
2) Walked to the service station from their vehicle, sat on another seat inside the service station and then walked back to their vehicle from the service station
3) Walked in the surrounding areas of the car park

Although the type of activity undertaken when away from the vehicle is difficult to define due to the design of the study, it can be said with that subjects’ activity would fall under one of the 3 categories. This provides a useful insight into driver behaviour during long duration driving as previous literature is yet to define driver behaviour during breaks from driving and although more research is required to produce a detailed analysis of behaviour during breaks, this study has produced useful categories under which driver activities can be defined:

1) Sit in the vehicle
2) Walk
3) Walk and sit in another seat

It is shown that any combination of these 3 activity types may be carried out by subjects, however in order to produce simplified descriptions of activity type, these definitions can be applied to any of the subjects observed. Another potential category would be ‘Walk & Stand’ however due to the design of the study this was almost impossible to obtain data for and it can be assumed that subjects would not stand for a substantial amount of time. These observations will provide a useful
insight when designing the study to be conducted Chapter 7 as driver behaviour during breaks must be controlled and realistic if any study that investigates driver activity during breaks is to be successful. The simplified categories defined may be directly applicable when investigating breaks from driving in a laboratory setting.

6.5.3 Recommendations for Future Research

The ultimate aim of this study was to provide an insight into real driver behaviour in order to design an experiment with external validity that determines the effect of having a break from a long term drive on driver discomfort. If breaks from driving are to be implemented in a laboratory study, the results of this study should be used to inform the design of the break from driving.

As the mean break duration for all participants observed during this study was 11 minutes 48.6 seconds, if a break from driving is to be implemented in a laboratory study, this break should reflect these findings and aim to investigate a similar duration. If the study is focused on drivers who are driving alone, there is the potential for this duration to be reduced to 9 minutes 32 seconds as subjects who were alone were observed to record shorter break duration.

Furthermore, this study has defined the type of activity undertaken by the subjects to a reasonable degree. Therefore, any study that implements breaks from driving should reflect these findings in the design of the break. Using the simplified categories of activity type, a number of break types can be defined that may be useful when designing a study that includes breaks from driving.

Further research should also aim to develop upon the research carried out during this study. As this study was mainly conducted to inform the design of Chapter 7, the method and sample observed were not as extensive as a larger study has the potential to be. An interesting project idea would be to continue this research further and ask subjects to complete a brief questionnaire to gain a further insight into typical driving durations before taking breaks and a more detailed evaluation of break duration and activity type may produce some useful findings regarding breaks from long term driving.


6.6 Conclusions

The field observation study presented in this chapter aimed to determine the behaviour of drivers during a break from a long duration drive in UK. Most importantly this study was designed so that the findings could inform the design of the study to be conducted in Chapter 7. This section will draw conclusions on the success of the study with reference to each of the research hypotheses for the chapter.

**H6.1: The average break duration for subjects will be similar to the duration recommended in the guidelines provided in the literature.**

The results of this study determined that mean break duration of 11 minutes 49 seconds was found for the sample observed. If abnormally long break durations were removed, this duration decreased to 11 minutes and 9 seconds. This duration is significantly shorter than the recommended break duration as proposed by the Department for Transport (Horne & Reyner, 1999) and suggests that drivers undertaking a long term drive do not necessarily adhere to the guidelines available for best practice. This may be due to motivations such as minimising total journey time and there is a possibility that the benefits of breaks from driving are not well understood or ignored. Additionally, it was proposed that drivers who are travelling alone will record significantly shorter break durations of approximately 9 minutes 30 seconds when compared to those not travelling alone, this may have some implications on the design of future research that investigates single drivers.

Ultimately, any study implementing breaks from driving should aim to include a break of approximately 9 – 12 minutes in order to accurately represent the typical duration recorded by drivers in real world conditions, depending on the aims of the study. Therefore, the findings of this study will be referred to when determining the design of the study in Chapter 7.

Further research should also aim to investigate the effect of break duration as there are many potential benefits of taking a longer break, as drivers may better recover from the effects of discomfort over a longer duration. A comparison should be made between the benefits of taking a 15 minute break, as recommended,
compared to a 9 – 12 minute break as observed. Furthermore, this study should be replicated in more detail, aiming to incorporate a larger sample, during many different time periods. For the purpose of this research, this study was sufficient to provide recommendations for the design of the study to be conducted in Chapter 7, however there is the potential for many interesting findings if this study can be built upon.

**H6.2: There will be large variation in the type of activity drivers undertake during breaks from driving.**

The findings of this study showed that drivers did in fact record large variations in activity type during the observed break from driving. However, these activity types have been defined under 3 simplified categories and it was determined that drivers may undertake a combination of these 3 activity types during a break from long term driving.

Therefore, any study that aims to investigate breaks from a long term drive should represent these findings in the design of the activity to be undertaken during a break. The study in Chapter 7 will utilise the 3 simplified activity types in order to design multiple break conditions where the effect on driver discomfort will be investigated.

Finally, as this study was conducted in order to determine the design of the laboratory study in Chapter 7, the study has been successful as the findings of this study provide a useful insight into driver behaviour and will be used to determine a number of break types to be investigated in the next chapter.
CHAPTER 7

Subjective and Objective Discomfort when Taking Breaks during Long Duration Driving

This chapter presents the third in the series of laboratory studies carried out during this research, conducted at the Environmental Ergonomics Research Centre, Loughborough University, UK. The study was designed to further investigate the effects of long duration driving on driver discomfort and how the implementation of breaks from driving may impact driver discomfort during a long term drive. The previous study in Chapter 6 provided an evaluation of driver behaviour during breaks from long term driving and the findings of Chapter 6 were used to inform the design of this study.

Furthermore, this study aimed to build upon the findings of the previous laboratory experiments by further evaluating the success of the objective measure of driver discomfort in the form of Seat Fidgets and Movements (SFM). A strong positive correlation between subjective discomfort and SFM frequency has been observed in the findings of Chapter 4 and Chapter 5, suggesting that the method may be sufficient to replace subjective assessment. In order to examine this relationship further, this study aims to investigate the method under a range of conditions to establish how the method is affected by fluctuations in subjective discomfort caused by breaks from driving.

Therefore, the study aimed to utilise the same experimental parameters as Chapter 4 with alterations in the driving conditions that subjects were required to undertake, in the form of breaks from driving. As the main aim of this research was to determine the success of the objective measure of discomfort, it is crucial to evaluate the ability of the method to distinguish between experimental conditions and therefore acute changes in discomfort as this is likely the primary use for the method if successfully implemented into the automotive industry.
7.1 Introduction

During a long term drive, there becomes a point upon which improvements in seat design become ineffective as sitting in one posture for an extended duration will result in increases in discomfort regardless of how well the seat has been designed. At this moment the responsibility is with the driver to identify and manage their own discomfort. Moreover, discomfort may not be the only issue. Drivers who drive for extended durations frequently are placing themselves under great risk of developing negative health effects due to long term sitting and vibration exposure (Mansfield, 2005). One of the main objectives of this research was to determine how drivers can effectively manage their discomfort and help to combat the effects of long duration driving.

One of the methods proposed in order to combat the effects of long term discomfort is to implement breaks into a long-term drive. The benefits of taking a break from driving have been well documented with regards to safety (Horne & Reyner, 1999; Horne & Reyner, 1995), however breaks from driving may also have a positive impact on discomfort as it provides the driver with the opportunity to alter ones posture whilst away from the driving task and in turn relieve pressure on compressed body parts, increasing blood flow to areas of the body that may be causing the discomfort. One study that successfully determined the effect of breaks from driving on discomfort was Ravnik et al. (2008) where subjective driver discomfort was measured across a 100 minute drive, a 15 minute break and a further 65 minute drive. It was established that discomfort was reduced to almost zero following the 15 minute break from driving suggesting that breaks from driving can have a positive impact on discomfort.

Furthermore, the vehicle is a dynamic environment and vibration exposure is a key contributing factor to long discomfort experienced by drivers (Mansfield et al., 2014). Breaks from vibration exposure may allow the negative effects of vibration exposure on discomfort to be reduced following the cessation of vibration, however little research is available that supports this theory. Yonekawa et al. (1998) investigated the effect of rest time on Temporary Threshold Shift (TTS) due to
intermittent vibration exposure when using hand held tools. The growth and recovery of TTS was examined and the results determined that the proposed rest time of 5 minutes by the Labour Ministry in Japan should be increased to 10 minutes in order to allow full recovery from TTS. This suggests that benefits from breaks from vibration exposure may have positive effects on the individual and that the effect of breaks on whole body vibration exposure should be investigated.

Although the benefits of taking a break, especially from a safety perspective, are well-researched and well-advertised, as shown by the guidelines discussed in the previous chapter, there is little research that investigates the effects of breaks from a long term drive on driver discomfort and the benefits are yet to be determined. It could be argued that drivers may be more willing to accept the guidelines for taking a break if these guidelines discussed the benefits in terms of minimising discomfort as well as safety, as drivers feel they have less control over discomfort increase as opposed to their own safety. Many drivers perceive that they can control their own safety and that they can combat the negative effects of fatigue and drowsiness personally. However, this cannot be argued for discomfort, as all drivers will unavoidably experience increased discomfort whilst undertaking a long-term drive and if the benefits of breaks from driving can be proposed in a manner that highlights the benefits of comfort, as well as safety, this may encourage more drivers to accept the need for breaks from long-term driving.

On a broader scale, the benefits of taking a break from vibration exposure whilst seated in a vehicle may also have wider implications. The effect of taking a break from vibration exposure on discomfort is not well documented and this research may provide a useful insight into the human response that could be utilised in many other industries. For example, anecdotal evidence suggests, it was discussed that many of the drivers operating heavy machinery will work throughout the day with no breaks, out of choice. These drivers are exposed to much greater magnitudes of vibration than normal road users and therefore the long term effects of vibration exposure on discomfort will be severely increased (Mansfield et al., 2014). If the benefits of taking a break from vibration exposure can be determined during this
study, there is the opportunity for these findings to be implemented into industries such as these, not simply within the automotive industry alone.

Furthermore, in order to test the validity of the SFM method, it is crucial to test this method against a range of conditions. If the method is to be deemed successful, it needs to possess the ability to predict overall discomfort in any scenario, as well as during a continuous long term drive as shown in Chapter 4 and Chapter 5. Therefore, implementing breaks in the trial will test the method’s ability to predict fluctuations in overall discomfort that may be observed after a break from the driving task. If the method can accurately determine differences between conditions this implies that the method will be more useful as this suggests the potential for the method to be used to compare different vibration exposures and different seat designs which is crucial for the automotive industry.

7.2 Aims and Objectives

The first aim of this study is therefore to evaluate the effectiveness of taking a break during a long term drive in order to further understand how temporal factors, dynamic factors and dynamic fatigue factors related to overall car seat discomfort can be influenced by breaks from the driving task. Furthermore this study aims to investigate the effect of break type to determine how driver behaviour during breaks from a long term drive may influence overall car seat discomfort.

The second aim of this study is to further validate the success of the SFM method by testing this method in a range of conditions. The design of this study will allow conclusions to be drawn as to how successful the method is at coping with breaks in the driving task and will aim to determine how SFMs are affected by breaks and any resulting fluctuations in subjective discomfort.

The objectives of this study are:

- To determine the effect of taking breaks during a long term drive on overall car seat discomfort.
- To compare different break types and determine how driver behaviour during breaks may influence overall car seat discomfort.
• To further investigate and validate the relationship between subjective overall car seat discomfort and driver seat fidgets and movements.
• To determine how driver seat fidgets and movements are influenced by taking a break from a long-term drive.

Therefore, the hypotheses for this study are:

\textbf{nH7.1}: Taking a break from a long term drive will not affect subjective discomfort during the break

\textbf{H7.1}: Taking a break from a long term drive will affect subjective discomfort during the break

\textbf{nH7.2}: Taking a break from a long term drive will not affect subjective discomfort at the end of the total drive time

\textbf{H7.2}: Taking a break from a long term drive will affect subjective discomfort at the end of the total drive time

\textbf{nH7.3}: Behaviour during a break from a long term drive will not affect the effectiveness of the break in reducing subjective discomfort, both immediately and at the end of the drive

\textbf{H7.3}: Behaviour during a break from a long term drive will affect the effectiveness of the break in reducing subjective discomfort, both immediately and at the end of the drive

\textbf{nH7.4}: SFM frequency will not increase with duration of driving

\textbf{H7.4}: SFM frequency will increase with duration of driving

\textbf{nH7.5}: SFM magnitude will not increase with duration of driving

\textbf{H7.5}: SFM magnitude will increase with duration of driving

\textbf{nH7.6}: No relationship will be observed between subjective discomfort and SFMs

\textbf{H7.6}: A relationship will be observed between subjective discomfort and SFMs
7.3 Methods

The study described in this chapter was conducted at Loughborough University, UK, and as with Chapter 4, utilises the methodologies for the UK laboratory studies as outlined in Section 3.3. The equipment and procedures used in this study that were common to all UK laboratory studies have been detailed previously and this section will outline the methodologies implemented specific to this study. Firstly the sample recruited to take part in the study will be defined followed by an outline of how the study aimed to satisfy the hypotheses for the study stated previously. The independent and dependant variables for the study will be defined including a description of the different break types to be implemented. The section will conclude with a detailed description of the experimental protocol undertaken during this study. The study was designed so that most of the equipment and driving task were identical to those implemented in the study reported in Chapter 4, with alterations in driving duration, driving rig and the addition of a break from driving.

7.3.1 Sample

The participants recruited for this study were sampled from the local, staff and student population of Loughborough University. All participants were subjected to the inclusion criteria outlined previously in Section 3.3.5 and all participants completed the various health screening, ethical clearance and consent forms. Participant characteristics are defined in Table 21.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>10</td>
</tr>
<tr>
<td>Gender</td>
<td>7 male; 3 female</td>
</tr>
<tr>
<td>Age</td>
<td>21 – 35 years (mean ± sd: 25.9 ± 4.8 years)</td>
</tr>
<tr>
<td>Stature</td>
<td>155 – 183 cm (mean ± sd: 176 ± 8.1 cm)</td>
</tr>
<tr>
<td>Mass</td>
<td>43 – 70.5 kg (mean ± sd: 71.8 ± 12.1 kg)</td>
</tr>
</tbody>
</table>
7.3.2 Independent Variables

7.3.2.1 Driving Task and Duration

All participants were required to drive continuously for two set durations on the driving simulator housed at Loughborough University detailed in Section 3.3.2 with a break from driving in between. These durations were both 60 minutes with a 10 minute break separating the two driving durations and all participants completed the same duration of driving. The total duration of the trial was therefore 130 minutes, with 120 minutes driving. Participants all completed the same task on the driving simulator as subjects were required to follow pre-determined routes that were commanded to the subject via the use of GPS navigation style instructions as described by Section 3.3.2.

Subjects completed the driving task required whilst seated on a driving rig that had been installed on the MAViS platform and all participants used the same driving rig. This rig was UK Rig B as described by Section 3.3.3 and all participants were allocated time prior to the start of the experiment to adjust the seat as to best replicate their normal driving position. In order to further test the validity of the SFM method, the vehicle seat and packaging dimensions were altered via the use of Rig B to ensure that the success of the SFM method was not a product of the seat and rig design used in Chapter 4 and therefore determine that the method can be used to measure the performance of any vehicle seat and packaging design.

7.3.2.2 Vibration Exposure

All participants were exposed to 6-axis vibration throughout the duration of driving on the simulator. Vibration exposure was simulated by the MAViS platform housed at Loughborough University with a mean total magnitude of $0.241m/s^2$ weighted r.m.s. System characterisation ensured that all participants were exposed to a vibration magnitude of within 10% of the desired exposure.

7.3.2.3 Break Design

After 60 minutes of driving on the simulator, participants were required to have a 10 minute break from the driving task as this was the approximate break duration defined in Chapter 6. As the aim of the study was not only to investigate the
effectiveness of breaks from driving on driver discomfort but also to investigate how behaviour and activity during breaks, or ‘break type’, can influence driver discomfort, a repeated measures design was implemented whereby participants were required to complete three trials. Each trial was designed to include a different break type and participants were assigned a random order in which to complete the trials.

Break types were intended to represent typical types of break that drivers may conduct during a long term drive and using the results of the observation study discussed in Chapter 6; break types were defined as:

1. Sit – where participants were required to stop the driving task, but remain seated in the car seat.
2. Walk – where participants were required to stop the driving task, leave the car seat and perform continuous walking on a treadmill maintained at 4km/h.
3. Walk & Sit – where participants were required to stop the driving task, leave the car seat and sit in a standard chair.

7.3.3 Dependant Variables

7.3.3.1 Subjective Discomfort Assessment

Throughout the duration of the study participants were required to provide subjective discomfort ratings via the use of 2 part discomfort questionnaire (Local and Overall discomfort) discussed previously in Section 3.3.6. Due to the addition of the break from driving, participants were required to provide more frequent ratings at the start of the drive, at the start of the break and upon returning to the driving task. Therefore, subjective discomfort ratings were reported at 0, 2, 10, 20, 30, 40, 50, 60, 62, 70, 72, 80, 90, 100, 120, and 130 minutes of the trial.

7.3.3.2 Objective Discomfort Assessment

Participants were also video recorded in order to conduct the analysis of subjects’ SFMs post trial. This was conducted in accordance to the methodology stated in Section 3.3.7.
7.3.4 Experimental Protocol

The design of the study was such that each participant completed 3 trials at the laboratory located at Loughborough University and each trial had a duration of approximately 140 minutes, including 10 minutes of paperwork. Upon arrival to the laboratory, the participants were asked to complete the health screening, MSSQ, ethical clearance and consent forms before recording the required anthropometric data (age, stature, mass).

Participants were then asked to embark the driving rig, adjust the seat as appropriate, apply the safety harness and perform 1 minute of driving on the driving simulator in order to familiarise themselves with the task. This was conducted with no exposure to vibration. Participants were then asked to assist the experimenter in conducting the necessary vibration exposure system characterisation by remaining seated in the car seat whilst exposed to vibration for a further minute. This was recorded using the Biometrics DataLOG MWX8 and accelerometer and the input to the MAViS platform was adjusted if necessary. Participants were then trained in the use of the subjective rating scales and details regarding the subjective data collection were explained. When confident the participants were ready to begin the trial they were asked if they had any questions before starting.

Each trial consisted of 60 minutes continuous driving on the driving simulator, a 10 minute break from driving in which participants completed one of the three break type conditions, followed by a further 60 minutes of continuous driving on the simulator. Whilst driving, participants were exposed to vibration with an average of 0.241m/s² weighted r.m.s.

During the 10 minute break from driving, participants were asked to complete one of three tasks. Therefore, each participant completed three trials on separate days and was assigned a random order to complete the trials. Condition 1 required participants to remain seated in the car seat, the driving task on the driving simulator and the vibration exposure were stopped and participants were instructed to remove the safety harness. Upon completing the 10 minute break
participants were instructed to start the driving task again and vibration exposure was restored. Condition 2 required participants to stop the driving task, vibration exposure was stopped and the MAViS platform was set to its neutral position. When it was safe to disembark the platform, participants were instructed to do so and were then asked to walk to the next room and embark a treadmill. This treadmill was a HP Cosmos Mercury 4.0 and once the participant was ready the speed was steadily increased until reaching 4km/h. This speed was determined as a normal walking speed (Whittle, 1991). 45 seconds before the end of the 10 minute break participants were instructed to return to the car seat, the MAViS platform was returned to its engaged position and upon completion of the 10 minute break participants were instructed to begin the driving task and vibration exposure was restored. Condition 3 required participants to stop the driving task, vibration exposure was stopped and the MAViS platform was set to its neutral position. When it was safe to disembark the platform, participants were instructed to do so and were then asked to walk to the next room and sit in a standard chair. 45 seconds before the end of the 10 minute break participants were instructed to return to the car seat, the MAViS platform was returned to its engaged position and upon completion of the 10 minute break participants were instructed to begin the driving task and vibration exposure was restored.

