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Innovation Report

**Understanding and Managing Motion Sickness in Future
Vehicles**

by
Joseph Smyth

30th September 2019

This work is submitted in partial fulfilment of the requirements for the degree of Doctor of Engineering

Abstract

Almost everyone is susceptible to motion sickness, and around one in three people are known to be highly susceptible. It has been argued that the use of automated vehicles will increase motion sickness severity and onset frequency for those who already regularly suffer from it, as well as for those who are susceptible, but don't regularly get motion sick in traditional vehicles. This is primarily due to the engagement with non-driving activities which cause sensory conflict, the relinquishing of control which prevents apprehension of current and upcoming motion, and the limited ability to self-mitigate due to potential vehicle designs and the inability to take control of the dynamic driving task in a fully automated vehicle. This research first contextualised the relationship between motion sickness and future automotive technologies – covering both research focused driving simulators as well as 'real-world' use cases for on-road partially to fully automated vehicles. A framework for future research was developed and three core projects were established, positioned to cover the breadth of the field. Following this framework, the first project explored the impact of motion sickness on human performance, this was followed by the development of a method of reducing susceptibility to motion sickness and finally, objective measurements of motion sickness were explored.

Motion sickness is a consideration for not only the day-to-day utility of future automated vehicles, but also within the development and simulator-based testing of such technology. Despite the myriad benefits of driving simulators for developing future technology, one significant side effect is simulator-induced motion sickness or 'simulation sickness'. The first project, using both simulator-based and real-world experimentation, explored the effect of motion sickness on human performance – informing our understanding about transferability of simulator data to 'real-world' as well as providing insights into the relationship between motion sickness and productivity for future vehicles.

The second research project proposes, develops, tests and validates a novel method of reducing motion sickness susceptibility by way of specific visual-cognitive training activities. Experimentation began using a high fidelity driving simulator where it was first shown how it is possible to increase visuospatial skills through a novel assimilation and application of a pen-and-paper training pack. Subsequently, this increased visuospatial skill reduced both subjective simulator sickness by 58%, and dropouts due to severe motion sickness by 60%. This simulator-based study was followed up with an on-road study where the visuospatial training pack was further validated for 'real-world' utility and was shown to be responsible for a reduction in motion sickness by 52% across the experimental group. Further to the core findings presented, an industry-focused workshop identified ways in which this new knowledge can be exploited for consumer-focused utility. This research also contributes to the fundamental understanding of the relationship between visuospatial ability and motion sickness susceptibility.

Through extensive simulator-based and on-road motion sickness experimentation, the third research project pulls together physiological and subjective motion sickness data to explore concepts for objectively measuring and detecting motion sickness in real-time. Building upon literature from both motion sickness and machine learning fields, a wide range of data types, from demographics, to vehicle conditions, to occupant activity and route design are highlighted to be potentially useful in future objective motion sickness studies. Based on these sources of data, and many more, a new model is proposed through which motion sickness related data can be collected to aid in the objective measurement of motion sickness.

The research conducted here provides a novel contribution in understanding motion sickness related human performance degradation and provides an interesting discussion about the impact this may have for both simulator trials, and automated vehicle utility. Through the design and validation of a novel training tool for reducing motion sickness susceptibility (in simulators and 'real-world') this research adds to the knowledge about our fundamental understanding of motion sickness and provides an innovative solution to address the issue of motion sickness. Further contributions are found within the research looking at objective measurements of motion sickness and among other various design recommendations.

Declaration

I declare that the work contained in this submission is my own, unless otherwise acknowledged.

A handwritten signature in black ink, appearing to read 'J Smyth' with a stylized flourish at the end.

Joseph Smyth



Acknowledgements

I would like to thank my academic supervisors Professor Stewart Birrell and Professor Paul Jennings for their support, guidance and mentorship throughout this EngD. Both supervisors provided invaluable support throughout the entire four-year project and through their unique expertise and commitment to mentorship, I was given all the tools needed to create a successful EngD project. I would also like to thank my WMG and University of Warwick colleagues who have offered support at various stages throughout this project. Over this project I have run a series of experiments and user trials, so I am also greatly appreciative of all those who took part in my experiments and volunteered themselves as participants for my trials. Further support was given by my close family including that of my parents and Rebecca, without whom this may not have been possible. Finally, I am very grateful for the financial and project support given by the sponsoring company of this EngD - Jaguar Land Rover.