During the 130 minute trial participants were required to provide subjective discomfort ratings verbally at set time intervals via the use of the 2 part discomfort questionnaire. These time intervals were 0, 2, 10, 20, 30, 40, 50, 60, 62, 70, 72, 80, 90, 100, 110, 120 and 130 minutes. Participants were also video recorded throughout the trial.

Upon completion of the 130 minute trial, participants were asked for any qualitative feedback they may have and asked to wait until the MAViS system had depressurised before disembarking the platform and ending the trial.
7.4 Results

This results section will firstly consider the subjective discomfort data to address the original hypotheses. The results will describe the influence of breaks from driving on overall discomfort and then the influence on local discomfort. The results will include both the effect of breaks from driving on subjective discomfort during the break and the effect on subjective discomfort upon completing the trial.

Furthermore, this results section will consider the objective discomfort data in the form of SFMs and describe the relationship between the subjective and objective discomfort responses. This analysis will include the effect of breaks from driving on the SFM data collected during the study.

7.4.1 Subjective Overall Discomfort

The results show that mean overall discomfort (part two of the rating scale) increased with duration of driving for all 3 conditions, supporting the findings of the previous literature (Mansfield et al., 2014; Gyi & Porter, 1998), the previous studies in Chapter 4 and Chapter 5, and Mansfield et al.’s (2014) model of overall car seat discomfort. Figure 97 displays the mean overall discomfort ratings observed for all 3 conditions over time.

Data collected during each of the conditions follow a nominally identical trend between 0 – 60 minutes, as would be expected due to all 3 conditions following the same design up until this point (Figure 97). However, a much larger decrease is observed in the ‘Walk’ condition when compared to the ‘Walk & Sit’ condition at 62 minutes corresponding to the start of the break from the driving task. A larger decrease still is observed when compared to the ‘Sit’ condition at the same time interval. A further decrease in discomfort is observed in all conditions at 70 minutes, the end of the break.
Upon returning to the driving task, a steady increase in overall discomfort is observed in all 3 conditions with the ‘Sit’ condition recording the greatest mean overall discomfort rating after 130 minutes of 29.1, followed by the ‘Walk & Sit’ condition, 24.7, which showed a slight reduction in overall discomfort when compared to the ‘Sit’ condition and then the ‘Walk’ condition which recorded the lowest overall discomfort rating, 16.95, after completion of the 130 minute trial.

7.4.2 Subjective Local Discomfort

The results for local discomfort (part one of the rating scale) follow a similar trend to the results observed for overall discomfort and support the findings for part two of the rating scale. As shown in Figure 98, Figure 99 and Figure 100, the mean local discomfort ratings for all conditions follow a similar trend between 0 – 60 minutes, supporting the findings for overall discomfort.
Furthermore, the results for local discomfort also reflect the differences between conditions observed for overall discomfort, as the largest decrease in discomfort is observed in the ‘Walk’ condition during the break from the driving task, in comparison with a smaller decrease observed in the ‘Walk & Sit’ condition and the smallest decrease observed in the ‘Sit’ condition. Additionally, the mean local discomfort ratings after 130 minutes follow a similar trend to those observed for overall discomfort with the ‘Sit’ condition recording the greatest mean local discomfort rating, followed by the ‘Walk & Sit’ condition and the ‘Walk’ condition recording the lowest mean local discomfort rating upon completion of the trial.

Figure 98: Mean local discomfort ratings over time for the ‘Sit’ condition
**Figure 99:** Mean local discomfort ratings over time for the 'Walk' condition

**Figure 100:** Mean local discomfort ratings over time for the 'Walk & Sit' condition
7.4.3 Objective Seat Fidgets and Movements

In addition to the subjective discomfort ratings collected, participants’ SFM data was collected in order to provide a comparison between subjective and objective data and determine whether a relationship is observed.

The results can be seen in Figure 101, Figure 102 and Figure 103 and show that the mean data recorded for participants’ seat fidgets and movements also follows a very similar trend to those recorded for mean overall discomfort. The results display that a close relationship can be observed between the subjective overall discomfort ratings collected and SFM frequency for each condition with the results demonstrating similar differences between conditions as observed in the results for overall discomfort.

The results for participants’ SFMs show that each condition records very similar results for SFM frequency until 60 minutes, supporting the findings of the subjective rating scales. No data was recorded during the break from driving due to the design of the study but a clear decrease in SFM frequency, or the number of SFMs, is observed when comparing the results for 50-60 minutes and those for 70-80 minutes in the ‘Walk’ condition. A smaller decrease is observed when comparing the same time intervals for the ‘Walk & Sit’ condition, however an increase is observed in the ‘Sit’ condition. These results also support the findings of part one and two of the subjective discomfort questionnaire. Furthermore, when comparing the number of SFMs recorded between 120-130 minutes for each condition, the greatest number of SFMs were recorded in the ‘Sit’ condition, 6.9, followed by the ‘Walk & Sit’ condition, 5.6, with the fewest SFMs recorded in the ‘Walk’ condition, 5.1, again supporting the findings of the subjective discomfort rating scales.

When comparing the mean overall discomfort ratings recorded against the number of SFMs per 10 minutes, a clear positive relationship is observed in all 3 conditions (Figure 104, Figure 105, Figure 106). This suggests that as overall discomfort increases, the number of SFMs per 10 minutes, or SFM frequency, also increases. This supports the findings of the previous studies in Chapter 4 and Chapter 5 and it
can be determined that a positive relationship exists between overall discomfort and SFM frequency.

**Figure 101:** Mean overall discomfort ratings and number of SFMs over time for the 'Sit' condition

**Figure 102:** Mean overall discomfort ratings and number of SFMs over time for the 'Walk' condition
Figure 103: Mean overall discomfort ratings and number of SFMs over time for the 'Walk & Sit' condition

Figure 104: Scatter graph displaying the mean number of SFMs against the mean overall discomfort ratings for the 'Sit' condition
Figure 105: Scatter graph displaying the mean number of SFMs against the mean overall discomfort ratings for the 'Walk' condition

Figure 106: Scatter graph displaying the mean number of SFMs against the mean overall discomfort ratings for the 'Walk & Sit' condition
7.5 Discussion

This section will firstly discuss the subjective discomfort ratings recorded in this study to address the hypotheses H7.1, H7.2 and H7.3. This section will then discuss the objective SFM data recorded in order to satisfy H7.4, H7.5 and comparisons will be made with the subjective data to satisfy H7.6.

7.5.1 Subjective Overall Discomfort

During the first hour of exposure the participants’ responses to the three conditions were identical, as was expected, as each condition had the same vibration stimulus and the same task (Mansfield, 2005). During this epoch, there was no significant difference in the results as each condition followed a similar trend (Figure 97; Table 22), supporting the findings of the previous literature (Mansfield et al., 2014) and also following a similar trend to the data recorded in Chapter 4.

After 60 minutes, the mean overall discomfort reached a level corresponding to ‘Little Discomfort’ for all three conditions as shown in Table 22. This displays that no difference was found between conditions but also shows that the data collected during this study follows a similar trend to the data collected in Chapter 4, as the mean overall discomfort rating after 60 minutes recorded during the experiment in Chapter 4 was shown to be 16.35 and also corresponded to ‘Little Discomfort’. This is as expected due to the design of both experiments consisting of the same task and vibration stimulus but implies that there is a high level of reliability with this subjective method of discomfort assessment as the discomfort ratings recorded follow a similar trend when repeated. Any differences in overall discomfort between the two studies can therefore be attributed to the differences in seat design and packaging dimensions. This suggests that the overall discomfort rating scale developed may be a useful method for subjective assessment and may have implications on the ISO 2631-1 (1997) standard as major benefits have been highlighted with this approach in comparison with the currently proposed 6 point rating scale.

This is supported further when examining the gradients for the data collected in this experiment compared with the gradient of the data recorded in Chapter 4.
Regression showed that the gradient for the data recorded in Chapter 4 was 0.27; for the data recorded in this experiment, regression showed that the gradients were defined as 0.26 for the ‘Sit’ condition, 0.24 for the ‘Walk’ condition and 0.22 for the ‘Walk & Sit’ condition (Figure 109). This validates the findings of both studies further as no significant difference in discomfort is observed at 60 minutes across all conditions and both experiments and no difference is observed between gradients from 0 – 60 minutes. Differences between the conditions occurred from the start of the break from the driving task until the end of the trial.

7.5.1.1 Breaks from the Driving Task

During the break from the driving task, there was an acute decrease in the discomfort ratings for all three conditions which was immediately measurable (ie. at the 62 minute interval) and this decrease in discomfort continued throughout the following 8 minutes. Although the decrease in discomfort was observed in all three conditions, the effectiveness of the break from driving, or the amount of discomfort reduction, was dominated by the required activity during the break.

A much larger decrease in discomfort was observed after 2 minutes of the break in the ‘Walk’ condition. A mean decrease of 2.00 was observed in the ‘Sit’ condition, in comparison with a larger decrease of 6.68 in the ‘Walk & Sit’ condition and an again larger decrease of 9.7 in the ‘Walk’ condition. This suggests that after just 2 minutes of walking, drivers have already benefitted more, in terms of overall discomfort, than if they had sat in another chair for the duration of the break or remained seated in the vehicle for the duration of the 10 minute break. Furthermore, although not as beneficial as walking; leaving the vehicle seat and sitting in another chair is more beneficial in terms of overall discomfort reduction than remaining seated in the vehicle. This is simply supported by the discomfort descriptors displayed in Table 22 as after 2 minutes of the break from driving, the ‘Sit’ condition recorded a mean overall discomfort rating that corresponds to ‘Little Discomfort’, the ‘Walk & Sit’ condition recorded a mean overall discomfort rating that corresponds to ‘Very Little Discomfort’ and the ‘Walk’ condition recorded a mean overall discomfort rating that corresponds to ‘Just Noticeable Discomfort’.
Table 22: Overall discomfort rating and discomfort descriptor at each interval for all 3 conditions

<table>
<thead>
<tr>
<th>Time (m)</th>
<th>Discomfort Rating</th>
<th>Descriptor</th>
<th>Discomfort Rating</th>
<th>Descriptor</th>
<th>Discomfort Rating</th>
<th>Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No Discomfort at all</td>
<td>0</td>
<td>No Discomfort at all</td>
<td>0</td>
<td>No Discomfort at all</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>No Discomfort at all</td>
<td>0.1</td>
<td>No Discomfort at all</td>
<td>0.55</td>
<td>No Discomfort at all</td>
</tr>
<tr>
<td>10</td>
<td>2.05</td>
<td>Just Noticeable Discomfort</td>
<td>1.75</td>
<td>Just Noticeable Discomfort</td>
<td>1.8</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>20</td>
<td>4.25</td>
<td>Very Little Discomfort</td>
<td>4.7</td>
<td>Very Little Discomfort</td>
<td>4.05</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>30</td>
<td>6.75</td>
<td>Very Little Discomfort</td>
<td>6.15</td>
<td>Very Little Discomfort</td>
<td>6.1</td>
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</tr>
<tr>
<td>40</td>
<td>9</td>
<td>Very Little Discomfort</td>
<td>9.45</td>
<td>Very Little Discomfort</td>
<td>8.45</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>50</td>
<td>12.85</td>
<td>Little Discomfort</td>
<td>11.75</td>
<td>Little Discomfort</td>
<td>11.35</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>60</td>
<td>15.5</td>
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<td>14.15</td>
<td>Little Discomfort</td>
<td>13.43</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>62</td>
<td>13.5</td>
<td>Little Discomfort</td>
<td>4.45</td>
<td>Just Noticeable Discomfort</td>
<td>6.75</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>70</td>
<td>10.7</td>
<td>Little Discomfort</td>
<td>1.45</td>
<td>Just Noticeable Discomfort</td>
<td>5.9</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>72</td>
<td>11.3</td>
<td>Little Discomfort</td>
<td>1.9</td>
<td>Just Noticeable Discomfort</td>
<td>6.05</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>80</td>
<td>14.7</td>
<td>Little Discomfort</td>
<td>4.1</td>
<td>Just Noticeable Discomfort</td>
<td>10.2</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>90</td>
<td>18.6</td>
<td>Moderate Discomfort</td>
<td>6.45</td>
<td>Very Little Discomfort</td>
<td>12.95</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>100</td>
<td>21</td>
<td>Moderate Discomfort</td>
<td>10.4</td>
<td>Very Little Discomfort</td>
<td>16.53</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>110</td>
<td>25.1</td>
<td>Moderate Discomfort</td>
<td>12.9</td>
<td>Little Discomfort</td>
<td>18.75</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>120</td>
<td>26.25</td>
<td>Moderate Discomfort</td>
<td>15.65</td>
<td>Little Discomfort</td>
<td>20.75</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>130</td>
<td>29.1</td>
<td>Moderate-High Discomfort</td>
<td>16.95</td>
<td>Little Discomfort</td>
<td>24.7</td>
<td>Moderate Discomfort</td>
</tr>
</tbody>
</table>

233
A further similar decrease in discomfort is observed in all three conditions by the end of the break from the driving task and participants recorded a mean overall discomfort rating of 1.45 at the end of the break for the ‘Walk’ condition; less than the discomfort recorded after 10 minutes of driving. This suggests that on average, drivers will have almost returned to the discomfort rating at which they began the drive after a break of walking for 10 minutes. It can be considered that the discomfort is ‘reset’ with 10 minutes of walking.

The decrease in overall discomfort is less in the ‘Walk & Sit’ condition as participants’ discomfort decreased to an average of 5.9, similar to the average overall discomfort rating recorded after about 30 minutes of driving. It can be considered that discomfort is improved but not ‘reset’ with 10 minutes of taking break from driving, leaving the seat but remaining seated in another seat. The decrease in overall discomfort is less still in the ‘Sit’ condition as participants’ discomfort rating decreased to an average of 10.7, similar to the average overall discomfort rating recorded after about 45 minutes of driving. Again, it can be considered that discomfort is slightly reduced but not ‘reset’ with 10 minutes of taking a break from driving but not leaving the vehicle seat.

In order to compare the three conditions and gain a greater understanding of the impact of behaviour and activity during breaks, repeated measures ANOVA’s were conducted that compared the overall discomfort ratings recorded at 62 and 70 minutes to establish whether a significant difference can be observed (\( \alpha = 0.05 \)).

At 62 minutes a repeated measures ANOVA with a greenhouse-geisser correction determined that mean discomfort ratings differed statistically significantly between conditions (\( F(1.581, 14.231) = 24.740, P < 0.05 \)). Post hoc tests using the Bonferroni correction revealed that participants benefitted more in terms of discomfort decrease by leaving the vehicle seat as the reduction in discomfort was shown to be statistically significant when comparing the ‘Sit’ condition with the ‘Walk’ and ‘Walk & Sit’ conditions (\( p = 0.001 \) and \( p = 0.000 \) respectively). However, when comparing the ‘Walk’ condition and the ‘Walk & Sit’ condition at 62 minutes, no statistically significant difference was found (\( p = 0.438 \)) implying that participants did not
benefit significantly in terms of discomfort decrease by walking for 2 minutes in comparison with sitting in another seat. Therefore it is concluded that at 62 minutes, or after 2 minutes of a break from driving, drivers will experience a significant reduction in discomfort by leaving the vehicle in comparison to remaining seated in the vehicle seat. However, the behaviour or activity undertaken after leaving the vehicle shows no significant importance. This is described by the graph displayed in Figure 107.

At 70 minutes another repeated measures ANOVA with a greenhouse-geisser correction determined that mean discomfort ratings differed statistically significantly between conditions \(F(1.393,12.535) = 22.729, P < 0.05\). Post hoc tests using the Bonferroni correction revealed that participants benefitted more in terms of discomfort decrease by leaving the vehicle seat as the reduction in discomfort was shown to be statistically significant when comparing the ‘Sit’ condition with the ‘Walk’ and ‘Walk & Sit’ conditions \(p = 0.001\) for both comparisons). Furthermore, when comparing the ‘Walk’ condition and the ‘Walk & Sit’ condition at 70 minutes, at statistical difference was found \(p = 0.033\) implying that participants benefitted significantly in terms of discomfort decrease by walking for 10 minutes in comparison with sitting in another seat. Therefore it can be concluded that at 70 minutes, or after 10 minutes of a break from driving, drivers will experience a significant reduction in discomfort by leaving the vehicle in comparison to remaining seated in the vehicle seat. Furthermore, the behaviour or activity undertaken after leaving the vehicle also has a significant effect on discomfort decrease as drivers who walk for 10 minutes will experience a significantly greater benefit in comparison with drivers who leave the vehicle but sit in another seat. This is described by the graph in Figure 108.
**Figure 107:** Estimated marginal means of overall discomfort for each break type at 62 minutes (1 = ‘Sit’ Condition, 2 = ‘Walk’ Condition, 3 = ‘Walk & Sit’ Condition)

**Figure 108:** Estimated marginal means of overall discomfort for each break type at 70 minutes (1 = ‘Sit’ Condition, 2 = ‘Walk’ Condition, 3 = ‘Walk & Sit’ Condition)
The reduction in overall discomfort observed during the ‘Walk’ condition holds some similarities to the effects observed in Yonekawa et al. (1998) where TTS was ‘reset’ after 10 minutes rest from vibration exposure and also Ravnik et al. (2008) where driver discomfort was reduced to nearly zero after a 15 minute break after 100 minutes of driving. During this experiment it was observed that overall discomfort was ‘reset’ following 10 minutes of walking during a rest from vibration exposure. This may have some implications on ISO 2631-1 (1997) where the benefits of breaks from whole body vibration exposure are not defined. The similarities observed between this study and Yonekawa et al. (1998) suggest that allocating 10 minutes rest from vibration exposure is crucial in fully reducing the negative effects of prolonged vibration exposure.

7.5.1.2 Comparing the Rate of Discomfort Onset upon Returning to the Driving Task

When returning to the driving task, discomfort again increased with duration of driving for all three conditions, with similar trends to those recorded for the first 60 minutes of the trial. A steady increase is observed in all three conditions between 70 – 130 minutes. As discussed previously, regression (lines shown in Figure 109) showed that for the first 60 minutes the gradient was 0.26 for the ‘Sit’ condition, 0.24 for the ‘Walk’ condition and 0.22 for the ‘Walk & Sit’ condition. This describes a similar rate of change in discomfort for all of the conditions, as expected due to each of the conditions containing the same task and vibration exposure for the first 60 minutes of driving.

During the second hour of driving, the gradient for the ‘Walk’ condition was 0.27, and therefore the rate of change in discomfort remained at a similar level to that of the first hour of driving. However, the gradient for the ‘Sit’ condition and the ‘Walk & Sit’ condition increased to 0.30 for both conditions between 70 – 130 minutes. This shows that there was a more rapid change in discomfort for the second hour of driving for the ‘Sit’ and the ‘Walk & Sit’ condition, despite the fact that discomfort started at higher rating at the end of the break.
This suggests that in addition to the greater reduction in discomfort during the break from driving, a 10 minute walk during a break from driving allows drivers to not only reduce discomfort but better cope with the rate of change in discomfort upon returning to the driving task.

### 7.5.1.3 Differences Observed Between Conditions upon Completion of the Trial

It is clear from the results that participants recorded significantly lower overall discomfort ratings in the ‘Walk’ condition after the break from driving and the benefits of this are observed upon completing the 130 minute trial. On average, at 130 minutes participants recorded an overall discomfort rating of 16.95 in the ‘Walk’ condition in comparison with a mean overall discomfort rating of 24.7 in the ‘Walk & Sit’ condition and 29.1 in the ‘Sit’ condition. When correlated with the verbal descriptors, these discomfort ratings correspond to ‘Little Discomfort’ for the ‘Walk’ condition, ‘Moderate Discomfort’ for the ‘Walk & Sit’ condition and ‘Moderate-High Discomfort’ in the ‘Sit’ condition, again highlighting the differences between the conditions and supporting the conclusion that participants recorded less overall discomfort in the ‘Walk’ condition upon completing the trial.

![Figure 109: Mean overall discomfort ratings for each condition with regression analysis](image)
In order to further compare the three conditions and establish whether a significant
difference was observed upon completion of the trial, a repeated measures ANOVA
with a greenhouse-geisser correction was conducted that compared the overall
discomfort ratings recorded at 130 minutes for each of the conditions and
determined that mean discomfort ratings differed statistically significantly between
conditions (F(1.1.432, 12.885) = 31.483, P < 0.05). Post hoc tests using the
Bonferroni correction revealed that participants recorded significantly lower overall
discomfort ratings upon completing the trial in the conditions where they were
required to leave the vehicle seat in comparison with remaining seated in the
vehicle seat as a significant difference was observed when comparing the ‘Sit’
condition with the ‘Walk & Sit’ condition (p = 0.014) and the ‘Walk’ condition (p =
0.000). This suggests that participants’ overall discomfort rating at the end of the
130 minute drive was significantly reduced due to the participant leaving the vehicle
seat during the break from driving. Furthermore, a significant difference was also
observed when comparing the ‘Walk & Sit’ condition and the ‘Walk’ condition (p =
0.001). This suggests that participants benefitted, in terms of discomfort reduction,
significantly from walking for 10 minutes during the break from driving in
comparison with sitting in another seat, even after completing a further 60 minutes
of driving.

This suggests that when taking a break from a long term drive, drivers’ comfort will
benefit greater from leaving the vehicle than remaining seated in the vehicle seat.
Furthermore, upon leaving the vehicle, drivers will benefit greater from taking a 10
minute walk than leaving the vehicle and sitting in another seat. As discussed
previously, people move unconsciously whilst seated with the purpose of relieving
pressure on compressed body parts with impeded blood flow (Hermann & Bubb,
2007) and the results of this study support this theory as walking for 10 minutes will
increase blood circulation to body parts compressed by extended duration sitting in
a driving posture.

This may have significant implications for drivers planning to undertake a long
duration drive as drivers concerned with minimising discomfort should aim to plan
breaks at regular intervals during a long term drive in order to reduce discomfort.
during and at the end of the journey. Drivers should aim to adapt their behaviour during breaks in order to gain the full benefit in terms of discomfort reduction, with a planned 10 minute walk providing the most positive effect, according to the findings of this study. As stated previously, the guidelines for drivers undertaking a long term drive suggest that a break of 15 minutes should be implemented every 2 hours (Department for Transport, UK); however these guidelines are focused on safety rather than comfort (Horne & Reyner, 1999). It may be of benefit for the findings to be incorporated into any future guidelines as there is the possibility that the benefits in terms of comfort improvement may encourage drivers to adhere to the guidelines and the importance of activity or behaviour during breaks should be well defined.

There may be wider implications for these findings, outside of non-commercial driving. Drivers who drive for extended durations as part of their job may find that taking effective breaks from driving may have added positive effects. The negative health effects associated with long term driving have been well documented. It has been established that drivers who drove extended durations and distances as part of their job ‘always’ or ‘often’ experienced lower back discomfort during driving (Gyi & Porter, 1998) and furthermore, commuters who travelled distances of over 25,000 kilometres per year missed on average, 24.4 days of work per year due to prolonged driving (Porter & Gyi, 2002). If implementing breaks during long duration driving can aid in reducing the discomfort experienced then this may have a positive impact on employee attendance and well-being.

Furthermore, drivers working in industries where they are exposed to much greater magnitudes of vibration, when compared with normal road driving, as part of their job may benefit substantially from breaks from driving and vibration exposure. Vibration magnitude has been shown to increase the rate of change in discomfort (Mansfield et al., 2014, Mansfield et al., 2015) and drivers working with heavy machinery may be placed at a lesser risk of developing negative symptoms associated with long term exposure to vibration if breaks with effective behaviour can be implemented into their work schedule. As mentioned previously, this supports the findings of a study by Yonekawa et al. (1998) where the benefits of a
10 minute break from vibration exposure were successfully determined. As similar findings have been established in this study, drivers working in environments with high vibration exposure should be made aware of the benefits breaks from driving may have on discomfort and subsequently health.

7.5.2 Seat Fidgets and Movements

As the main objective of this research was to determine the success of the objective measure of driver discomfort, it is crucial to evaluate the findings of the SFM method and how this is affected by the implementation of breaks from driving. If the method is to be deemed successful it is important that the method can distinguish the fluctuations in discomfort observed due to the different break types. Furthermore, as the findings of Chapter 4 and Chapter 5 demonstrated a strong positive correlation between subjective overall discomfort ratings and SFM frequency it is essential that this relationship be investigated further. Therefore this section will firstly discuss SFM frequency for all 3 conditions, then SFM magnitude (SFM type) to address H7.4 and H7.5, and finally draw conclusions on the relationship between SFMs and subjective overall discomfort to address H7.6.

7.5.2.1 SFM Frequency

Chapter 4 and Chapter 5 established that SFM frequency is shown to increase with duration of driving as the number of movements recorded by participants per minute increases with time spent driving. The results of this study again support this finding as SFM frequency is shown to increase across the duration of driving in all 3 conditions and further support the studies by Bendix et al. (1985), Jensen & Bendix (1992), Fenety et al. (2000) and Adler (2007).

Firstly, SFM frequency during the first 60 minutes of each trial must be discussed. It is clear from the results that SFM frequency increases between 0 – 60 minutes for each of the conditions. The mean number of SFMs per 10 minutes increased from 0.4 between 0 – 10 minutes to 2.2 between 50 – 60 minutes for the ‘Sit’ condition. The mean number of SFMs per 10 minutes increased from 0.5 between 0 – 10 minutes to 2.7 between 50 – 60 minutes for the ‘Walk’ condition and increased
from 0.9 between 0 – 10 minutes to 2.6 between 50 – 60 minutes for the ‘Walk & Sit’ condition.

T-tests were conducted to compare the number of SFMs at these time intervals and the findings represent a significant increase for each of the conditions (p < 0.05, two-tailed) suggesting that during this study, SFM frequency is shown to increase with duration of driving for the first 60 minutes of the trial. As each of the conditions exposed subjects to the same task and vibration exposure for the first 60 minutes it is expected that similarities would be observed between the conditions for the first hour of driving and SFM frequency is shown to increase at a similar rate for each of the conditions (Figure 110).

It is important to note, that when analysing individual subject data for SFM frequency, each participant recorded an increase in the number of SFMs recorded between 50 – 60 minutes when compared with the number of SFMs recorded between 0 – 10 minutes for each of the conditions. This validates the findings as SFM frequency is shown to increase for the whole population and not simply on average.

![Graph showing SFM frequency across different time intervals](image)

*Figure 110: Total number of SFMs at each time interval between 0 – 60 minutes for all conditions*
Upon returning to the driving task after the 10 minute break from driving, SFM frequency is again shown to increase with duration of driving, however larger differences are observed between the conditions. This is to be expected due to the differences in break type and differences in reported subjective discomfort, but when focusing on SFM frequency, each condition shows an increase between 70 – 130 minutes.

The mean number of SFMs per 10 minutes increased from 2.6 between 70 – 80 minutes to 6.9 between 120 – 130 minutes for the ‘Sit’ condition. The mean number of SFMs per 10 minutes increased from 0.8 between 70 – 80 minutes to 5.1 between 120 – 130 minutes for the ‘Walk’ condition and increased from 2.2 between 70 – 80 minutes to 5.6 between 120 – 130 minutes for the ‘Walk & Sit’ condition. T-tests were conducted to compare the number of SFMs at these time intervals and the findings represent a significant increase with time spent driving for each of the conditions (p < 0.05, two-tailed) and SFM frequency increased at a similar rate in each condition despite the differences observed between 70 – 80 minutes (Figure 111).

When analysing the individual subject data for SFM frequency, all participants again recorded an increase in SFM frequency across this time interval. Each participant recorded a greater number of SFMs during the last 10 minutes of each trial when compared with the number of SFMs recorded between 70 – 80 minutes, for each condition.
Figure 111: Total number of SFMs at each time interval between 70 - 130 minutes for all conditions

This increase in SFM frequency with driving duration supports the findings of Chapter 4 and Chapter 5 and validates the conceptual model proposed in Chapter 4 (Figure 70). These findings support the concept proposed by the model regarding the cognitive and physical process that may be the cause of driver seat fidgets and movements and the observed increase in SFM frequency. The model was based on a theoretical model (Figure 20) by Fujimaki & Noro (2005) and the findings regarding SFM frequency found in this study further validate both models and suggest that the development of these models may be useful in accurately describing the cause of SFMs.

7.5.2.2 SFM Magnitude

The 5th research hypothesis for this study (H7.5) was that SFM magnitude would increase with duration of driving. As discussed in Chapter 4 and Chapter 5, despite some of the findings in the literature suggesting that movement magnitude increases with duration of driving, no such finding has been established during this research (Figure 112, Figure 113 & Figure 114).

As with Chapter 4 and Chapter 5, no correlation was observed between SFM magnitude and time as the percentage of Type 2 and Type 3 SFMs did not increase
significantly with time. Two-way ANOVAs ($\alpha = 0.05$) were conducted that compared the percentage of each SFM type at each interval for each condition. No significant difference was found between the percentage of Type 2 or Type 3 SFMs at the beginning of the trial and at the end in any of the conditions. Therefore, the conclusion can be drawn that as SFM type is again not shown to change with driving duration, SFM magnitude does not increase with duration of driving. This finding will need to be addressed in further detail as no pattern in SFM types is observed in any of the conditions in this experiment. This implies that driving duration has no influence on the types of movements made by drivers and suggests that all movement types are equally important for drivers when coping with discomfort. There may be issues with the design of the method in evaluating SFM magnitude and further research is required to gain a better understanding of the relationship between SFM magnitude and driving duration.

![Figure 112](image-url): Changes in SFM type percentage over time for the ‘Sit’ condition

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Figure 113: Changes in SFM type percentage over time for the ‘Walk’ condition

Figure 114: Changes in SFM type percentage over time for the ‘Walk & Sit’ condition
7.5.3 Relationship between Subjective Overall Discomfort Ratings and SFMs

It has been established that during this study both subjective overall discomfort and SFM frequency increased with duration of driving. This supports the findings of the previous chapters detailed in this research; however the most important objective of this research was to determine the success of the objective measure of discomfort in predicting overall discomfort. Therefore, it is vital to determine the relationship observed in this study and in order to satisfy H7.6, the relationship between subjective overall discomfort and SFM frequency will be evaluated.

If a measure of SFMs is to be implemented into the automotive industry it is crucial that a similar relationship is observed during this study when compared to the relationship observed in previous chapters. Furthermore, if the method is to be used to evaluate different conditions, such as varying seat designs or vibration stimuli then it is important to understand how the method copes with fluctuations in subjective overall discomfort as observed due to the breaks from driving and discussed previously. This section will assess the relationship between subjective overall discomfort and SFM frequency for each condition and determine the success of the SFM method in predicting overall discomfort.

7.5.3.1 Observed Data

Regression analysis and Pearson Correlations were performed on the data recorded for each condition that compared the mean overall discomfort ratings at each time interval and mean SFM frequency, the mean number of SFMs per 10 minutes, throughout the duration of the trials. A large positive correlation was observed for each of the conditions. For the ‘Sit’ condition a correlation was found with an $r$ value of 0.945, 89.3% shared variance and was statistically significant ($r = 0.945$, $n = 12$, $p < 0.05$). For the ‘Walk’ condition a correlation was found with an $r$ value of 0.933, 87% shared variance and was statistically significant ($r = 0.933$, $n = 12$, $p < 0.05$). Finally, for the ‘Walk & Sit’ condition a correlation was found with an $r$ value of 0.98, 96% shared variance and was statistically significant ($r = 0.98$, $n = 12$, $p < 0.05$).
When comparing these results to those recorded in Chapter 4 and Chapter 5, similarities are observed in terms of correlation strength ($r^2$ value):

- Chapter 4: $r^2 = 0.927$
- Chapter 5: $r^2 = 0.968$
- Sit condition: $r^2 = 0.893$
- Walk condition: $r^2 = 0.87$
- Walk & Sit condition: $r^2 = 0.96$

The results determine that the strongest correlation was observed in the 'Walk & Sit' condition during this study, however all 3 conditions recorded a strong correlation between subjective overall discomfort and SFM frequency and the correlation strength was shown to be similar to that of Chapter 4 and Chapter 5. This suggests that the SFM method has been successful in representing the overall discomfort ratings for each condition, building upon the findings of the previous chapters.

7.5.3.1.1 Relationship during the First 60 Minutes of Driving

All 3 conditions were nominally identical for the first hour of driving and also followed much the same design as Chapter 4, except for the vehicle seat and packaging dimensions. In order to explore the relationship further, the results for all 3 conditions between 0 – 60 minutes can be averaged (Figure 115).

A Pearson Correlation determined that when comparing mean overall discomfort ratings with the mean total number of SFMs per 10 minutes for all conditions, a strong positive correlation is again observed with an r value of 0.96, 92.2% shared variance and was statistically significant ($r = 0.96$, $n = 18$, $p < 0.05$). This describes a very similar relationship to that observed in Chapter 4 as would be expected due to the laboratory, task and vibration exposure implemented in both experiments being more or less identical. This also suggests that any differences observed may be attributed to the slight differences between the vehicle seat designs and packaging dimensions.
Figure 115: Mean overall discomfort ratings and number of SFMs over time for all conditions between 0 - 60 minutes

A comparison between the first 60 minutes of this study and the study in Chapter 4 provides a measure of the methods repeatability as, if the method is to be successful, it would be expected that both experiments produced similar results. Therefore, using the mean data recorded for each of the 3 conditions, a comparison of both the subjective overall discomfort ratings and the total number of SFMs per 10 minutes has been made with the results in Chapter 4 (Figure 116).

It is clear that there are strong similarities between the two studies and suggests that the method is highly repeatable. The increase in mean overall discomfort ratings and the mean number of SFMs per 10 minutes is shown to be almost identical for both studies. A strong correlation is observed for Chapter 4 and each of the conditions in this study and no significant difference is observed after 4 repetitions of the same experiment.
Figure 116: Comparison between mean overall discomfort ratings and mean total number of SFMs between 0 - 60 minutes for each condition in this study and the results for Chapter 4

This suggests that the method is repeatable and reliable and reinforces the notion that there is the potential for the method focusing solely on SFM data to be implemented across the field of automotive research. The slight differences in results may be attributed to the differences between the vehicle seat and packaging dimensions used in both experiments; however the fact that no significant difference is observed suggests that there are no perceivable differences between the two seats and packaging designs when tested over this duration.

7.5.3.1.2 Relationship upon Returning to the Driving Task

Due to the design of the method, no data was collected for SFMs during the break from driving. Therefore no correlation can be made between subjective overall discomfort and SFM frequency during the break, however it is important to analyse the relationship observed upon returning to the driving task for the final 60 minutes of driving as this will provide some indication of how well the SFM method coped with fluctuations in discomfort due to the break from driving and whether the SFM method is able to accurately determine these differences.
The differences observed between conditions in overall discomfort ratings recorded after the break from driving are reflected by the number of SFMs recorded. This is shown by the number of SFMs recorded in the first 10 minutes after the break from driving. As discussed previously, a clear decrease in SFM frequency, or the number of SFMs, is observed when comparing the results for 50-60 minutes and those for 70-80 minutes in the ‘Walk’ condition. A smaller decrease is observed when comparing the same time intervals for the ‘Walk & Sit’ condition, however an increase is observed in the ‘Sit’ condition. This reflects the differences in overall discomfort ratings and a steady increase in SFM frequency is observed during the following 50 minutes of driving, again supporting the overall discomfort ratings. Therefore in order to determine the relationship, regression analysis and Pearson Correlations were again performed on the data for each of the conditions between 70 – 130 minutes.

The results determined that a strong positive correlation was again observed for each of the conditions, although the strength of the correlation is slightly less of that observed between 0 – 60 minutes. For the ‘Sit’ condition a correlation was observed with an r value of 0.91, 83.2% shared variance and was statistically significant (r = 0.91, n = 6, p < 0.05). For the ‘Walk’ condition, a correlation was observed with an r value of 0.88, 77.7% shared variance and was statistically significant (r = 0.88, n = 6, p < 0.05) and for the ‘Walk & Sit’ condition the strongest correlation was observed with an r value of 0.97, 94.3 shared variance and was statistically significant (r = 0.97, n = 6, p < 0.05).

This implies that there is a strong positive relationship between overall discomfort ratings and SFM frequency despite the differences between conditions and suggests that the SFM method has been successful in accurately describing differences between conditions. Although the correlations observed after the break from driving are not as strong as those observed before the break, this may be due to the larger variation in both individual subjective discomfort responses and individual SFM data recorded after the break and nevertheless, the relationship observed is still of significance. This finding further validates the success of the SFM method and implies that the method can be implemented to distinguish between different
driving conditions and may be extremely useful in future experiments when comparing multiple conditions. As the results have shown the method is able to cope with fluctuations in overall discomfort between conditions it is clear that SFM frequency is closely related to ratings of overall discomfort. Therefore the increase in SFM frequency can be attributed directly to perceptions of overall discomfort as the results of this study have shown that SFM frequency is not only a product of driving time and vibration exposure.

7.5.3.1.3 Predicting Overall Discomfort

As the overall aim of this research was to develop an objective measure that can be implemented into the automotive industry with the purpose of replacing subjective assessment, it is important to evaluate the success of the method in predicting overall discomfort ratings. As a close relationship has been observed between SFM frequency and overall discomfort ratings, regression analysis again produced an equation to predict overall discomfort. This regression analysis was conducted using the average data for all 3 conditions between 0 – 60 minutes, as this was the part of the trial that all 3 conditions were identical, and compared the mean overall discomfort ratings with the mean number of SFMs per 10 minutes (Figure 115) to produce the equation:

\[
\Psi = -1.1676 + 58.767sfm (7.1)
\]

Where: \( \Psi \) is the rating of overall discomfort and sfm is the number of SFMs per minute.

This equation (Equation 7.1) was then used to produce predicted values of overall discomfort using only SFM data and was applied to each of the conditions individually to determine whether the equation produced by the average data between 0 – 60 minutes was successful in predicting values when fitted for individual conditions (Figure 117, Figure 118 & Figure 119).
Figure 117: Observed vs Predicted overall discomfort using regression equation for the 'Sit' condition

Figure 118: Observed vs Predicted overall discomfort using regression equation for the 'Walk' condition
Figure 119: Observed vs Predicted overall discomfort using regression equation for the 'Walk & Sit' condition

As shown in Figure 117, Figure 118 and Figure 119, the predicted values of discomfort follow a close relationship with the observed values up until 60 minutes. This shows promise for using the regression equation (Equation 7.1) to predict values of discomfort; however this is expected due to the equation being a product of the average data for all 3 conditions in the first 60 minutes so a close relationship is probable. A more rigorous test is to evaluate the ability of the equation to predict values of discomfort after 60 minutes.

As no SFM data was recorded during the break from driving, 60 – 70 minutes, it is expected that the predicted values of discomfort be 0 for this time period. However, it is possible to determine the relationship after 70 minutes. Some similarities between the predicted and observed values can be seen between 70 – 130 minutes however, a less strong relationship is shown when compared to the first 60 minutes. This is due to the differences between conditions and that the equation has been produced using only mean data for all 3 conditions between 0 – 60 minutes. Therefore, it can be determined that although promising, the regression equation (Equation 7.1) is less effective in predicting discomfort ratings after the break from driving when developed in this way.
Nevertheless, one promising result is that differences between the conditions can still be observed when analysing the predicted values of discomfort. The differences between conditions are not as accurate or pronounced for predictions during the last 10 minutes of the trial; however predictions for 70 – 80 minutes fit the observed data well. This suggests that the method is still successful in determining differences between conditions and there is the potential for a developed method to more accurately predict these differences. To investigate this further, a comparison between these predictions and predictions produced by the data in previous experiments has been made (Figure 120, Figure 121 & Figure 122). The unweighted regression equations developed in Chapter 4 (Equation 4.2) and Chapter 5 (Equation 5.2) can also be applied to the SFM data recorded in this experiment to observe how fitting those predictions are for the data recorded in this experiment.