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Glossary of Terms

ADAS	Advanced Driver Assistance System
ANOVA	Analysis of Variance
AV	Autonomous Vehicle
BPM	Beats per Minute
BSREC	Biomedical and Scientific Research Ethics Committee
BUC	Built up Chassis
C	Central (an MSAQ subcategory)
CAD	Computer Aided Design
CAV	Connected and Autonomous Vehicle
D	Disorientation (an SSQ subcategory)
DDT	Dynamic Driving Task
DF	Degrees of Freedom
DLO	Daylight Opening
EDA	Electrodermal Activity
EGG	Electrogastrogram
FMS	Fast Motion Sickness Scale
fNIRS	Functional Near-Infrared Spectroscopy
G	Gastrointestinal (an MSAQ subcategory)
GSR	Galvanic Skin Response
HMI	Human Machine Interface
HRV	Heart Rate Variability
HVAC	Heating, Ventilation and Air Conditioning
IMC	International Manufacturing Centre
IVIS	In Vehicle Information System
JLR	Jaguar Land Rover
MRT	Mental Rotation Test
MS	Motion Sickness
MSAQ	Motion Sickness Assessment Questionnaire
N	Nausea (an SSQ subcategory)
NHTSA	National Highway Traffic Safety Administration)
O	Oculomotor (an SSQ subcategory)
ODD	Operational Design Domain
OEDR	Object and Event Detection, recognition, classification, and Response
OEM	Original Equipment Manufacturer
P	Peripheral (an MSAQ subcategory)
RACeD	Research for Advanced Concept Development
RMS	Root Mean Square
SAE	Society of Automotive Engineers
SD	Standard Deviation
Sig.	Significance figure
SLC	Self-Learning Car
SR	Sopite-related (an MSAQ subcategory)
SSQ	Simulation Sickness Questionnaire
TLX	Task Load Index
VIMS	Visually Induced Motion Sickness
WMG	Warwick Manufacturing Group

1 SETTING THE SCENE – A BACKGROUND TO AUTOMOTIVE

Over 100 years ago, in 1916, the American automaker Cadillac introduced the ‘Type 53’ motor vehicle. This particular vehicle is of significance to the world of automotive human factors, where for the first time this car featured the controls of ignition, steering wheel, three pedals (brake, clutch, accelerator) and handbrake in the layout as is familiar in vehicles today. There has been great progress in many aspects of transportation since then and a host of new in-vehicle technologies have emerged. However, the fundamental concept of what it means to drive a vehicle has not changed – people are still fundamentally required to interact with vehicles in the same way in 2019 as they were in 1916. Just nine years after the launch of the Type 53, technology challenging this concept of ‘driving’, was already emerging in the form of ‘driverless cars’. In 1925 the Houdina Radio Control company demonstrated a radio-controlled Chandler automobile driving through the streets of New York City (USA) with no driver present - hence the term ‘driverless car’ was coined. This demonstration, although significantly abstract from our current understandings and objectives of automation in vehicles, stands as the first step in revolutionising the concept of driving a car. Since then, many significant steps have been made to progress automated technology where the overall goal is to remove the need for a human driver from a car and have the vehicle drive by itself. This concept, when requiring no human interaction at all is commonly referred to as autonomous driving, although the agreed definition is generally ‘fully automated’ (SAE International, 2018). To contextualise the envisaged future of the automotive industry, the four key factors of future automotive trends are believed to be of most significance as presented in a modified diagram by (McKinsey & Company, 2018) below in Figure 1:

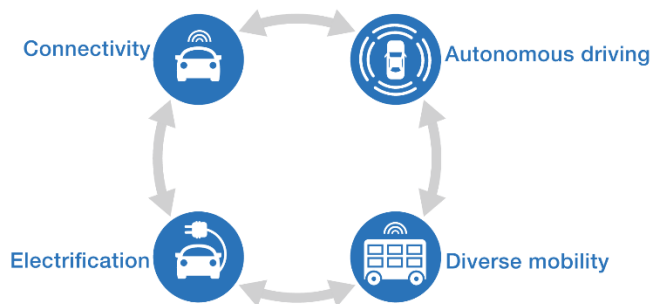


Figure 1 – Four Factors for the Automotive Revolution

It is believed these four ‘factors’ are of the most significance for the future of the automotive industry, and society as a whole. Each of them bring their own benefits and challenges. However, this report will be focusing primarily on ‘autonomous driving’ as a consideration. With increasing automation comes many potential benefits to mobility including that of traffic management, access to mobility for the disabled and above all, safety. Technological developments including various Advanced Driver

Assistance Systems (ADAS) and vehicle crash protection systems can be associated with an increase in vehicle safety and a decline in road related injury and fatalities observed over the years. However, there are still an astonishing number of crashes, injuries and fatalities recorded every year. The chart below in Figure 2 illustrates the number of reported road casualties in Great Britain from 1950-2017:

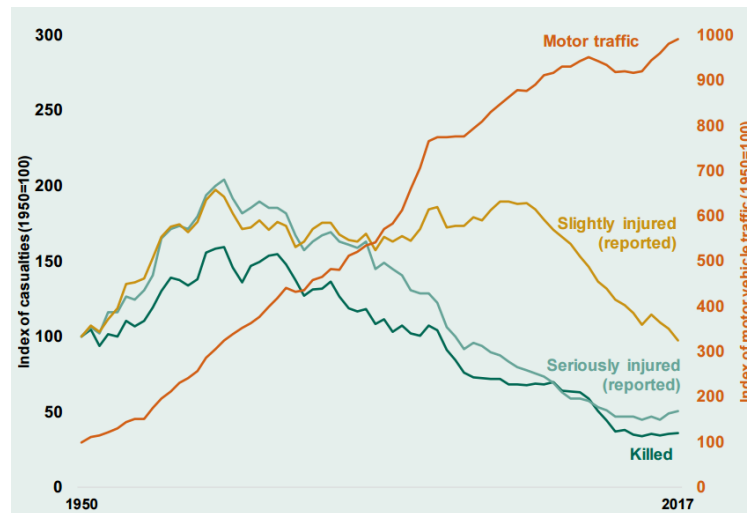


Figure 2 Reported Road Casualties by Severity and Motor Vehicle Traffic: Great Britain 1950 to 2017 (Department for Transport, 2018)

Figure 2 shows a general trend of a reduction in both injuries and fatalities over the recent years, despite an increase in traffic. However, with 144,369 people slightly injured, 24,831 seriously injured and 1,793 killed in 2017 on UK roads in 2018 (Department for Transport, 2018), there is still great incentive to further increase road safety and bring these figures down. The goal of fully autonomous vehicles is to bring down road deaths to zero - it is not uncommon to see predictions for up to and beyond a 90% reduction in road traffic collisions (Fagnant & Kockelman, 2015). An independent research group at Morgan Stanley estimate the US economy would save US\$488 billion per year due to the ability of fully autonomous vehicles to reduce road accidents (Morgan Stanley, 2013).

Aside from safety, increasing levels of automation bring many more benefits from a consumer perspective. Almost as soon as these original ‘driverless car’ prototypes were conceived, people have been envisaging how they will spend their time whilst traveling on the road – given that they no longer need to engage in the dynamic driving task (DDT). In 1956, America’s Independent Electric Light And Power Companies published an automated vehicle concept as is shown below:

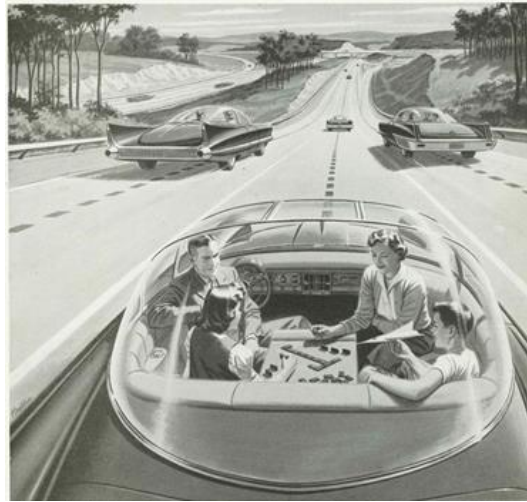


Figure 3 Automated Advertisement (America's Independent Electric Light And Power Companies , 1956)