It can clearly be seen in Figure 120, Figure 121 and Figure 122 that the predicted values of discomfort produced by each of the regression equations are closely related and also appear to follow a close relationship with the observed values. The relationship between the predicted values and the observed values was analysed in more detail by conducting regression analysis and Pearson Correlations.

![Graph](image)

**Figure 120:** Observed overall discomfort ratings vs Predicted, Predicted (Chapter 4) and Predicted (Chapter 5) discomfort ratings using regression equations for the ‘Sit’ condition
Figure 121: Observed overall discomfort ratings vs Predicted, Predicted (Chapter 4) and Predicted (Chapter 5) discomfort ratings using regression equations for the ‘Walk’ condition

Figure 122: Observed overall discomfort ratings vs Predicted, Predicted (Chapter 4) and Predicted (Chapter 5) discomfort ratings using regression equations for the ‘Walk & Sit’ condition
The results determined that for the ‘Sit’ condition, a strong positive correlation was observed between the observed values and the 3 sets of predicted values. This is described by the $r^2$ value for each of the comparisons:

- Observed vs Predicted: $r^2 = 0.893$
- Observed vs Predicted (Chapter 4): $r^2 = 0.893$
- Observed vs Predicted (Chapter 5): $r^2 = 0.889$

For the ‘Walk’ condition, a strong positive correlation was observed between the observed values and the 3 sets of predicted values. This is described by the $r^2$ values for each of the comparisons:

- Observed vs Predicted: $r^2 = 0.87$
- Observed vs Predicted (Chapter 4): $r^2 = 0.87$
- Observed vs Predicted (Chapter 5): $r^2 = 0.868$

For the ‘Walk& Sit’ condition, a strong positive correlation was observed between the observed values and the 3 sets of predicted values. This is described by the $r^2$ values for each of the comparisons:

- Observed vs Predicted: $r^2 = 0.961$
- Observed vs Predicted (Chapter 4): $r^2 = 0.961$
- Observed vs Predicted (Chapter 5): $r^2 = 0.975$

As a strong positive correlation is observed between the observed values of overall discomfort and the 3 sets of predicted values for each condition, it can be concluded that it is possible to predict overall discomfort using only SFM data and the regression equations derived from the results of each study in this thesis. The correlation $r^2$ value is shown to be slightly greater in some conditions than others but ultimately these results show that there is potential for an equation to be derived using all data obtained during this research to accurately predict overall discomfort using only SFMs. The graphs also show how fluctuations SFM frequency recorded may impact the relationship with subjective ratings as between 110-120 minutes the predicted discomfort ratings decrease in 2 conditions. This implies the need for a larger sample size or the ability to measure SFMs accumulatively.
7.5.3.2 SFM Weighting Factors

In the previous experimental chapters it was presented that by applying weightings to each of the SFM types, the correlation between overall discomfort and SFM frequency could be improved. Therefore, this method has been applied to the data collected in this study and, due to the design of the study, has been applied to the average data for all 3 conditions between 0 – 60 minutes, as this was the part of the trial that all 3 conditions were identical. The aim is to establish whether weighting factors can improve the correlation (r² value) and subsequently produce another regression equation to predict overall discomfort using weighted data.

Figure 123: Correlation strength (r² value) when applying weighting factors to each SFM type using mean data for all conditions between 0 – 60 minutes
As described by Figure 123, the relationship between the mean number of SFMs and mean overall discomfort can be improved by applying a weighting factor to each Type 2 and Type 3 movement recorded. As shown previously when applying weightings of 1:1:1, the $r^2$ value was shown to be 0.922. However after applying weighting factors this value can be increased to 0.931 by applying a weighting of 1 to Type 1 movements, 0.7 to Type 2 movements and 0.4 to Type 3 movements, suggesting an improved relationship. This is represented by:

$$Total\ sfm_w = Type\ 1 + (Type\ 2 \times 0.7) + (Type\ 3 \times 0.4)$$ (7.2)

Another regression analysis was conducted in order to produce another equation that included the weighting factors proposed for each SFM type:

$$\Psi = -1.078 + 75.4sfm_w$$ (7.3)

Where: $\Psi$ is the rating of overall discomfort and $sfm_w$ is the weighted number of SFMs per min.

This equation (Equation 7.3) was then used to produce predicted values of discomfort for each condition using only the weighted SFM data, comparisons between the observed overall discomfort ratings and the weighted predicted discomfort ratings for each condition can be seen in Figure 124, Figure 125 and Figure 126.

As applying the weighting factors to the average data for all conditions between 0 – 60 minutes showed an improved relationship ($r^2$ value), it is expected that an improved relationship would be seen between the observed discomfort ratings and the weighted predicted discomfort ratings for each of the conditions.

Therefore, Pearson Correlations were conducted on the data for each condition in order to determine the relationship between the observed values and the weighted predicted values and evaluate whether applying the weighting factors has in fact improved the relationship.
Figure 124: Observed vs weighted predicted overall discomfort for the ‘Sit’ condition using regression equation

Figure 125: Observed vs weighted predicted overall discomfort for the ‘Walk’ condition using regression equation
The results show that by applying the weighting factors proposed by the average data to the data for each condition, a reduction in correlation strength is observed for each condition. This is described by the $r^2$ values:

- Sit condition – observed vs weighted predicted, $r^2 = 0.88$
- Walk condition – observed vs weighted predicted, $r^2 = 0.81$
- Walk & Sit condition – observed vs weighted predicted, $r^2 = 0.95$

This implies that, on average, the weighting factors proposed are less successful when applied to the individual conditions. This is most likely due to the differences in overall discomfort observed after the breaks from driving and the fact that the weightings were derived from the average data for only 0 – 60 minutes. A better strategy may be to develop weighting factors for each condition based only on the results for each condition; however this contradicts the aim of applying weightings. In order for weighting factors to improve the SFM method, these weightings must be applicable for all data. Therefore this suggests that further analysis must be conducted to determine weighting factors that are appropriate for all sets of data. The weighting factors developed in Chapter 4 and Chapter 5 should also be tested.
against this data in order to determine whether these weightings are more appropriate (Figure 127, Figure 128 & Figure 129).

**Figure 127**: Observed overall discomfort vs weighted predicted, weighted predicted using Chapter 4 data and weighted predicted using Chapter 5 data for the ‘Sit’ condition

**Figure 128**: Observed overall discomfort vs weighted predicted, weighted predicted using Chapter 4 data and weighted predicted using Chapter 5 data for the ‘Walk’ condition
Figure 129: Observed overall discomfort vs weighted predicted, weighted predicted using Chapter 4 data and weighted predicted using Chapter 5 data for the 'Walk & Sit' condition.

When analysing the correlation between the observed values and the 3 sets of weighted predicted values, the results determined that for the 'Sit' condition, a strong positive correlation was observed between the observed values and the 3 sets of weighted predicted values. This is described by the $r^2$ value for each of the comparisons:

- Observed vs Weighted Predicted: $r^2 = 0.878$
- Observed vs Weighted Predicted (Chapter 4): $r^2 = 0.856$
- Observed vs Weighted Predicted (Chapter 5): $r^2 = 0.836$

For the 'Walk' condition, a strong positive correlation was observed between the observed values and the 3 sets of weighted predicted values. This is described by the $r^2$ values for each of the comparisons:

- Observed vs Weighted Predicted: $r^2 = 0.809$
- Observed vs Weighted Predicted (Chapter 4): $r^2 = 0.861$
- Observed vs Weighted Predicted (Chapter 5): $r^2 = 0.817$
For the ‘Walk & Sit’ condition, a strong positive correlation was observed between the observed values and the 3 sets of weighted predicted values. This is described by the $r^2$ values for each of the comparisons:

- Observed vs Weighted Predicted: $r^2 = 0.952$
- Observed vs Weighted Predicted (Chapter 4): $r^2 = 0.951$
- Observed vs Weighted Predicted (Chapter 5): $r^2 = 0.929$

Although the weighted predicted values produced using the data in this experiment are shown to be the most appropriate for the ‘Sit’ and the ‘Walk & Sit’ conditions, there is little difference in the correlation strengths ($r^2$ values) when using the weighting factors and regression equations produced during Chapter 4 (Equation 4.4) and Chapter 5 (Equation 5.4). Furthermore, for the ‘Walk’ condition it is shown that applying the weighting factors and regression equation from Chapter 4 is more appropriate for this condition. It is important to mention that although applying weighting factors to the SFM data has still shown a strong positive correlation in all conditions, the correlation strengths of each of these predictions show no improvement on the predictions made without implementing weightings. Therefore, it can be concluded that for this study, applying weightings has been less successful in establishing an improved method and that in order to produce weighting factors that may be appropriate for all data sets, the data collected during this research must be examined as a whole.

**7.5.3.3 Interpolated Data**

In the previous experimental chapters, applying an approach of interpolating the mean overall discomfort ratings has shown to lead to improvements in correlation strength due to a more accurate representation of the time intervals being evaluated. Therefore, this process was again conducted on the data recorded during this experiment for each condition (Figure 130, Figure 131 & Figure 132). The interpolated ratings for overall discomfort represent mean discomfort ratings for 5, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115 and 125 minutes.

Although previously applying this approach to the data collected in Chapter 4 and Chapter 5 has shown an improvement in the correlation strength ($r^2$ value) between
Overall discomfort and the number of SFMs per 10 minutes, no such improvement is witnessed with the data collected in this experiment.

**Figure 130**: Interpolated mean overall discomfort ratings and number of SFMs over time for the ‘Sit’ condition

**Figure 131**: Interpolated mean overall discomfort ratings and number of SFMs over time for the ‘Walk’ condition
Regression analysis and Pearson Correlations were conducted on the data and when evaluating the correlation strengths for each of the conditions, a reduction in correlation strength is observed for all conditions when compared with the non-interpolated observed discomfort ratings. This is represented by the $r^2$ value for each comparison:

- ‘Sit’ condition, $r^2 = 0.88$
- ‘Walk’ condition, $r^2 = 0.879$
- ‘Walk & Sit’ condition, $r^2 = 0.959$

It can be concluded that as no improvement in correlation strength is observed, interpolation of the data is not as applicable for the data recorded in this experiment. This suggests that further analysis is required that includes all of the data recorded during this research in order to fully understand the implications of interpolating the data on the success of the SFM method.

Therefore, weightings will not be applied to the interpolated data as the strongest correlation was shown when simply applying the observed SFM data to predict overall discomfort. This study has shown that although applying weightings and
interpolating the data in previous experiments has led to a marginally improved correlation, this approach may not be beneficial for all data sets and that in order to fully understand the relationship between SFMs and overall discomfort, the data recorded during this research must be evaluated as a whole.

7.5.4 Relationship between SFMs and Verbal Discomfort Descriptors

As the ultimate aim of this research was to establish an objective measure of discomfort to be implemented into the automotive industry, it is important to determine how a measure of SFM frequency translates to verbal discomfort descriptors. This may allow the method to bypass ratings of overall discomfort and simply be developed as its own scale.

Therefore, at each time interval a verbal discomfort descriptor was selected that corresponded to the average overall discomfort ratings recorded at that time interval using the verbal discomfort descriptors included on the overall discomfort rating scale described in Section 2.2.4. This verbal discomfort descriptor can then be correlated with the number of SFMs recorded during that time interval to gain an understanding of how the two are related for each condition (Table 23, Table 24 & Table 25).
Table 23: Comparison of SFM frequency with corresponding mean overall discomfort ratings and verbal discomfort descriptors for the ‘Sit’ condition

<table>
<thead>
<tr>
<th>Time</th>
<th>Overall Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.05</td>
<td>0.4</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>20</td>
<td>4.25</td>
<td>1</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>30</td>
<td>6.75</td>
<td>1.7</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>40</td>
<td>9</td>
<td>2</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>50</td>
<td>12.85</td>
<td>2</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>60</td>
<td>15.5</td>
<td>2.2</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>70</td>
<td>10.7</td>
<td>n/a</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>80</td>
<td>14.7</td>
<td>2.6</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>90</td>
<td>18.6</td>
<td>3.4</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>100</td>
<td>21</td>
<td>3.5</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>110</td>
<td>25.1</td>
<td>5.6</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>120</td>
<td>26.25</td>
<td>4.4</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>130</td>
<td>29.1</td>
<td>6.9</td>
<td>Moderate-High Discomfort</td>
</tr>
</tbody>
</table>

Table 24: Comparison of SFM frequency with corresponding mean overall discomfort ratings and verbal discomfort descriptors for the ‘Walk’ condition

<table>
<thead>
<tr>
<th>Time</th>
<th>Overall Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.75</td>
<td>0.5</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>20</td>
<td>4.7</td>
<td>0.9</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>30</td>
<td>6.15</td>
<td>1</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>40</td>
<td>9.45</td>
<td>1.9</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>50</td>
<td>11.75</td>
<td>1.9</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>60</td>
<td>14.15</td>
<td>2.7</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>70</td>
<td>1.45</td>
<td>n/a</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>80</td>
<td>4.1</td>
<td>0.8</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>90</td>
<td>6.45</td>
<td>1.6</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>100</td>
<td>10.4</td>
<td>2.3</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>110</td>
<td>12.9</td>
<td>3.3</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>120</td>
<td>15.65</td>
<td>2.6</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>130</td>
<td>16.95</td>
<td>5.1</td>
<td>Little Discomfort</td>
</tr>
</tbody>
</table>
Table 25: Comparison of SFM frequency with corresponding mean overall discomfort ratings and verbal discomfort descriptors for the 'Walk & Sit' condition

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Overall Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.8</td>
<td>0.9</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>20</td>
<td>4.05</td>
<td>0.2</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>30</td>
<td>6.1</td>
<td>1.8</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>40</td>
<td>8.45</td>
<td>2.1</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>50</td>
<td>11.35</td>
<td>2.2</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>60</td>
<td>13.43</td>
<td>2.6</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>70</td>
<td>5.9</td>
<td>n/a</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>80</td>
<td>10.2</td>
<td>2.2</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>90</td>
<td>12.95</td>
<td>3.2</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>100</td>
<td>16.53</td>
<td>3.9</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>110</td>
<td>18.75</td>
<td>4.1</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>120</td>
<td>20.75</td>
<td>5.4</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>130</td>
<td>24.7</td>
<td>5.6</td>
<td>Moderate Discomfort</td>
</tr>
</tbody>
</table>

Table 23, Table 24 and Table 25 were produced using the data recorded in this experiment. Using the equation produced by the regression analysis of the mean results recorded between 0 – 60 minutes for all conditions another table can be produced that defines the ranges of number of SFMs (per min) and overall discomfort ratings against the verbal discomfort descriptors, as conducted in Chapter 4 and Chapter 5. This table was produced by rearranging the regression equation (Equation 7.1) as such:

1) \[ \Psi = -1.1676 + 58.767sfm \]

2) \[ sfm = (-1.1676 - \Psi) / -58.767 \]  \hspace{1cm} (7.4)

Then, using the boundaries for overall discomfort ratings, ranges for SFM frequency were calculated that relate to the equivalent verbal discomfort descriptor. This can be seen in Table 26.
Table 26 provides the basis for discomfort assessment to be made using only SFM data. The table suggests that a driver experiencing ‘Very Little Discomfort’ would record an SFM less than once every 5 minutes 20 seconds whereas a driver experiencing ‘Moderate-High Discomfort’ would record an SFM roughly once every 1 minute 45 seconds. This finding allows for measurements of SFM frequency to be associated with direct descriptions of discomfort, removing the need for subjective evaluation and suggests that the SFM method can be implemented successfully into automotive seating assessment and evaluation.

Table 26 is a replica of Table 13 and Table 18 from Chapter 4 (Section 4.5.4) and Chapter 5 (Section 5.5.4) however the SFM ranges have been produced using the regression equation produced by this data. A comparison between the SFM frequency ranges produced by this data and the SFM frequency ranges produced by the data in the previous studies is required to determine whether the ranges are similar and therefore applicable for all data sets (Table 27).

Table 27 describes that although the SFM frequency (SFMs/min) ranges produced by the three studies are not identical; similarities are observed when discomfort is greater than ‘Little Discomfort’. For example, when comparing the upper and lower boundaries for ‘Moderate Discomfort’, all studies define similar ranges for SFM frequency (SFMs/min). This suggests that the ranges proposed when discomfort is greater than ‘Little Discomfort’ are applicable for all data and therefore will be very
useful as a way of defining the SFM frequency associated with different verbal discomfort descriptors. Although the ranges produced are not completely identical, the table suggests that if SFM frequency ranges can be defined using all of the data collected during this research, some appropriate ranges may be found that can be useful for any SFM data.

7.6 Conclusions

**H7.1: Taking a break from a long term drive will affect subjective discomfort during the break**

Subjective discomfort was shown to decrease during a break from a long term drive in all conditions as an acute decrease in local and overall discomfort ratings was shown for all three conditions which was immediately measurable (ie. at the 62 minute interval). This decrease in discomfort continued throughout the following 8 minutes of the break suggesting that a longer break is more beneficial than a
shorter break, in terms of discomfort reduction. All participants recorded reductions in overall discomfort at the end of the break from the driving task. Therefore, it can be concluded that taking a break from a long term drive will have a positive effect in reducing discomfort experienced as a result of long duration driving, regardless of activity during the break.

**H7.2: Taking a break from a long term drive will affect subjective discomfort at the end of the total drive time**

Taking a break from a long term drive was shown to have a positive impact, in terms of discomfort reduction, upon completion of the 130 minute trial in all conditions. As discomfort was shown to continually increase prior to the break from driving, it can be assumed that discomfort would continue to increase at a similar rate if a break had not been taken. This is supported by the findings of Chapter 4 where discomfort continued to increase across the duration of a 140 minute drive, despite not maintaining a linear increase. As discomfort increases steadily after the break from driving at a similar rate to that observed prior to the break from driving, it can be concluded that by taking a break from driving, drivers have actively reduced the total overall discomfort experienced upon completion of the drive. This suggests that when undertaking a long term drive, drivers should plan to implement breaks at regular time intervals during the journey in order to minimise the discomfort experienced during, and at the end of the drive.

As benefits are shown in terms of discomfort reduction, these findings may have implications on the guidelines available for drivers discussed in Section 2.6.1. It may be of benefit for the findings of this study to be incorporated into any future guidelines as there is the possibility that the benefits in terms of comfort improvement may encourage drivers to adhere to the guidelines and the importance of activity or behaviour during breaks should be well defined. Information available to drivers such as the ‘THINK! Don't drive tired’ campaign may benefit from including the comfort benefits of breaks as well as the other benefits highlighted with safety and performance. Mercedes-Benz has recently implemented an attention assist system into their vehicles and systems such as this may be useful
when informing drivers that a break from driving is necessary, not only to improve safety, but also to minimise discomfort. Furthermore, any future work that aims to predict or model driver discomfort will need to account for the reductions observed in discomfort due to breaks from driving.

**H7.3: Behaviour during a break from a long term drive will affect the effectiveness of the break in reducing subjective discomfort, both immediately and at the end of the drive**

The type of activity performed whilst taking a break from driving has a large influence on the effectiveness of the break, both immediately and at the end of the drive. The results of this study determined that drivers who leave the vehicle seat will benefit significantly in terms of discomfort reduction. Furthermore, drivers are recommended to stop and take a walk, rather than sit in another seat when taking a break from long term driving and exposure to whole-body vibration as it was determined that discomfort was ‘reset’ after taking a 10 minute walk during a break. This supports the findings of Yonekawa et al. (2011) where the effects of TTS were ‘reset’ after 10 minutes rest from vibration exposure and also Ravnik et al. (2008) where driver discomfort was reduced to nearly zero after a 15 minute break after 100 minutes of driving. These findings may have implications on ISO 2631-1 (1997) where the effects of breaks from whole-body vibration are not well defined. Additionally these findings may have an impact outside of normal road driving. Drivers exposed to greater magnitudes of vibration, such as with construction work, may benefit most from taking effective breaks and the importance of behaviour during breaks from driving should be highlighted.

**H7.4: SFM frequency will increase with duration of driving**

SFM frequency was again shown to increase with duration of driving as participants recorded significantly greater numbers of SFMs during the final 10 minutes of each 60 minute drive when compared to the first 10 minutes of each 60 minute drive for all conditions. These findings support the results discussed in Chapter 4 and Chapter 5 and in the previous literature. SFM frequency is shown to increase with duration of driving regardless of the activity undertaken during the break from driving and
increased at a similar rate in all 3 conditions. These findings support the conceptual model proposed in Section 4.5.2.1 and further validate the SFM method.

**H7.5: SFM magnitude will increase with duration of driving**

As with the previous experiments in Chapter 4 and Chapter 5, no relationship was observed between SFM magnitude and driving duration during this study, for each of the conditions. Therefore it is concluded that further research is required to fully understand the effect of driving duration on SFM magnitude and that the design of the method may need to be improved in order to account for differences in individual movement magnitude. This implies that time and driving duration has no influence on the type of movements made by drivers and for the purpose of this method, suggests that all movement types are equally important for drivers when coping with discomfort.

**H7.6: A relationship will be observed between subjective discomfort and SFMs**

A strong positive correlation between subjective overall discomfort ratings and SFM frequency is again observed in this study, supporting the previous findings of this research. Drivers are shown to move more frequently as discomfort increases despite the differences in conditions. It is shown that SFM measurements can be used to accurately predict overall discomfort ratings and suggests that the method has been successful in reflecting the acute differences observed in driver discomfort between the different conditions. It can be concluded that the method may be of use when replacing subjective assessment and has shown the ability to distinguish between experimental conditions which may be extremely useful when implemented into the automotive industry.
CHAPTER 8

Determining the Success of the SFM Method

In order to determine the success of the SFM method, the results reported by each laboratory experiment in this thesis will be discussed both individually and as a whole and evaluations will be made using a combination of the data collected in each study. Therefore, in order to produce data that represents an average of the 3 experimental studies, data was taken from each study between 0 – 60 minutes as this time interval was common to all studies. The data recorded for 0 – 60 minutes in Chapter 4 and Chapter 5 was included and data recorded between 0 – 60 minutes for one of the conditions in Chapter 7 was included. Only one of the conditions was included as to ensure that the data was not skewed towards the data from Chapter 7. If all 3 conditions were included this would multiply the effects of the data for the 10 participants in Chapter 7 and may have negative implications on the results. In order to identify which of the 3 conditions was included, comparisons of the correlation strength ($r^2$ value) between overall discomfort ratings and SFM frequency were made for each of the conditions between 0 – 60 minutes:

- Chapter 7 ‘Sit’: $r^2 = 0.813$
- Chapter 7 ‘Walk’: $r^2 = 0.958$
- Chapter 7 ‘Walk & Sit’: $r^2 = 0.748$

Data for the ‘Sit’ condition was chosen as this best represents an average of the 3 conditions in terms of correlation strength. Therefore, overall discomfort ratings and the number of SFMs were averaged at each time interval across all 3 studies to produce data that represents the mean findings of all 3 studies (Figure 133).

As with each of the individual chapters, SFM frequency is shown to increase with driving duration and when comparing the results for overall discomfort and the SFM data recorded, it is clear that a close relationship exists. It can be concluded that there is a positive relationship between mean overall discomfort and the mean
number of SFMs recorded in the 10 minutes that preceded it; as discomfort increases, the frequency of SFMs also increases (Figure 134).

Figure 133: Mean overall discomfort ratings and number of SFMs against time for all 3 studies

Figure 134: Mean number of SFMs against mean overall discomfort ratings for all 3 studies
The average data displayed in Figure 133 and Figure 134 will be used to add to the discussion in this chapter, as it is important to develop the SFM method with regards to the whole sample. If the SFM method is to be successful it is important that the method can be applied to any population and the most important aim of this chapter is to determine how the method should be applied in future research.

8.1 SFM Frequency

Firstly, one aspect of the SFM method that was evaluated during this research was the effect of driving duration on SFM frequency. In each of the laboratory experiments conducted during this research SFM frequency was shown to increase with driving duration. This supports the findings of the previous literature discussed in Chapter 2 (Grandjean et al., 1960; Jurgens, 1989; Michel & Helander, 1994; Bhatnager et al., 1985; Fenety & Walker, 2002; Adler, 2007) and supports the theory that individuals will increase the frequency of their movements, at a conscious or unconscious level, as duration of sitting increases (Fenety et al., 2000).

The rationale behind this is that people move when seated with the purpose of relieving pressure of compressed body parts with impeded blood flow (Hermann & Bubb, 2007, Odell, 1978). SFMs may therefore be a direct result of compromised blood flow as this urges the sitter to change position to reinstate normal or at least improved blood flow. Consequently the amount of time between those movements may relate to discomfort created by tissue compression. This suggests that drivers move in the vehicle seat when discomfort reaches a detection threshold that is consciously or unconsciously perceived. As the frequency of SFMs increased with time, this implies that as the duration of driving increased, drivers reached this detection threshold faster. This is described by the conceptual model (Figure 135) first proposed in Chapter 4.
A driver’s detection threshold can be described as a driver’s acceptable comfort level. An SFM occurs when discomfort reaches this threshold and becomes detectable to the driver. During the study in Chapter 5, SFM frequency is shown to increase at a much quicker rate when compared with the increase observed in Chapter 4 and Chapter 7. This suggests that as the factors affecting driver discomfort are altered, this will in turn alter the gradient of the instantaneous discomfort sensation. For example, when vibration magnitude is increased, as with Chapter 5, this has been shown to lead to an increase in the rate of discomfort increase (Mansfield et al., 2014) and therefore the increase in the instantaneous discomfort sensation will be more rapid, causing drivers to record SFMs more frequently.

Ultimately the SFM method has been successful in describing this phenomenon and the method has shown that in all instances, the frequency of movements made by drivers increased over the duration of a long term drive. The method has accurately reported these changes and possesses the ability to measure differences in the rate of increase in SFM frequency as a result of different driving conditions.
8.2 SFM Magnitude

Another aspect of the SFM method that was evaluated in each laboratory experiment was the effect of driving duration on SFM magnitude. Previous research into driver posture changes and ICMs had suggested that as the duration of sitting increases, the amplitude or magnitude of recorded movements would also increase as discomfort reaches increased levels. For example, Adler (2007) determined that the amplitude of posture changes in drivers increased with time, especially for the head and trunk.

Therefore, the method was developed with the aim of detecting differences in movement magnitude via the use of ‘SFM Types’. These SFM types were defined as each representing movements of different magnitudes, with Type 1 movements representing small movements or posture changes, Type 2 representing medium sized movements and Type 3 representing large movements. This approach was taken due to the design of the SFM method itself and the aim was to determine the correlation between SFM magnitude and driving duration.

As no relationship between SFM magnitude, or SFM type, and driving duration was observed in any of the studies conducted during this research, this implies that either the size of movements made by drivers has no relation to the duration of driving, or that the method has been unsuccessful in detecting these differences. Perhaps the likely conclusion is that the method is incorrect to define movement type as a measure of magnitude. For example, although Type 1 movements all consist of the same small postural change, some Type 1 changes may be greater in terms of magnitude than others.

Further work may need to be conducted in order to determine the effect of driving duration on SFM magnitude and adaptations may need to be made to the method. For the purpose of this research, it can be concluded that the current design of the method is unable to detect changes in movement magnitude and that when analysing the type of movement, as with this research, movement types are not influenced by the duration of driving and may not reflect magnitude. This suggests that in terms of the success of this method, no movement type can be deemed
more important than another, and that drivers use a combination of these movement types when actively trying to minimise discomfort in different body regions.

One proposed method to measure magnitude in future research is to directly measure the distance, or displacement, of each individual movement regardless of type. This will provide a direct measure of individual movement magnitude rather than magnitude via SFM type. This may be difficult to achieve with the current strategy for recording SFMs however may be possible via a technological approach, this will be discussed later in this chapter.

8.3 Relationship between Subjective Overall Discomfort Ratings and SFMs

The results of each laboratory experiment determined that both mean subjective overall discomfort and mean SFM frequency increase with time. However, the most important aim of this research was to determine the relationship between the subjective ratings of discomfort and the objective measure of SFM frequency. A positive correlation has been determined in each of the laboratory studies and this is crucial if the method is to be successfully implemented into the automotive industry. Therefore this section will evaluate the data in its entirety and determine the correlation between the subjective and objective measures of discomfort in addition to producing a method to predict overall discomfort using SFM data.

8.3.1 Observed Data

A Pearson Correlation and regression analysis were performed on the average data described by Figure 133 and Figure 134 that compared the mean overall discomfort ratings at each time interval with the mean number of SFMs per 10 minutes, or SFM frequency. A large positive correlation was shown with an r value of 0.978 with 95.6% shared variance and was statistically significant (r = 0.978, n = 6, p < 0.05). When comparing the correlation strength (r² value) with those defined in each laboratory study it is shown that averaging the data from all 3 experiments produces a similar correlation:
• Chapter 4: $r^2 = 0.927$
• Chapter 5: $r^2 = 0.968$
• Chapter 7 ‘Sit’ condition: $r^2 = 0.893$
• Chapter 7 ‘Walk’ condition: $r^2 = 0.87$
• Chapter 7 ‘Walk & Sit’ condition: $r^2 = 0.96$
• All studies: $r^2 = 0.956$

It can be concluded that SFM frequency does not only increase with driving duration but is closely related to subjective discomfort increase. However, the overall aim of the research is to develop an objective measure that can be implemented into the automotive industry and used to predict overall discomfort. Therefore, linear regression comparing the mean overall discomfort for all studies and the mean number of SFMs for all studies at each time interval produced the equation:

$$\Psi = -2.201 + (64.2sfm)$$  \hspace{1cm} (8.1)

Where: $\Psi$ is the rating of overall discomfort and sfm is the number of SFMs per minute.

This equation (Equation 8.1) was then used to produce predicted values of discomfort using only SFM data and can be seen in Figure 136.

The predicted values are closely related to the observed values ($r^2 = 0.956$). It is now important to determine how successful the regression equation (Equation 8.1) produced by the average data for all studies is when predicting discomfort using the data obtained in each of the laboratory experiments. Therefore, the regression equation was used to predict values of overall discomfort using the SFM data reported in each of the laboratory experiments and was compared with the observed values of discomfort reported in each laboratory experiment (Figure 137, Figure 138, Figure 139, Figure 140 & Figure 141).
Figure 136: Observed vs Predicted overall discomfort using regression equation

Figure 137: Observed vs Predicted overall discomfort using regression equation and the data recorded in Chapter 4
Figure 138: Observed vs Predicted overall discomfort using regression equation and the data recorded in Chapter 5

Figure 139: Observed vs Predicted overall discomfort using regression equation and the data recorded in Chapter 7 for the 'Sit' condition
**Figure 140:** Observed vs Predicted overall discomfort using regression equation and the data recorded in Chapter 7 for the 'Walk' condition

**Figure 141:** Observed vs Predicted overall discomfort using regression equation and the data recorded in Chapter 7 for the 'Walk & Sit' condition
Pearson correlations were then conducted to determine the success of the predictions by analysing the correlation strength \( (r^2 \text{ value}) \) between the observed and predicted values:

- Observed (Chapter 4) vs Predicted: \( r^2 = 0.926 \)
- Observed (Chapter 5) vs Predicted: \( r^2 = 0.968 \)
- Observed (Chapter 7 ‘Sit’) vs Predicted: \( r^2 = 0.893 \)
- Observed (Chapter 7 ‘Walk’) vs Predicted: \( r^2 = 0.87 \)
- Observed (Chapter 7 ‘Walk & Sit’) vs Predicted: \( r^2 = 0.967 \)

The predicted values are shown to be highly correlated with the observed values for each of the conditions and imply that the regression equation produced by the average data (Equation 8.1) is useful for predicting discomfort for any sample evaluated during this research.

### 8.3.2 SFM Weighting Factors

In the previous chapters, weighting factors applied to each SFM type was shown to improve the correlation between overall discomfort and SFM frequency. Therefore, weightings were applied to the average data to establish whether this improves the correlation \( (r^2 \text{ value}) \) (Figure 142).

As described by Figure 142, the relationship can be improved by applying weighting factors. When applying weightings of 1:1:1, the \( r^2 \) value was shown to 0.956. However, Figure 142 describes that this value can be increased to 0.977 by applying weightings of 1 to Type 1 movements, 0.3 to Type 2 movements and 0.6 to Type 3 movements. Represented by:

\[
Total sfm_{w} = Type1 + (Type2 \times 0.3) + (Type3 \times 0.6) \quad (8.2)
\]

Therefore, another regression was conducted in order to produce another equation that included the weighting factors proposed for each SFM type:

\[
\Psi = -0.028 + (89.51sfm_{w}) \quad (8.3)
\]

Where: \( \Psi \) is the rating of overall discomfort and \( sfm_{w} \) is the weighted number of SFMs per minute.
**Figure 142**: Correlation strength ($r^2$ value) when applying weighting factors to each SFM type

Predicted values were again produced using this equation (Equation 8.3) and the weighted SFM data. A comparison between the observed values and the weighted predicted discomfort ratings can be seen in Figure 143.

It is now important to determine how successful the regression equation produced by the weighted average data for all studies (Equation 8.3) is when predicting discomfort using the data obtained in each of the laboratory experiments.

Therefore, the regression equation (Equation 8.3) was again used to predict values of overall discomfort using the weighted SFM data reported in each of the laboratory experiments and was compared with the observed values of discomfort reported in each laboratory experiment (Figure 144, Figure 145, Figure 146, Figure 147 & Figure 148).
**Figure 143**: Observed vs Predicted (w) overall discomfort using weighted SFM data and regression equation

**Figure 144**: Observed vs Predicted (w) overall discomfort using weighted regression equation and the data recorded in Chapter 4
**Figure 145**: Observed vs Predicted (w) overall discomfort using weighted regression equation and the data recorded in Chapter 5

**Figure 146**: Observed vs Predicted (w) overall discomfort using weighted regression equation and the data recorded in Chapter 7 for the 'Sit' condition
Figure 147: Observed vs Predicted (w) overall discomfort using weighted regression equation and the data recorded in Chapter 7 for the 'Walk' condition

Figure 148: Observed vs Predicted (w) overall discomfort using weighted regression equation and the data recorded in Chapter 7 for the 'Walk & Sit' condition
Pearson correlations were then conducted to determine the success of the weighted predictions by analysing the correlation strength ($r^2$ value) between the observed and predicted (w) values:

- Observed (Chapter 4) vs Predicted (w): $r^2 = 0.955$
- Observed (Chapter 5) vs Predicted (w): $r^2 = 0.98$
- Observed (Chapter 7 ‘Sit’) vs Predicted (w): $r^2 = 0.861$
- Observed (Chapter 7 ‘Walk’) vs Predicted (w): $r^2 = 0.846$
- Observed (Chapter 7 ‘Walk & Sit’) vs Predicted (w): $r^2 = 0.955$

The predicted values are again shown to be highly correlated with the observed values for each of the conditions and imply that the regression equation (Equation 8.3) produced by the weighted average data is useful for predicting discomfort for any sample reported in this research.

**8.3.3 Interpolated Data**

It was established previously that interpolating the mean overall discomfort ratings may provide a more accurate representation of time due to the fact that SFM data was recorded over the 10 minutes that preceded each discomfort rating. Therefore this process has again been conducted for the average data for all conditions (Figure 149).

The interpolated ratings for overall discomfort displayed represent mean discomfort ratings between all 3 studies collected at 5, 15, 25, 35, 45 and 55 minutes. In comparison with the mean observed data there is a slight improvement in correlation strength, supporting the findings of Chapter 4 and Chapter 5. Regression analysis and Pearson Correlation determined that the correlation strength between the interpolated data and the mean number of SFMs (per 10 minutes) is $r^2 = 0.965$, compared with 0.956 for the mean observed data. This suggests that on average, measurements of SFM frequency better represent discomfort ratings at an average of the time interval for which they were recorded.
Figure 149: Interpolated mean overall discomfort ratings and number of SFMs against time for all 3 studies

As with the observed data, weighting factors can now be applied to the SFM data then correlated with the interpolated overall discomfort data in order to evaluate whether this relationship ($r^2$ value) can be improved further (Figure 150).

Figure 150 shows that by applying the same weighting factors as with the mean observed data (Equation 8.2), the correlation strength with the mean interpolated discomfort ratings can be improved to correspond with an $r^2$ value of 0.985.
Figure 150: Correlation strength ($r^2$ value) when applying weighting factors to each SFM type using interpolated discomfort data

As a result of the improved relationship, another linear regression was conducted to produce another equation that included the weightings for each SFM type and could predict values of discomfort that represent the interpolated discomfort ratings:

$$\Psi = -1.739 + (86.68sfm_w)$$ (8.4)

Where: $\Psi$ is the rating of overall discomfort and $sfm_w$ is the weighted number of SFMs per minute.

This equation (Equation 8.4) was then used to produce predicted values of discomfort using weighted SFM data and was compared with the interpolated mean discomfort ratings (Figure 151).
It is now important to determine how successful the regression equation produced by the weighted and interpolated average data for all studies is when predicting interpolated discomfort using the data for each of the laboratory experiments.

Therefore, the regression equation (Equation 8.4) was again used to predict values of interpolated overall discomfort using the weighted SFM data reported in each of the laboratory experiments and was compared with the interpolated values of discomfort reported in each laboratory experiment (Figure 152, Figure 153, Figure 154, Figure 155 & Figure 156).
Figure 152: Interpolated vs Predicted (w/int) overall discomfort using weighted regression equation and the data recorded in Chapter 4

Figure 153: Interpolated vs Predicted (w/int) overall discomfort using weighted regression equation and the data recorded in Chapter 5
Figure 154: Interpolated vs Predicted (w/int) overall discomfort using weighted regression equation and the data recorded in Chapter 7 for the ‘Sit’ condition.

Figure 155: Interpolated vs Predicted (w/int) overall discomfort using weighted regression equation and the data recorded in Chapter 7 for the ‘Walk’ condition.
Pearson correlations were then conducted to determine the success of the weighted predictions by analysing the correlation strength ($r^2$ value) between the interpolated and predicted (w/int) values:

- Interpolated (Chapter 4) vs Predicted (w/int): $r^2 = 0.978$
- Interpolated (Chapter 5) vs Predicted (w/int): $r^2 = 0.986$
- Interpolated (Chapter 7 ‘Sit’) vs Predicted (w/int): $r^2 = 0.846$
- Interpolated (Chapter 7 ‘Walk’) vs Predicted (w/int): $r^2 = 0.855$
- Interpolated (Chapter 7 ‘Walk & Sit’) vs Predicted (w/int): $r^2 = 0.966$

The weighted predicted values are shown to be highly correlated with the interpolated values for each of the conditions and imply that the regression equation produced by the average data is useful for predicting discomfort for any sample recorded during this research.
Table 28: Correlation strength ($r^2$ value) for each comparison

<table>
<thead>
<tr>
<th>Condition</th>
<th>Observed</th>
<th>Interpolated Discomfort</th>
<th>Weighted SFMs</th>
<th>Weighted SFMs &amp; Interpolated Discomfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 4</td>
<td>0.926</td>
<td>0.932</td>
<td>0.955</td>
<td>0.978</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>0.968</td>
<td>0.98</td>
<td>0.98</td>
<td>0.986</td>
</tr>
<tr>
<td>Chapter 7 ‘Sit’</td>
<td>0.893</td>
<td>0.88</td>
<td>0.861</td>
<td>0.846</td>
</tr>
<tr>
<td>Chapter 7 ‘Walk’</td>
<td>0.87</td>
<td>0.879</td>
<td>0.846</td>
<td>0.855</td>
</tr>
<tr>
<td>Chapter 7 ‘Walk &amp; Sit’</td>
<td><strong>0.967</strong></td>
<td>0.96</td>
<td><strong>0.955</strong></td>
<td><strong>0.966</strong></td>
</tr>
</tbody>
</table>

Table 28 shows the correlation strength for each comparison discussed in this chapter. The ‘Observed’ column describes the correlations between the observed mean overall discomfort ratings collected during each experiment and the predicted discomfort using the observed number of SFMs for each condition and the regression equation (Equation 8.1) produced using the average data for all 3 experiments between 0 – 60 minutes. The ‘Interpolated Discomfort’ column describes the correlations between the interpolated mean overall discomfort ratings collected during each experiment and the predicted overall discomfort using the observed number of SFMs for each condition and the regression equation (Equation 8.1). The ‘Weighted SFMs’ column describes the correlations between the observed mean overall discomfort ratings collected during each experiment and predicted discomfort ratings from the regression equation (Equation 8.3) produced by the weighted mean number of SFMs (per 10 minutes) using the weighting factors determined in this chapter (Equation 8.2). The ‘Weighted SFMs & Interpolated Discomfort’ column describes correlations between the interpolated mean overall discomfort ratings collected during each experiment and the predicted values of discomfort using the regression equation (Equation 8.4) and the weighted mean number of SFMs (per 10 minutes) using the weighting factors determined in this chapter (Equation 8.2).