The advertisement in Figure 3 depicts a family scene playing a game together whilst the two front seats have rotated to create a communal space within the vehicle. In this image, no occupant is required to monitor the road or interact with the vehicle controls. Jumping forward to the modern day and it is interesting to see this concept of occupant activities has remained relatively consistent. In 2017 Mercedes-Benz released their concept of a highly automated vehicle (the model F 015) depicting a similar scene to that of the scene from 1956, although bringing in more modern technology such as display screens:



Figure 4 The Mercedes-Benz F015 (Eliot, 2019)

2019 is a pivotal point in time for the development of automated vehicles, where there is great support for the technology (evidenced by substantial financial investment from both the private and public sector) and a rapidly growing consumer desire for vehicles with various levels of automation. However, perhaps overshadowed by the potential safety benefits, there is still a great deal of uncertainty around the human as a

consideration in automated vehicles. There are a many challenges which face the automotive industry as drivers become vehicle occupants and relinquish control of the vehicle to automated systems. Some challenges are found within the subjects of information requirements, control handover, trust, acceptance etc. Many of these areas have had a significant research effort evidenced in the literature. However, one concern that has seen less attention is that of motion sickness. The US National Library of Medicine reports how one in three people are considered highly susceptible to motion sickness (U.S. National Library of Medicine, 2019), and goes on to explain that almost everyone can become motion sick depending on the severity of the scenario. Motion sickness onset, frequency and severity is expected to increase significantly with the introduction of automated vehicles due to a number of factors including the loss of vehicle control (Rolnick, 1984), propensity to engage in non driving related activities (Diels C. , 2014) and vehicle design (Diels & Bos, 2015). There has been little motivation or incentive to develop an understanding of motion sickness thus far. However, this is no longer the case – increased automation is growing rapidly and consumer vehicles are already on the road with various automated features. Considering those with higher levels of autonomy it has been reported that Audi aims to have a highly automated car on the road by 2020, General Motors by 2020 or sooner and BMW by 2021 (Driverless Future, 2017). If people are likely to get motion sick in automated vehicles, there is a pressing need to understand the impact, implications and mitigation strategies of this, to enable the successful rollout and adoption of automated vehicles.

1.1 AIMS AND OBJECTIVES

The aim of this research project is therefore to explore the relationship between motion sickness and future automotive technologies to gain an enhanced understanding of both the impact and management of motion sickness for the automotive industry.

Objectives:

1. To critically review the body of literature covering motion sickness with an emphasis on impact to automotive applications
2. To explore the impact of motion sickness on human performance to inform transferability of simulator data to real-world
3. To advise on the most appropriate way to conduct user trials for future simulator-based experimentation (including that of motion sickness management) to inform ‘best practice’ of vehicle simulator trials.

4. To consider the impact motion sickness may have on the utility of future automated vehicles
5. To detail state of the art methods for managing motion sickness in vehicles
6. Design, test and validate a method of reducing personal susceptibility to motion sickness
7. Provide information on the ways through which a motion sickness management method could be implemented in production vehicles
8. Explore methods for the measurement and detection of motion sickness
9. Explore the feasibility of physiological data as objective measures of motion sickness and provide information about useful metrics through which motion sickness may be measured objectively.

2 AN INTRODUCTION TO THE INNOVATION REPORT

From September 2015 to September 2019 the British automotive manufacturer Jaguar Land Rover (JLR) sponsored this Engineering Doctorate (EngD) to help develop competency in human factors concerns related to future vehicles. This project sat within the RACeD project (Research for Advanced Concept Development) at the University of Warwick and was fully funded by JLR. As required by the University of Warwick's EngD student handbook this Innovation Report will, along with presenting the research, discuss "the value and implication of the research work to the wider world" (WMG Reserach Degrees Office at the University of Warwick, 2018), and the sponsoring company. This report will therefore contain a summary of the work completed over this four-year period and pull out the key findings, impact to the sponsoring company, contributions to the field, and innovations.