Ultimately, the results show that although improvements can be made in terms of correlation strength by performing transformations on the data, the greatest improvements are not consistent with one approach and improvements in
correlation strength are only slight, when compared with the observed data. Importantly each correlation was statistically significant (P < 0.005). This suggests that although improvements in correlation strength can be obtained, no statistical significance is gained by doing so. Therefore, for the purpose of this research it can be concluded that the most appropriate approach is to take the observed data when recording SFMs and suggests that predictions made by the regression equation (Equation 8.1) produced using the average data for all 3 conditions between 0 – 60 minutes will be sufficient in predicting values of overall discomfort that represent both discomfort at the end of the time interval at which they were recorded and as an average of that time interval. As a result of this finding, any further analysis will solely focus on the observed values of overall discomfort and SFM frequency and any predictions will be made using the regression equation for the average observed data of all 3 experiments between 0 – 60 minutes (Equation 8.1). Furthermore, as weighting factors will no longer be applied, the number of SFMs will be described as a total of all 3 types rather than by individual type. This is supported by the findings of the SFM magnitude analysis as no type of movement was deemed to be more important in terms of discomfort reduction and suggests that types can be disregarded when making this correlation.

As the ultimate goal of this research was to provide an objective measure of driver discomfort to predict subjective responses, in order for the method to be considered successful it must be applicable for any individual. It is already been established that a strong positive relationship exists between mean overall discomfort ratings and mean SFM frequency for each sample in this research; however this relationship should be evaluated for each individual. A comparison was made between the individual discomfort ratings recorded during each study and the number of movements recorded that corresponds to that discomfort rating for all participants (Figure 157).
Figure 157 shows that although the mean data recorded during this research show a strong positive relationship, when analysing individual participant data a larger variation is observed, especially at lower levels of discomfort and fewer numbers of SFMs. The data shows that for participants who recorded 3 SFMs over 10 minutes, the equivalent overall discomfort ratings varied between 0 and 60 on the discomfort rating scale. This may be a result of individual differences and how the individual perceived the overall discomfort rating scale but may also be a result of the design of the SFM method.

As discomfort accrues with time, this suggests that the discomfort experienced at any time interval is influenced by the discomfort level perceived at the previous time interval. For example the discomfort rating at 60 minutes represents an accumulation of the discomfort experienced for the whole 60 minutes that preceded it, not just the 10 minutes before. Therefore, it is a possibility that SFM data should also be considered accumulatively as with discomfort. Another comparison was made between the individual discomfort ratings and the accumulative number of SFMs that preceded it (Figure 158).
Figure 158: Individual overall discomfort ratings against the accumulative number of SFMs

As less variation is observed when describing the accumulative number of SFMs, the relationship between accumulative SFMs and overall discomfort must be investigated.

8.3.4 Accumulative SFM Data

In order to assess the relationship between the accumulative SFM data and overall discomfort ratings, this approach was first applied to the average data for all 3 studies between 0 – 60 minutes as described in Figure 133. The observed mean overall discomfort ratings were plotted against the accumulative number of SFMs at each time interval (Figure 159).

A clear positive relationship is observed between mean subjective overall discomfort and accumulative SFMs. As overall discomfort increases, the total number of SFMs accumulated prior to that time interval also increases. This is further supported when plotting overall discomfort against the total accumulative number of SFMs (Figure 160).
Figure 159: Mean overall discomfort ratings and the accumulative number of SFMs over time for all 3 studies

Figure 160: Mean overall discomfort against the accumulative number of SFMs
Regression analysis and Pearson Correlation determined that when comparing mean overall discomfort ratings with the mean total accumulative number of SFMs, a strong positive correlation is observed with an $r$ value of 0.996, 99.3% shared variance and was statistically significant ($r = 0.996$, $n = 6$, $p < 0.05$). This describes an improvement in terms of correlation strength when compared with the correlation between overall discomfort and the number of SFMs (per 10 minutes), or interval SFM frequency.

This approach can then be used to determine the relationship between the mean accumulative number of SFMs and mean overall discomfort ratings recorded for each laboratory study conducted during this research. All of the results collected during Chapter 4 and Chapter 5 will be included. As the study in Chapter 7 included breaks from the driving task, only data collected prior to the breaks will be included. Further research will need to be conducted to determine the effect of breaks on accumulative SFMs during long term driving. As subjective discomfort decreases during breaks from driving, this suggests that the accumulative number of SFMs should also be reduced. However, no data was collected to support this and therefore should be excluded from the analysis until further research has defined the relationship between breaks and total SFM reduction.

Pearson correlations and regression analysis determined that when comparing mean overall discomfort ratings with the mean accumulative number of SFMs, a strong positive correlation is observed for each of the conditions, described by the $r^2$ value for each comparison:

- Chapter 4: $r^2 = 0.874$
- Chapter 5: $r^2 = 0.996$
- Chapter 7 ‘Sit’ 0 - 60: $r^2 = 0.994$
- Chapter 7 ‘Walk’ 0 - 60: $r^2 = 0.962$
- Chapter 7 ‘Walk & Sit’ 0 - 60: $r^2 = 0.967$
Figure 161: Mean overall discomfort ratings and the mean accumulative number of SFMs over time for Chapter 4

Figure 162: Mean overall discomfort ratings against the mean accumulative number of SFMs for Chapter 4
Figure 163: Mean overall discomfort ratings and the mean accumulative number of SFMs over time for Chapter 5

Figure 164: Mean overall discomfort ratings against the mean accumulative number of SFMs for Chapter
Figure 165: Mean overall discomfort ratings and the mean accumulative number of SFMs over time for Chapter 7 'Sit' Condition

Figure 166: Mean overall discomfort ratings against the mean accumulative number of SFMs for Chapter 7 'Sit' Condition
Figure 167: Mean overall discomfort ratings and the mean accumulative number of SFMs over time for Chapter 7 'Walk' Condition

Figure 168: Mean overall discomfort ratings against the mean accumulative number of SFMs for Chapter 7 'Walk' Condition
Figure 169: Mean overall discomfort ratings and the mean accumulative number of SFMs over time for Chapter 7 'Walk Sit' Condition

Figure 170: Mean overall discomfort ratings against the mean accumulative number of SFMs for Chapter 7 'Walk & Sit' Condition
Implementing an approach of accumulating the mean number of SFMs recorded across the duration of each trial has shown a strong positive correlation for each condition. This suggests that this method can be deemed equally as successful as the previous approach of recording the number of SFMs at intervals (per 10 minutes). Therefore another regression analysis was conducted that compared the average data for all 3 studies (Figure 159) to produce the equation:

$$\Psi = 4.285 + 1.433sfm_a$$  \hspace{1cm} (8.5)

Where: $\Psi$ is the rating of overall discomfort and $sfm_a$ is the accumulative number of SFMs.

This equation (Equation 8.5) can then be used to produce predicted values of discomfort for using the accumulative SFM data.

![Observed vs Predicted (a) overall discomfort ratings for all 3 studies](image)

*Figure 171: Observed vs Predicted (a) overall discomfort ratings for all 3 studies*

As the observed and predicted values are shown to be closely related, it is important to test the ability of the equation (Equation 8.5) to predict values of overall discomfort when applied to each of the individual studies.
Figure 172: Observed vs Predicted (a) overall discomfort ratings for Chapter 4

Figure 173: Observed vs Predicted (a) overall discomfort ratings for Chapter 5
Figure 174: Observed vs Predicted (a) overall discomfort ratings for Chapter 7 'Sit' Condition 0 - 60

Figure 175: Observed vs Predicted (a) overall discomfort ratings for Chapter 7 'Walk' Condition 0 - 60
The results show that by applying the accumulative approach and producing predicted values of overall discomfort using the regression equation (Equation 8.5) and the accumulative number of SFMs recorded in each study produces similar results to the observed data. This is described by the correlation strength between the observed and predicted values, discussed previously.

As described by Figure 172, Figure 173, Figure 174, Figure 175 and Figure 176 the predictions made for overall discomfort are successful up until about 60 minutes of driving. This is highlighted by the predicted values of discomfort for Chapter 4 where the predictions made over estimate overall discomfort after an hour of driving. This may be a result of the ceiling effect observed in subjective overall discomfort as time increases. It was determined that the rate of increase in overall discomfort decreases after approximately 80 minutes during the experiment in Chapter 4 and this may be the cause for the differences observed in the predicted and observed discomfort ratings after an hour. Furthermore, as Equation 8.5 was produced using the average data between 0 – 60 minutes for all studies, this may have a negative impact on the ability of the equation to predict overall discomfort ratings for any duration over an hour. Further research will need to be conducted.
with extended driving durations in order to fully understand the effect of durations over an hour on accumulative SFMs as this research only tested 10 individuals for continuous driving over an hour in duration.

It can be concluded that this method can be useful for predicting overall discomfort for up to an hour in duration as a strong positive correlation is observed for all studies during this time interval.

### 8.3.5 Comparison between Interval SFM Analysis and Accumulative SFM Analysis

As both approaches of recording interval SFMs (Number of SFMs per 10 minutes) and accumulative SFMs have shown success in predicting overall discomfort ratings for the mean of the samples recorded during this research it is now important to determine which of the approaches better fits for individuals.

Table 29 and Table 30 describe the correlation strength between the observed overall discomfort ratings and both interval SFM data and accumulative SFM data for each participant in each condition. It is shown that all participants recorded a positive correlation for each comparison; however the strength of the correlation varied. The tables show that when analysing the data for individual participants, the accumulative approach seems more appropriate as this better fits for a larger number of participants. This is determined by the number of participants who recorded $r^2$ values that represent a strong positive correlation. This is described by Figure 177 where the percentage of participants who recorded correlation strengths of greater than 0.3, 0.5, 0.7, 0.8 and 0.9 are shown for both the interval approach and accumulative approach. These $r^2$ values were chosen as they represent different correlation strengths, as such:

- $> 0.3 = \text{weak positive correlation}$
- $> 0.5 = \text{moderate positive correlation}$
- $> 0.7 = \text{fairly strong positive correlation}$
- $> 0.8 = \text{strong positive correlation}$
- $> 0.9 = \text{very strong positive correlation}$
Table 29: Correlation strength for each participant in Chapter 4 and Chapter 5 for interval and accumulative SFMs and overall discomfort

<table>
<thead>
<tr>
<th>Condition</th>
<th>Participant Number</th>
<th>Interval SFMs ($r^2$ value)</th>
<th>Accumulative SFMs ($r^2$ value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.351</td>
<td>0.826</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.382</td>
<td>0.932</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.194</td>
<td>0.789</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.585</td>
<td>0.944</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.620</td>
<td>0.881</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.607</td>
<td>0.949</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.781</td>
<td>0.836</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.074</td>
<td>0.461</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.380</td>
<td>0.777</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.399</td>
<td>0.523</td>
<td></td>
</tr>
<tr>
<td>Chapter 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.400</td>
<td>0.942</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.919</td>
<td>0.985</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.750</td>
<td>0.989</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.713</td>
<td>0.835</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.259</td>
<td>0.996</td>
<td></td>
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<tr>
<td>6</td>
<td>0.017</td>
<td>0.897</td>
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<td>7</td>
<td>0.958</td>
<td>0.888</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.033</td>
<td>0.750</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.910</td>
<td>0.888</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.192</td>
<td>0.968</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.976</td>
<td>0.948</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.749</td>
<td>0.922</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.771</td>
<td>0.986</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.525</td>
<td>0.929</td>
<td></td>
</tr>
</tbody>
</table>
Table 30: Correlation strength for each participant in Chapter 7 for interval and accumulative SFMs and overall discomfort

<table>
<thead>
<tr>
<th>Condition</th>
<th>Participant Number</th>
<th>Interval SFMs ($r^2$ value)</th>
<th>Accumulative SFMs ($r^2$ value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 7</td>
<td>1</td>
<td>0.467</td>
<td>0.920</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.683</td>
<td>0.799</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.389</td>
<td>0.933</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.343</td>
<td>0.982</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.575</td>
<td>0.853</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.580</td>
<td>0.987</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.817</td>
<td>0.982</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.552</td>
<td>0.810</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.801</td>
<td>0.889</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.706</td>
<td>0.957</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>1</td>
<td>0.137</td>
<td>0.956</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.570</td>
<td>0.801</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.382</td>
<td>0.919</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.548</td>
<td>0.979</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.739</td>
<td>0.873</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.234</td>
<td>0.615</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.903</td>
<td>0.885</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.992</td>
<td>0.835</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.671</td>
<td>0.827</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.765</td>
<td>0.981</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>1</td>
<td>0.344</td>
<td>0.943</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.615</td>
<td>0.937</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.432</td>
<td>0.933</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.140</td>
<td>0.987</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.840</td>
<td>0.836</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.499</td>
<td>0.821</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.620</td>
<td>0.960</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.872</td>
<td>0.921</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.660</td>
<td>0.960</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.638</td>
<td>0.967</td>
</tr>
</tbody>
</table>
Ultimately, Figure 177 describes that the accumulative approach better fits for the individual participants with 94.4% of participants recording an $r^2$ value of greater than 0.7 and 55.5% recording an $r^2$ value of greater than 0.9. The discussion in this section has determined that both approaches may be beneficial when evaluating driver SFMs as an average of the population, however the accumulative approach may be a more effective approach when evaluating individual drivers. As these findings have been established only using the data recorded during this research, further work is required to determine which of the approaches is more successful for a larger population than previously tested, however it can be concluded that this research has shown that SFMs can be effective in predicting overall discomfort.

8.4 Relationship between SFMs and Verbal Discomfort Descriptors

The overall aim of this research was to develop an objective measure of overall car seat discomfort that can be implemented into the automotive industry, with the aim of replacing subjective assessment. Therefore, it was vital to understand how SFM data relates to verbal discomfort descriptors. This will allow for the SFM method to be applied independently of subjective assessment and produce tangible descriptions of the overall discomfort this data represents.
As both interval SFM data (Number of SFMs per 10 minutes) and accumulative SFM data have shown to be applicable when predicting overall discomfort ratings, both approaches will be considered and related to verbal descriptions of discomfort. In the previous chapters the regression equations have been used to produce ranges of discomfort, therefore ranges will be developed that represent the average data recorded in this research.

### 8.4.1 Interval SFMs

Using the average data for all 3 studies and the regression equation (Equation 8.1) a table was produced that determines the range of number of SFMs (per min) and overall discomfort rating against the verbal discomfort descriptors. This table was developed by rearranging the regression equation (Equation 8.1), as such:

\[
\begin{align*}
1) \quad \Psi &= -2.201 + (64.2sfm) \\
2) \quad sfm &= \frac{-2.201 - \Psi}{-64.2} \quad (8.6)
\end{align*}
\]

Then, using the boundaries for overall discomfort ratings, ranges for SFM frequency were calculated that relate to the equivalent verbal discomfort descriptor. This can be seen in Table 31.

<table>
<thead>
<tr>
<th>Overall Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No Discomfort at all</td>
</tr>
<tr>
<td>0 – 4</td>
<td>0 – 0.097</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>4 – 10</td>
<td>0.097 – 0.19</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>10 – 17</td>
<td>0.19 – 0.299</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>17 – 23</td>
<td>0.299 – 0.393</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>23 – 28</td>
<td>0.393 – 0.47</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>28 – 33</td>
<td>0.47 – 0.548</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>33 +</td>
<td>0.548 +</td>
<td>High Discomfort</td>
</tr>
</tbody>
</table>

Table 31 provides the basis for discomfort evaluations to be made using SFM analysis independently from subjective evaluation. The table suggests that a driver experiencing ‘Very Little Discomfort’ would record an SFM less than once every 5.2
minutes whereas a driver experiencing ‘Moderate-High Discomfort’ would record an SFM less than roughly once every 2 minutes. There is a need for this method to be tested against new data, however when fitting to the average data collected during this research, the interval SFM method serves to successfully replace subjective ratings of overall discomfort and can be effectively utilised to provide a verbal description of the discomfort experienced by recording drivers’ seat fidgets and movements.

8.4.2 Accumulative SFMs

This process was then repeated to produce ranges for the accumulative SFM data. Using the average data for all 3 studies and the regression equation (Equation 8.5) another table was produced that determines the range of total accumulative number of SFMs and overall discomfort ratings against the verbal discomfort descriptors. This table was produced by rearranging the regression equation (Equation 8.5), as such:

1) \[ \Psi = 4.285 + (1.433sfm_a) \]
2) \[ sfm_a = \frac{(4.285 - \Psi)}{-1.433} \] (8.7)

Then, using the boundaries for overall discomfort ratings, ranges for SFM frequency were calculated that relate to the equivalent verbal discomfort descriptor. This can be seen in Table 32.

<table>
<thead>
<tr>
<th>Overall Discomfort Rating</th>
<th>Total Number of SFMs</th>
<th>Verbal Descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No Discomfort at all</td>
</tr>
<tr>
<td>0 – 4</td>
<td>0 – 0.198</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>4 – 10</td>
<td>0.198 – 3.988</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>10 – 17</td>
<td>3.988 – 8.873</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>17 – 23</td>
<td>8.873 – 13.06</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>23 – 28</td>
<td>13.06 – 16.549</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>28 – 33</td>
<td>16.549 – 20.038</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>33 +</td>
<td>20.830 +</td>
<td>High Discomfort</td>
</tr>
</tbody>
</table>
Table 32 provides the basis for discomfort assessments to be made using SFM analysis independently from subjective evaluation. The table suggests that a driver experiencing ‘Very Little Discomfort’ would record a total of approximately 4 SFMs throughout the duration of driving prior to the evaluation whereas a driver experiencing ‘Moderate-High Discomfort’ would approximately record between 16.5 and 20 SFMs. There is a need for this method to be tested against new data, however when fitting to the average data collected in this research, the accumulative SFM method serves to successfully replace subjective ratings of overall discomfort and can be utilised to provide a verbal description of the discomfort experienced by recording drivers’ seat fidgets and movements.
CHAPTER 9

General Discussion

The overall aim of the thesis was to further the ergonomic understanding and quantification of driver discomfort in long duration driving, specifically focusing on developing and evaluating a novel objective measure to quantify driver discomfort. The results may be used to implement this method into the automotive industry and the findings may have an impact on both current driver discomfort assessment and current vibration standards regarding both subjective and objective discomfort assessment (such as, ISO 2631-1 (1997)). Previous studies have investigated objective measures of discomfort for use in the automotive industry, however these have shown varying levels of success and no specific method has been standardised across the industry due to each possessing their own issues. The approach taken in this thesis was to firstly apply a subjective method of discomfort evaluation which has shown promise in recent studies and then correlate these findings with a novel objective measure of discomfort which focused on driver seat fidgets and movements (SFMs). These measures were assessed through a series of laboratory studies that aimed to evaluate a range of factors that may influence the validity and robustness of the method. This section will discuss the success of this research in meeting the research aims.

9.1 Subjective Driver Discomfort

Subjective driver discomfort was reported in all laboratory studies conducted during this research. Although the primary aim of subjective assessment was to provide a measure with which to correlate the results of the novel objective measure being evaluated, the results of the subjective assessment do provide some useful findings. As one general aim of the thesis was to further the understanding of driver discomfort in long duration driving, the findings of the subjective assessment alone have some implications on the discipline.

The subjective results obtained during this research show that driver discomfort increases with driving duration, supporting much of the literature discussed in
Chapter 2 (Mansfield et al., 2014; Mansfield et al., 2015; Porter et al., 1999). Subjective local and overall discomfort was shown to increase with driving duration in each of the laboratory experiments conducted during this research. Discomfort was shown to increase at a linear rate in all experiments up until approximately 80 minutes of driving supporting the findings of previous research and validating the quantitative model proposed by Mansfield et al. (2014) for predicting driver discomfort. However, in Chapter 4, the rate of subjective discomfort increase was shown to decrease after around 80 minutes of driving and consequently no longer increased at a linear rate. This implies that the model proposed for predicting discomfort (Mansfield et al., 2014) may need to be adapted to cope with the change in rate of discomfort increase observed with extended journey durations (>80 minutes). This also highlights the need for a successful method to accurately predict driver discomfort during long duration driving.

The rate of discomfort increase was also shown to be affected by vibration exposure as discomfort increased at a quicker rate with greater magnitudes of vibration exposure, supporting the literature (Mansfield et al., 2014; Ebe & Griffin, 2000). When subjects were exposed to greater vibration magnitudes as with the study in Chapter 5, a much quicker increase was observed when compared with subjects exposed to lower magnitudes, as with Chapter 4 and Chapter 7. Furthermore, the signal waveform of the vibration may also have an influence on subjective discomfort as shocks have been shown to lead to increased discomfort (Mansfield et al., 2000).

### 9.1.1 Combatting the Effects of Driver Discomfort

Subjective discomfort was also shown to be greatly affected by cessation of vibration exposure and breaks from driving. As one of the areas highlighted by the literature review was to explore how drivers can help combat the effects of discomfort due to long term driving, breaks from driving were investigated. During the experiment in Chapter 7, subjective discomfort was shown to significantly decrease during breaks from long duration driving and prolonged vibration exposure. Driver behaviour during breaks was also shown to influence the effectiveness of the break from driving in reducing subjective discomfort as drivers
who walked for 10 minutes recorded a significantly greater reduction in discomfort than those who sat in the vehicle or sat in another seat.

These findings support the study by Yonekawa et al. (2011) and Ravnik (2011) as discomfort experienced due to prolonged vibration exposure was shown to be reduced to almost zero after a 10 minute walk and break from exposure to vibration. This finding may also have implications on ISO 2631-1 (1997) as the effects of taking breaks from whole-body vibration exposure have not been well documented. If further research can be conducted and the findings can be expressed in the standard, this may have implications on industries outside of normal road driving. Drivers who are exposed to much greater magnitudes of vibration as part of their job are at most risk from the negative effects of vibration exposure (Mansfield, 2005) and may benefit most from breaks from vibration exposure. However, in order for this to be determined, further research will need to be conducted that aims to implement a similar methodology and experimental design whilst using the different seat designs, vibration conditions and drivers associated with the different industries.

Furthermore, the findings may impact the current guidelines for drivers taking breaks when undertaking a long duration drive as discussed in Section 2.6.1. There are multiple campaigns advising drivers to take regular breaks during long duration journeys in addition to the guidelines for commercial vehicle drivers regarding breaks from driving (Horne & Reyner, 1999; Horne & Reyner, 1995). The findings of this research may impact these guidelines as the benefits in terms of discomfort reduction are not well defined. Further research should be conducted that firstly aims to further determine the typical implementation of breaks by drivers undertaking a long term drive and the behaviour of drivers during these breaks to build upon the findings of this research. Furthermore, more research should aim to further establish the benefits of breaks from driving on driver discomfort, especially in industries with high vibration exposure.
9.1.2 Success of the Method

This research implemented a newly developed method of subjective discomfort measurement which had shown promise in a previous study by Mansfield et al. (2015). The subjective method applied consisted of a combination of a local discomfort rating scale (discussed in Section 3.3.6) and an overall discomfort rating scale (discussed in Section 2.2.4) and this approach has been shown to be useful in obtaining reliable discomfort ratings. The method of asking participants to report their local discomfort for 5 different body regions prior to reporting overall discomfort has proved beneficial in priming participants and improving the responses obtained for overall discomfort. Many previous researchers have used a method of totalling individual local discomfort scores to produce one overall rating (Porter et al., 1999; Smith et al., 2015) however, due to the design of the local discomfort rating scales, accurate responses and acute changes in overall discomfort were difficult to obtain.

The method implemented in this research has shown that the use of a separate detailed overall discomfort scale allows for acute changes in discomfort to be easily detected. Some participants recorded increases of as little as 0.5 on the overall discomfort scale which previously would have gone undetected by subjective methods applied in previous research (Gyi & Porter, 1999; Smith et al., 2015). This can be important over long duration driving trials with relatively low magnitudes of vibration exposure, as experienced in high quality non-commercial vehicles, and even more useful when investigating seats with minor design differences.

The use of this approach has resulted in highly repeatable and reliable discomfort ratings. This is shown by the similarities in the results obtained during the first 60 minutes of each condition in the study in Chapter 7. This was discussed previously in Section 7.5.1 and as both mean overall discomfort ratings and the gradient of discomfort increase were shown to be almost identical for all conditions, this implies that this method is highly repeatable. In addition, this claim is further supported when analysing overall discomfort ratings for individual participants. When comparing the discomfort ratings reported by each individual subject for the first 60 minutes of each condition, similarities are observed. Discomfort ratings are
shown to be consistent for the individual when the participant is exposed to the same driving conditions.

The method has also shown its ability to reflect the differences in discomfort when the factors influencing driver discomfort have been altered. When comparing the results collected in the first 60 minutes of the trials in Chapter 4 with those collected in Chapter 5, clear differences are observed in overall discomfort ratings and the rate of increase in discomfort. These differences are observed as a result of drastically altered conditions and show the ability of the method to accurately reflect major differences in the factors affecting overall discomfort. When comparing the results collected in the first 60 minutes of Chapter 4 and the first 60 minutes of Chapter 7, although the differences in overall discomfort ratings observed are small, this is expected due to both studies possessing an almost identical design until this point. Therefore, as the only major difference in the design of the experiments was the design of the seat and packaging dimensions, this suggests that any differences observed in the results can be attributed to the alterations in seat design and packaging dimensions. This implies that the method can be extremely useful when evaluating differences between vehicle seats and supports the study in Mansfield et al. (2015) where the same subjective method was used to accurately determine differences between seat foam types.

Another advantage of implementing this approach was due to the fact that participants did not stop the driving task to provide subjective responses, unlike much of the previous literature (Smith et al., 2015). This allowed for subjective ratings collected to more accurately represent discomfort experienced in long term driving as subjects were not given any opportunity to have a break from the driving task, unless intended. This improved the validity of the results collected and has shown that continuous driving is crucial when conducting long term driving evaluations.

Although not the primary aim of this thesis, the research conducted has made it clear that there are some strong benefits in standardising subjective discomfort evaluation across the automotive industry in addition to standardising objective
discomfort evaluation. There may be some instances in future research where subjective evaluation may be useful and currently, as determined by the literature review, there are a wide range of different subjective methods in place across the industry which negatively affects the discipline (De Looze et al., 2003). The method proposed in this research has shown success and should be considered for researchers aiming to implement a subjective approach.

Moreover, this may have implications on the ISO 2631-1 (1997) standard as there have been issues highlighted with the current method of discomfort evaluation proposed by the standard. As the method proposed in this research has been extremely successful in quantifying subjective discomfort, if discomfort evaluation is to be standardised with the aim of improving the quality of the discipline, this approach should be considered.

9.2 Seat Fidgets and Movements

As the success of the SFM method has already been determined in Chapter 8, this section will discuss the implications of the method and how the method may be implemented into the automotive industry.

9.2.1 Application to ISO 2631-1 (1997)

The findings of this research may have implications on the ISO 2631-1 (1997) standard with regards to comfort evaluation. The current standard proposes a table in Section C.2.3 outlining ranges for vibration magnitudes and the approximate discomfort levels these may evoke from the sitter, as stated in Section 3.3.5.1. One potential impact of this research on the standard is the addition of Seat Fidgets and Movements to this table using the ranges determined in Section 8.4. Two tables have been developed to show how the ranges developed for SFMs may be added to the current comfort reaction to vibration environments table, one focusing on interval SFM evaluation and one focusing on accumulative SFM evaluation (Table 33, Table 34).

It is necessary that more research be conducted to support the methodology developed with a larger population, however based on the findings of this research,
the recommendations made by these tables may provide the basis for development of the standard. Furthermore, the method will need validation in the field, for this to be achieved it will need to be proposed as a new work item (NWI) through ISO technical committee TC108/SC4. In addition to this an update would need to be made to the text in the same section of the standard in order to outline the use of SFM measurement during long term vibration exposure and to clarify the understanding of SFMs.

**Table 33:** Proposed update to ISO table including values for comfort reactions to vibration environments evaluation and SFMs (Interval SFMs)

<table>
<thead>
<tr>
<th>Vibration Magnitude</th>
<th>Discomfort Rating</th>
<th>Number of SFMs (per min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 0.315 m/s²</td>
<td>Not uncomfortable</td>
<td>0</td>
</tr>
<tr>
<td>0.315 m/s² to 0.63 m/s</td>
<td>A little uncomfortable</td>
<td>0 – 0.097</td>
</tr>
<tr>
<td>0.5 m/s to 1 m/s</td>
<td>Fairly uncomfortable</td>
<td>0.097 – 0.19</td>
</tr>
<tr>
<td>0.8 m/s to 1.6 m/s</td>
<td>Uncomfortable</td>
<td>0.19 – 0.393</td>
</tr>
<tr>
<td>1.25 m/s to 2.5 m/s</td>
<td>Very uncomfortable</td>
<td>0.393 – 0.548</td>
</tr>
<tr>
<td>Greater than 2 m/s</td>
<td>Extremely uncomfortable</td>
<td>0.548 +</td>
</tr>
</tbody>
</table>

**Table 34:** Proposed update to ISO table including values for comfort reactions to vibration environments evaluation and SFMs (Accumulative SFMs)

<table>
<thead>
<tr>
<th>Vibration Magnitude</th>
<th>Discomfort Rating</th>
<th>Number of SFMs (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 0.315 m/s²</td>
<td>Not uncomfortable</td>
<td>0</td>
</tr>
<tr>
<td>0.315 m/s² to 0.63 m/s</td>
<td>A little uncomfortable</td>
<td>0 – 0.198</td>
</tr>
<tr>
<td>0.5 m/s to 1 m/s</td>
<td>Fairly uncomfortable</td>
<td>0.198 – 3.988</td>
</tr>
<tr>
<td>0.8 m/s to 1.6 m/s</td>
<td>Uncomfortable</td>
<td>3.988 – 13.06</td>
</tr>
<tr>
<td>1.25 m/s to 2.5 m/s</td>
<td>Very uncomfortable</td>
<td>13.06 – 20.038</td>
</tr>
<tr>
<td>Greater than 2 m/s</td>
<td>Extremely uncomfortable</td>
<td>20.830 +</td>
</tr>
</tbody>
</table>

**9.2.2 Training Form for Reporting SFMs**

A training form was developed that describes the process for recording driver SFMs and provides the basis for this method to be implemented in further research. The aim of the training form is to standardise the collection of SFMs and provide a detailed procedure for researchers wishing to implement the same approach. The guidelines presented are representative of the data recorded in this research and
will need to be validated against a larger population. This training form can be found in Appendix A5.

**9.2.3 Implementing a Technological Approach**

One of the major issues with the methodology is that although the method is designed to provide an objective measure of driver discomfort, there is still an aspect of subjective evaluation required when implementing the SFM approach. This is due to the fact that when recording SFM data, the experimenter is required to record driver SFMs via video analysis. Therefore, although the recording of SFMs was aimed to be standardised via the development of the SFM training form there may be some individual perceptions about what qualifies as an SFM when the experimenter recording SFMs varies.

This factor was controlled during this research as only one experimenter was responsible for reporting SFMs and recorded SFMs using a strict set of guidelines as to which movements qualify as an SFM. Therefore any individual differences in perception of SFMs were removed, however if the method is to be tested in further research and implemented across the automotive industry a technological approach may be necessary in addition to the training form developed previously.

One type of technology that has seen a vast increase in its use in the field of ergonomics is motion capture equipment and software. There are a range of systems currently available that range from ‘Active Infrared’ systems and ‘Passive Infrared’ systems to accelerometers and ‘Inertia Systems’. Systems such as ‘CODA Motion’ have been implemented across many different industries to measure varying parameters and the implementation of a similar system could be useful in developing this method of discomfort evaluation. The use of CODA Motion in measuring SFMs was trialled at Loughborough University, UK, following the findings of this research and a pilot consisting of one participant was conducted using the same laboratory set up as implemented in Chapter 4 and Chapter 5.

It was shown that CODA Motion can be useful in replacing the human being when recording SFMs. The system was able to detect driver movements and record the time of each movement, therefore successfully performing the job of the
experimenter. Furthermore, the system was able to provide a measure of amplitude for each individual movement, removing the need for SFM types and providing the opportunity for the effect of driving duration on SFM magnitude/amplitude to be investigated further. Each individual movement was therefore recorded with a time and distance travelled, allowing further research to report both SFM frequency and SFM magnitude regardless of SFM type, as the system would be able to determine differences between a large Type 3 movement, in terms of distance travelled, with a small Type 3 movement.

Another major benefit of implementing a motion capture system (such as CODA Motion) is that this would act as a major time saving tool when measuring SFMs. One issue associated with the method is that analysing video recordings to record SFM data is extremely time consuming. The development of a motion capture system would allow the process for measuring SFMs to be almost completely autonomous and measured in real-time. As the method has been shown to accurately predict subjective discomfort ratings, there is the possibility that, if a motion capture system could be developed to record SFMs whilst a subject is driving, there will be no need for any interaction between the experimenter and the subject during the drive. Furthermore the subjects’ SFM data would be almost immediately accessible upon completion of the trial.

The main issue highlighted in the testing of CODA Motion as a method to measure SFMs was that the system would need to be developed in order to accurately distinguish between SFMs and movements related with the driving task. This is perhaps one area in which human analysis of video data was useful as the experimenter was quickly able to differentiate between movements related to the driving task and movements associated with discomfort, or SFMs. Any successful approach that implements the use of technology will need to establish a method whereby the equipment used can also quickly distinguish between these movements. During the pilot testing of CODA Motion some programming of the software showed promise in performing this task however more work will need to be conducted in order to develop a technological system that possesses the ability to perform this task autonomously. This issue is also apparent due to the dynamic
environment of the vehicle. The vibration exposed to the driver may result in a level of ‘noise’ affecting the recording of movements when using motion capture equipment. Therefore, any method must also possess the ability to filter the noise produced by vibration exposure whilst still detecting low magnitude SFMs. One potential method to eliminate this factor would be to also measure the movement of the seat. The movement of the seat can then be used to distinguish between movements produced by the dynamic environment of the vehicle and driver movements.

Ultimately, although more work is needed to develop and evaluate an autonomous real-time system, there are some promising findings and advanced equipment available that possesses the ability to cope with the potential difficulties highlighted with implementing such a system. A range of equipment will need to be tested in order to find a suitable system that can be used in both laboratory and field trials with minimal invasiveness on subjects being tested. However, if a successful method can be developed the possibilities for the SFM method to be implemented across the industry are promising. There is the possibility for multiple driver discomfort assessments to be made congruently, autonomously, in real time, in any environment or vehicle.

9.2.4 Influence on Automotive Seating Design

Although the focus of this research was to develop an objective measure that can successfully determine the success of a seat design in terms of discomfort, another aim was to further the understanding of discomfort in long term driving and the findings may have some implications on future seat design, with the aim of minimising driver discomfort. It has been determined that driver movements increase in frequency as drivers become more uncomfortable. Some previous investigators have suggested that this is due to the fact that drivers will use fidgets and movements as a method of relieving some of the discomfort they are experiencing (Adler, 2007). The theory is that as drivers are placed in static postures for long periods of time, the muscles in the lower back are forced to maintain static contractions to support the upper body’s centre of mass during driving (Reed et al., 1991). These prolonged contractions have been shown to decrease muscle
oxygenation (McGill et al., 2000) and increase muscular fatigue (Jorgensen et al., 1988). Decreased muscle oxygenation is thought to facilitate the development of localised ischemia, allowing metabolites and blood pH to pool locally, resulting in discomfort and pain in the lumbar region (Morgan, 2011). It is also thought that as the lower back muscles fatigue during long term driving, they also lose their ability to maintain the demand resulting from the upright position (Reed et al., 1991), allowing the spine to be placed in a more flexed posture as driving time increases. This in turn will cause discomfort and pain in the passive tissues in the lower back (McGill & Brown, 1992). Furthermore, compression of body parts due to the contact with the seat may result in reduced blood flow to these areas (Hermann & Bubb, 2007, Odell, 1978). The insufficient blood flow, decreased blood oxygenation and discomfort experienced will eventually reach a detection threshold (Figure 70) and urge the sitter to change position to restore normal or at least an improved state, highlighted by the occurrence of an SFM.

If a seat can be designed whereby the seat actively produces SFMs for the user by altering the posture of the user there is the possibility that drivers will never reach this detection threshold and therefore be less aware of any discomfort. Previous research has already proven that changing driver posture regularly may extend the amount of time drivers can safely remain seated without damaging tissues or becoming uncomfortable (Cooper et al., 2000) and that sitting should be dynamic (Reynolds, 1993). When vehicle ergonomists are asked, “What is the most comfortable posture?” by seat designers, the best possible answer to this question is “The next one” (Mansfield, 2005) as it is natural to continually change postures to use and rest alternative muscle groups. Callaghan & McGill (2001) proposed that there is no single ideal seated posture as a variable posture is the best strategy to minimise muscle tissue overload as it has also been shown that with prolonged sitting, a constant change in posture is necessary (Ravnik et al., 2008).

These findings suggest that active motion produced by the seat may aid in minimising the discomfort perceived by drivers. This theory has been tested in a small number of studies where micro adjustments of the lumbar posture were shown to reduce the prevalence of lower back pain and improve seating comfort.
(Kolich & Taboun, 2002; Reinecke et al., 1994) and changes in seat back angle were successfully shown to reduce long-term discomfort in pilots (Lapa et al., 2000) and drivers (Adler, 2007). Furthermore, in similar studies, small rotations of the seat pan were implemented and were shown to reduce spinal shrinkage and discomfort (Van Deursen et al., 1999; Van Deursen et al., 2000). If SFM measurement data can be used to further the understanding of driver behaviour and accurately predict movement patterns, these findings may be invaluable when designing seats that produce active motion for drivers. If a seat can be designed whereby the seat can monitor and imitate the driver’s SFM patterns, this seat may be successful in reducing the discomfort associated with long-term driving.

9.3 Limitations and Recommendations for Future Research

A number of limitations associated with the studies conducted during this research have been discussed throughout the thesis. Furthermore, a range of recommendations have been made for areas to be considered for future work. The general limitations and recommendations will be briefly summarised in this section. Areas for future work that are suggested during this thesis include further determining:

- The success of the SFM method and associated training form with a larger population and over longer journey durations
- Which of the SFM approaches outlined in this thesis is more applicable with a larger population and over longer journey durations
- The effect of driving duration on SFM magnitude
- The success of the SFM method when implemented into other industries
- How drivers implement breaks during a long duration drive and typical behaviour during breaks
- The effect of breaks from driving on driver SFMs

Two key limitations and areas to be considered when conducting further research will now be discussed in more detail.
9.3.1 Context
The research conducted in this thesis investigated only one environmental context, normal road driving in vehicles with a traditional seat design. However, there are many other environments in which people are exposed to long duration sitting and exposure to whole-body vibration. These environments include vehicles where occupants are exposed to much greater magnitudes of vibration, such as heavy goods vehicles and construction vehicles. Within the time frame of this research, investigating such environments was not feasible however some of the findings of this research may be of benefit to other industries and environments outside of the automotive industry. Expanding the findings of this research to include air travel, rail travel and sea travel may be of benefit in addition to vehicle environments with high vibration exposure.