Considering the broad nature and size of the EngD as a project, an explanation is first given into how this Innovation Report is formed and what to expect from the various sections. To begin, an explanation of the portfolio plan is presented – containing an insight into all of the submissions made over the 4-year EngD and providing a visual representation of how this Innovation Report sits as an overall summary. The methodology of the project is highlighted within the explanation of this portfolio plan. This tells the story of this research and demonstrates the EngD's inherent positioning between fundamental research and industry-focused outputs. The sponsoring company (JLR) is then presented as a case study establishing the state of competency, knowledge and influence of the company on this research. This introduction to the sponsoring company helps illustrate how this project was able to address the aims from the business, which in turn helped fuel this project. In summary of the requirements from JLR, and with an anticipation of the demands from the literature,

the broad research themes can be set out, which capture all the objectives of the research.

With the introductory sections complete, a formal introduction to the two subjects of automated vehicles (AVs) and motion sickness (MS) will be presented – bringing the reader up to date with the state of the art (SOTA) for each subject. Evidencing the ‘sustaining innovation’ approach, these two subjects of motion sickness and automated vehicles are brought together and the challenges that arise within the marriage of the two fields of study are explored. The combination of these two subjects is key for this Innovation Report, and provides an understanding into where the true challenges lie for this research. The three key projects, which make up the main body of this Innovation Report are then presented. Looking back on the three core projects, it will then be possible to revisit, in the closing sections, how this research has addressed the challenges, aims and objectives set out early on in this Innovation Report. Concluding, it is then possible to summarise the impact this work has had on the case study of Jaguar Land Rover as the sponsoring company.

2.1 PORTFOLIO PLAN AND REPORT STRUCTURE

As part fulfilment of this EngD, submissions have been made along the way to document and present distinct sections and/or research projects completed. Although this Innovation Report stands as the overall summary of these submissions, these documents hold within specifics and in-depth details of the work presented and discussed here. It is advantageous to present the structure of these submissions to provide a context to each submissions’ research contribution, which combined, make up this EngD. Figure 5 below shows how the research took place chronologically and shows the submissions in order of their completion:

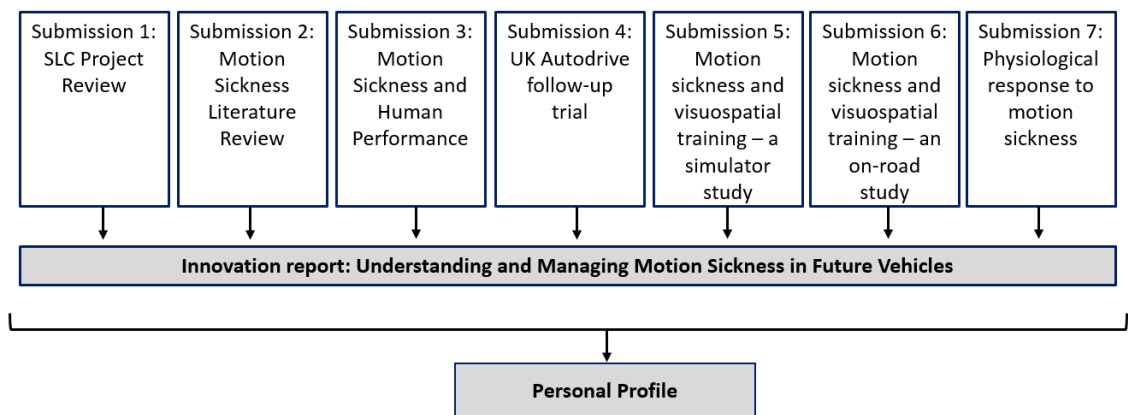


Figure 5 Portfolio Plan Version 1

Viewing the portfolio in chronological order helps in understanding how this project developed. Initially, work began within the Self-Learning Car (SLC) team at Jaguar Land Rover. However soon after starting research, the business decided to progress the SLC project from research to ‘mainstream engineering’ – thus the project, which initially enabled this EngD, was dissolved. This led to a period of, futurescaping and problem identification to find a new scope for research to address the overall aims and objectives of this EngD. Moving away from automating in-vehicle features, this research moved towards the subject of motion sickness. Submission 2 was the first submission made in this new direction and contains an in-depth and critical review of the literature surrounding motion sickness and automated vehicles. From then, each submission ran relatively consecutively and demonstrates a logical progression of the project. Considering the change in direction of the research stemming from the disbandment of the SLC team, this EngD portfolio plan is reordered, moving away from a chronological timeline, but instead to reveal the true story of this EngD as three core projects and is presented below in its finalised version in Figure 6.