The method of evaluating SFMs may provide a useful comfort evaluation tool for other industries; however this will need to be tested in further work. Furthermore, the findings regarding driver discomfort in long duration driving may have an impact on other industries, especially relating to the effect of breaks on reducing discomfort. Drivers exposed to high magnitudes of vibration for long durations, as with the construction industry, may be at more risk of discomfort and health effects associated with long term vibration exposure and the findings of Chapter 7 should be tested in such environments.

9.3.2 Sampling
During the laboratory studies, the participants primarily consisted of students and staff associated with the two universities. This was largely due restrictions associated with time constraints. Furthermore, although each study aimed to include a range of anthropometry, a wide range was difficult to achieve within the timeframe of this research. Therefore, a greater number of participants need to be tested to ensure that the findings of this research are a true representation of a larger population and a wider range of anthropometry and ages should be tested.
CHAPTER 10

General Conclusions

The research presented in this thesis was designed to enhance the knowledge regarding three key aspects of driver discomfort in long duration driving that had not previously been determined, with varying levels of importance. The first aim was to further determine the effects of long duration driving on driver discomfort with specific regards to extended duration vibration exposure. The second and most important aim was to develop and evaluate a novel objective measure of driver discomfort that can be implemented into the automotive industry, with the view of standardising automotive seating evaluations and replacing subjective assessment. The final aim was to determine how the negative effects of long term driving and vibration exposure can be combatted by the driver, as there becomes a point where improvements in seat design are no longer effective in reducing driver discomfort.

Sitting in one posture with exposure to vibration for an extended duration will result in increases in discomfort regardless of how well the seat has been designed. This was addressed by investigating breaks from driving during a long duration journey and how driver activity during breaks can help manage a driver’s overall discomfort level. The findings of this research will be concluded with regards to the overall aims of the thesis.

*Determine the effects of long duration driving on driver discomfort and gain a greater understanding of the dynamic and temporal factors surrounding long term driver discomfort.*

The results of each laboratory experiment showed that driver discomfort significantly increased with driving duration. All subjects recorded an increase in discomfort upon completing a long duration drive and distinct similarities were observed between the subjective responses recorded for overall discomfort and local discomfort. Discomfort was shown to increase at a linear rate for all studies during the first hour of driving, supporting the findings of previous research (Mansfield et al., 2014; Mansfield et al., 2015) however the rate of discomfort
increase was shown to decrease with continuous driving that exceeded an hour in duration. Temporal factors associated with long term driving have been shown to be crucial when evaluating driver discomfort and when designing a seat, long term discomfort must be considered.

The rate of discomfort increase was shown to be influenced by the factors affecting driver discomfort, with specific regards to dynamic factors and dynamic fatigue factors associated with whole-body vibration exposure. When the factors affecting driver discomfort were altered, this in turn altered the rate of increase in driver discomfort. When vibration exposure was increased, as with the study in Chapter 5, in the form of greater vibration magnitude and a different waveform signal that included shocks, the rate of discomfort increase was shown to be significantly increased. This supports the previous literature investigating the effects of vibration exposure on driver discomfort and ultimately shows that the long term effects of vibration exposure are crucial in fully understanding driver discomfort. Furthermore, the effect of varying seat designs and vehicle packaging dimensions were also determined.

*Investigate a novel objective measure of discomfort to be implemented into the automotive industry and determine the success of this method in accurately predicting drivers’ perceived discomfort.*

A novel objective measure of driver discomfort in the form of driver seat fidgets and movements (SFM) was developed and evaluated in each of the laboratory experiments conducted as part of this research. Objective discomfort was shown to be closely related with subjective ratings of discomfort as similar increases were observed with driving duration.

SFM frequency was shown to increase with driving duration in all experiments as participants recorded significantly more SFMs towards the end of a long duration drive when compared with the beginning of a long term drive. A model was proposed that aimed to describe the effect of long term driving on SFM frequency and suggested that drivers will record SFMs when discomfort reaches a detection threshold that is consciously or unconsciously perceived. As driving duration
increases, drivers will reach this detection threshold with increased frequency as drivers aim to manage discomfort associated with long term driving and vibration exposure by moving in the vehicle seat.

The relationship between SFM magnitude and driving duration should be further investigated as no correlation was observed during this research. The design of the SFM method may need to be adapted in order to more accurately determine changes in movement magnitude with extended driving durations, as proposed by previous research (Adler, 2007).

Ultimately, the results of each laboratory study have shown that a measure of driver SFMs can be effectively implemented and used to predict overall driver discomfort in a range of driving conditions. A strong positive correlation was observed between subjective ratings of discomfort and predicted values of discomfort for each laboratory experiment and when analysing the sample as a whole. The method for recording SFMs and predicting values of discomfort based on SFM assessment has been defined using both an interval approach and an accumulative approach providing the basis for driver discomfort assessments to be made via remote monitoring of SFMs. SFM assessment has been shown to accurately reflect acute changes in driver discomfort due to changes in the factors affecting driver discomfort as a range of conditions were investigated and validated with varying samples. There is need for future research to further validate the findings of this research with a larger sample and with greatly extended driving durations, however the results of the objective measure presented in this research have been shown to successfully replicate subjective driver discomfort evaluation.

To determine how driver behaviour can influence driver discomfort and how implementing the correct behaviour during a long duration drive can help combat the effects of discomfort associated with long duration driving.

The effects of breaks from driving during a long duration journey were investigated as a method to combat the discomfort associated with long duration driving and vibration exposure. Discomfort was shown to decrease during a break from a long term drive and was immediately measureable. Decreases in discomfort were
observed across the duration of the breaks from long term driving and suggests that a longer break is more beneficial in terms of comfort reduction than a shorter break. All participants recorded significant decreases in discomfort after a break from driving and the positive implications of a break from driving were further observed upon the completion of a long duration drive. This may have implications on the current guidelines available to drivers regarding taking breaks during a long term drive and the current vibration standards where the effects of cessation of vibration on discomfort have not been well defined.

The type of activity undertaken during a break from a long term drive was also shown to have a large influence on the effectiveness of the break in reducing driver discomfort, both during the break and at the end of a long term journey. Drivers who leave the vehicle will benefit significantly in terms of discomfort reduction when compared to drivers who remain seated in the vehicle seat. Furthermore, drivers are recommended to stop and take a walk rather than sit in another seat when taking a break from long term driving and whole-body vibration exposure as it was shown that discomfort is ‘reset’ with a 10 minute walk. These findings should be further investigated but there is the possibility that breaks from driving may be of most benefit to drivers in environments with high vibration exposure. Ultimately, drivers will continue to increase the frequency of movements in the vehicle seat until levels of discomfort reach a threshold whereby a break from driving is necessary. A 10 minute walk during a break from driving can be considered the ultimate SFM, serving to best combat the negative effects of long duration driving.


THE EFFECT OF LONG TERM DRIVING ON DRIVER DISCOMFORT, WITH EXPOSURE TO VIBRATION

George Sammonds
Loughborough University
Loughborough
Leicestershire
LE11 3TU
G.Sammonds@lboro.ac.uk
01509 228485
07779042181

Prof. Neil Mansfield
Loughborough University
Loughborough
Leicestershire
LE11 3TU
N.J.Mansfield@lboro.ac.uk

What is the purpose of the study?

The purpose of the study is to investigate the extent to which long term exposure to vibration can effect on long term car seat discomfort. To improve driver comfort it is important to understand how comfort changes over an extended period of driving. By carrying out this study we hope to gain a greater understanding of how driver discomfort is affected by exposure time.

Who is doing this research and why?

The study is a student research project funded by Loughborough University. The research has been commissioned by Bridgestone to develop knowledge of driver discomfort. The student conducting the research is George Sammonds under the supervision of Prof. Neil Mansfield.
SUBJECTIVE AND OBJECTIVE MEASURES OF HUMAN RESPONSE TO WHOLE-BODY VIBRATION

Thank you for agreeing to participate in this experiment investigating subjective rating of whole-body vibration.

The experiment will proceed as follows:

1. Paperwork You will need to complete a health screening questionnaire so that we can be sure that you are healthy, and a consent form that confirms that you give your consent to participate in the experiment and that you understand these instructions.

2. Set-up You will be required to sit on the shaker seat and have your posture adjusted and lap-strap fitted. When the area surrounding the simulator is clear of personnel, the simulator will be started and will rise approximately 15 cm to its central position. You will then have an opportunity to experience some of the vibration stimuli that you will be exposed to in the main experiment and to practise giving subjective ratings. This will also allow the experimenter to fine-tune the system for you. When you and the experimenter are confident that you know what to do, the experiment will begin.

3. Experiment You will be exposed to 140mins of vibration stimuli. This will be no different to the magnitude of vibration experienced during real road driving. You will be asked to perform tasks on the driving simulator whilst exposed to vibration and asked to provide some subjective feedback regarding your experience. The vibration will continue throughout the 140mins and will be maintained at a constant level.

4. Dismount After the experiment the seat will lower about 15 cm back to the resting position. IMPORTANT: you may not leave the seat or release the lap strap until told that it is safe to do so by the experimenter – the system remains pressurised for some time after any sounds coming from the pump have stopped.

5. Debrief When the experiment is over you can ask any more questions that you might have or make comments about your experiences. You may then leave.

You are free to withdraw from the experiment at any time. If you decide to withdraw then please inform the experimenter who will stop the equipment and you can follow the dismount procedure and leave. You do not need to give a reason for withdrawal. Do not climb off the apparatus until told that it is safe to do so by the experimenter.

If you have any questions then ask the experimenter now.
# HEALTH SCREEN FOR STUDY VOLUNTEERS

**Name or Number ..........................**

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present**, do you have any health problem for which you are:
   - (a) on medication, prescribed or otherwise .......................... Yes [ ] No [ ]
   - (b) attending your general practitioner .............................. Yes [ ] No [ ]
   - (c) on a hospital waiting list ........................................ Yes [ ] No [ ]

2. **In the past two years**, have you had any illness which require you to:
   - (a) consult your GP .................................................. Yes [ ] No [ ]
   - (b) attend a hospital outpatient department ....................... Yes [ ] No [ ]
   - (c) be admitted to hospital ........................................ Yes [ ] No [ ]

3. **Have you ever** had any of the following:
   - (a) Convulsions/epilepsy ............................................ Yes [ ] No [ ]
   - (b) Asthma or respiratory disease ................................. Yes [ ] No [ ]
   - (c) Diabetes ............................................................ Yes [ ] No [ ]
   - (d) Head injury .......................................................... Yes [ ] No [ ]
   - (e) Digestive problems or disease of gastro-intestinal tract ........................................ Yes [ ] No [ ]
   - (f) Disease of genito-urinary system .............................. Yes [ ] No [ ]
   - (g) Heart problems or disease of cardiovascular system  ... Yes [ ] No [ ]
   - (h) Problems with bones or joints ................................. Yes [ ] No [ ]
   - (i) Disturbance of balance/coordination .......................... Yes [ ] No [ ]
   - (j) Disturbance of vision or retinal detachment .......... Yes [ ] No [ ]
   - (k) Kidney or liver problems ....................................... Yes [ ] No [ ]
   - (l) Back pain ............................................................ Yes [ ] No [ ]

4. **Do you** use any prosthetic device (not including dentures, external hearing aids, spectacles and contact lenses)
   Yes [ ] No [ ]

If YES to any question, please describe briefly if you wish (e.g. to confirm problem was/is short-lived, insignificant or well controlled.)

............................................................................................................................
..................................................................................................................
Continued…

Additional questions for female participants

(a) Could you be pregnant? ......................................... Yes ☐ No ☐

Thank you for your cooperation!

Guidance for experimenter (from ISO 13090-1):

Medical contra-indications to participation in experiments involving whole-body mechanical vibration and repeated shock

General
It is accepted that any person suffering from a disease process or pathology likely to be aggravated by mechanical vibration and shock exposure or emergency stop acceleration should not be an experimental subject. If the experimenter is uncertain that the well-being of a potential test subject with a particular medical or surgical disability or disorder will not be impaired by a particular mechanical vibration and shock exposure or emergency stop acceleration, then the opinion of an experienced medical practitioner should be sought.

Mental health
The subject should be of sound mind and understanding and not suffering from any mental disorder that would raise doubt that his/her consent could not be relied upon as being a true and informed consent.

Recent trauma and surgical procedures
Persons who have recently had surgical operations or suffered traumatic lesions (e.g. fractures) and are still under medical supervision should not act as test subjects. The period for which such persons should not be exposed to mechanical vibration and shock depends on many factors and, in certain cases, their medical history may exclude them from any further participation in experiments involving such exposure. The opinion of the person’s surgeon or medical adviser should be sought if there is any doubt about his/her suitability as a test subject.

Prostheses
The presence of an internal or external prosthesis usually renders the person unsuitable as a test subject, although dentures, external hearing aids, spectacles and contact lenses should not preclude participation.

Specific disorders
Persons with any of the following conditions may be unsuitable as test subjects:

a) active disease of the respiratory system, in particular a recent history of haemoptysis (coughing up blood) or chest pain;
   b) active disease of the gastro-intestinal tract, in particular the presence of an internal (e.g. hiatus) or external (e.g. inguinal) hernia, peptic ulceration, recent history of gall bladder disease, rectal prolapse, anal fissure, haemorrhoids or pilonidal sinus;
   c) active disease of a genito-urinary system, in particular renal calculi (stones), urinary incontinence or retention, or difficulty in micturition (passing urine), female genital prolapse and other uterine disorders (e.g. large fibroids);
   d) active disease of the cardiovascular system, in particular hypertension requiring treatment, angina of effort, valvular disease of the heart, or blood abnormality with prolongation of bleeding time (e.g. haemophilia);
   e) active disease or defect of the musculo-skeletal system, in particular degenerative or inflammatory disease of the spine, long bones or major joints, or a history of repeated injury with minor trauma;
   f) active or chronic disease or disorder of the nervous system, including organs of special sense (the eye and the ear), in particular, any disorder involving impairment of motor controls of the limbs or head, wasting of muscles, epilepsy and retinal detachment.

Pregnancy
Only such women who are sure that they are not pregnant should participate as subjects in mechanical vibration or shock experiments.
MOTION SICKNESS SUSCPTABILITY QUESTIONNAIRE FOR STUDY VOLUNTEERS

Name or Number ..........................  

1. Please state your Age: ............ Years.

2. Please state your Sex:  
   Male [ 1 ]  
   Female [ 2 ]  

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

3. As a CHILD (before age 12), how often you felt Sick or Nauseated (tick boxes):

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Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

4. Over the LAST 10 YEARS, how often you felt Sick or Nauseated (tick boxes):

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SUBJECTIVE AND OBJECTIVE MEASURES OF HUMAN RESPONSE TO WHOLE-BODY VIBRATION

INFORMED CONSENT FORM
(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence.

I agree to participate in this study.

Your name

__________________________________________

Your signature

__________________________________________

Signature of investigator

__________________________________________

Date

__________________________________________
Appendix A2

Informed Consent Form (Japan Laboratory Study)

自動車の安全性・快適性に関する技術開発
に係る実験についての説明と参加へのお願い

近畿大学工学部機械工学科
計測制御工学研究室 櫻野 泰也

このたびは、「自動車の安全性・快適性に関する技術開発」の実験への参加を御検討頂き、誠にありがとうございます。

標記のように、この研究グループでは、安全・快適な車両作りのために、さまざまなメカと車両と車両を共用で研究を実施しており、今回お願いしている実験がその一つです。

今回の実験の目的は、人間の知覚能力を調査する実験です。場合によっては、乗り物に乗ったときと類似した体験をします。その為、疲れを感じたり、乗り物酔い症状（吐き気、眩暈など）がでたり、身体の不調を感じることがあるかもしれませんが、最終的に実験への参加に同意するかしないかは、自由意志で決めて頂きます。また、実験参加に同意して頂いた後でも、理由の如何を問わず辞退することも可能です。実験で得られたデータは、被験者属性（性別、年齢、身長、職業歴、利き腕など）とともに記録・保存させていただきますが、実験結果は個人が特定されないように致します。実験終了後、データを取り下げるいただくことも可能です。実験について最終的にとりまとめた結果についても、請求があれば、原則として公開いたします。

以上のことから本実験について何かお知りになりたいことやご心配な点がございましたら、遠慮なく申し出下さい。

λ = 0.1495
μ = 0.0326
θ = 0.4864

連絡先：近畿大学工学部機械工学科
計測制御工学研究室 櫻野 泰也
〒739-2116 広島県東広島市高屋うめの辺1番
e-mail tatsu@hiro.kindai.ac.jp
TEL 082-434-7000（代表） 内線 838
FAX 082-434-7890

実験参加同意書

私は、本実験への参加に先立ち、上記文書と口頭により実験に関する説明を受け、その内容を理解したので、自らの自由意志により本実験への参加に同意します。

平成 29年 2月 21日

実験参加者氏名：（名前）
実験者

（ここには実験者が記入します）

360
To whom it may concern,

This letter is in the possession of Mr George Sammonds, Postgraduate Researcher at Loughborough Design School and is to certify that the holder is undertaking a research project on behalf of Loughborough University.

The research being conducted is discrete observation of drivers during breaks from driving in order to gain a greater understanding of behaviour during breaks.

No personal information will be recorded regarding the people observed and all research practice is being carried out under ethical guidance of Loughborough University.

If you require any further information please contact me via:

Email: n.j.mansfield@lboro.ac.uk
Tel: +44 (0)1509 228483

Yours Faithfully,

Professor Neil Mansfield
## Appendix A4

### Data Collection Sheet (Chapter 6)

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</tbody>
</table>
SFM Training Form

Driver Seat Fidgets & Movements (SFMs): Part 1

**Type 1 Movements**

Defined as:
- Any movement of the limbs not related to the driving task

Excluding:
- Transition from two hands to one on the steering wheel, and vice versa.
- Any scratching/itching of the head and body.

**Type 2 Movements**

Defined as:
- Any movement of the torso not related to the driving task

Excluding:
- Leaning to obtain a better view (i.e., at a junction with impaired view)
- Reaching secondary controls (i.e., radio)

**Type 3 Movements**

Defined as:
- Any movement of the whole body not related to the driving task

Excluding:
- Reaching secondary controls (i.e., radio)

Recording Details:
- All movement types should be recorded during SFM evaluation
- Images above describe body areas and typical movement patterns
- SFMs can occur in any directional axis (Forward, Lateral, Vertical, Roll, Pitch, Yaw)
- The time of each SFM should be recorded
- The type of each SFM should be recorded
Driver Seat Fidgets & Movements (SFM)/s: Part 2

**Recording**

<table>
<thead>
<tr>
<th>Time Interval (Minutes)</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Interval Total</th>
<th>Accumulative Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
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<td>110 - 120</td>
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</tr>
</tbody>
</table>

Typical SFM recording sheet

**Analysis**

**Interval:** The number of SFMs should be counted per 30 minutes and divided to represent SFMs/min.

<table>
<thead>
<tr>
<th>SFMs/min</th>
<th>Discomfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Discomfort at all</td>
</tr>
<tr>
<td>0 - 0.097</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>0.097 - 0.19</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>0.19 - 0.299</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>0.299 - 0.393</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>0.393 - 0.47</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>0.47 - 0.548</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>0.548 +</td>
<td>High Discomfort</td>
</tr>
</tbody>
</table>

**Accumulative:** The total number of SFMs should be counted for the whole duration of driving.

<table>
<thead>
<tr>
<th>Total SFMs</th>
<th>Discomfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No Discomfort at all</td>
</tr>
<tr>
<td>0 - 0.198</td>
<td>Just Noticeable Discomfort</td>
</tr>
<tr>
<td>0.198 - 5.986</td>
<td>Very Little Discomfort</td>
</tr>
<tr>
<td>5.986 - 5.075</td>
<td>Little Discomfort</td>
</tr>
<tr>
<td>5.075 - 13.06</td>
<td>Little-Moderate Discomfort</td>
</tr>
<tr>
<td>13.06 - 16.549</td>
<td>Moderate Discomfort</td>
</tr>
<tr>
<td>16.549 - 20.038</td>
<td>Moderate-High Discomfort</td>
</tr>
<tr>
<td>20.038 +</td>
<td>High Discomfort</td>
</tr>
</tbody>
</table>

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