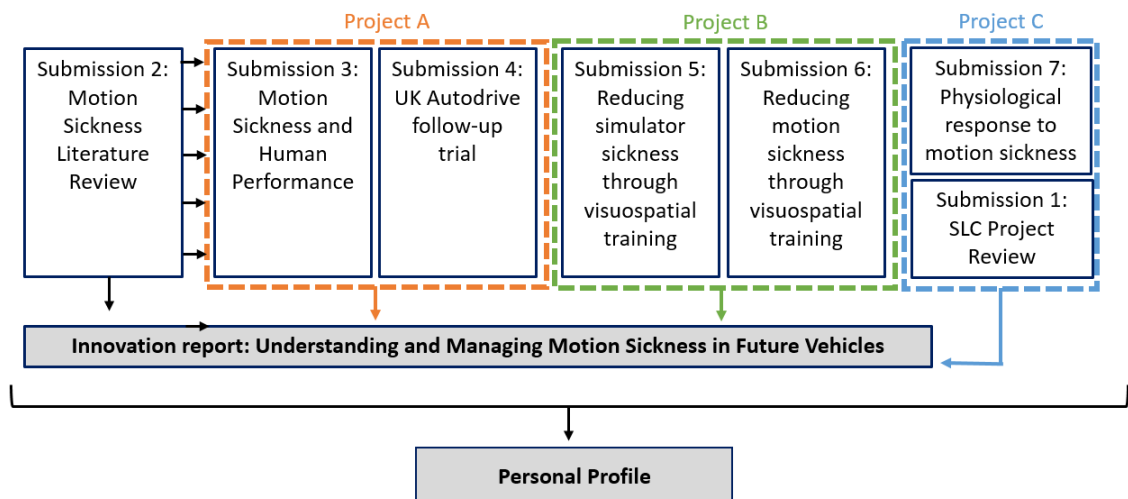


Figure 6 Portfolio Plan Version Finalised

Figure 6 above, presents the portfolio plan for the structure of this EngD and Innovation Report. There are a few notable differences from the original chronological plan set out in Figure 5, which will be explained along with a brief overview of the submissions to give an appreciation for the overall methodology of this project.

Submission 2, setting the scene for this motion sickness research was a literature review focused on motion sickness with an emphasis on the automotive industry. This review provided the background learning and understanding of many concepts of motion sickness, covering a wide range of fundamental literature ranging from biological explanations of the condition to discussing design recommendations for the management of motion sickness. This literature review was strategically kept broad so that this submission could stand as the backbone behind subsequent research projects. The problem of motion sickness and automated vehicles at the time of this

report was still ill-defined within the published literature and in general understanding. Therefore covering a wide range of subjects allowed for the opportunity to scope this EngD in such a manner to ensure maximum validity for future projects and not limit future work by way of omitting various areas of the literature. The outcome of this literature review evidenced innovation in the contextualisation of existing literature surrounding motion sickness as a specific subject, and expectations for future automotive trends (e.g., automated vehicles and driving simulators). This literature review also served as the reference for the problem identification carried through this EngD research. The conclusion of Submission 2 presented a series of challenges and research questions on which the subsequent EngD projects could be based.

The challenges and research areas from Submission 2 were developed into a framework of future research which highlighted three distinct areas of recommended motion sickness future research. These categories were identified to be of most utility to explore for this EngD considering the state of the literature and the demands from industry. The framework loosely follows the same linear style progression of the Technology Readiness Level (TRL) (NASA, 2012) scale where fundamental research tends to sit to the far left of the framework, and applications to the right. A modified version of this framework is presented below in Figure 7, where the original version includes a summary of areas for further explanation found during the literature review.

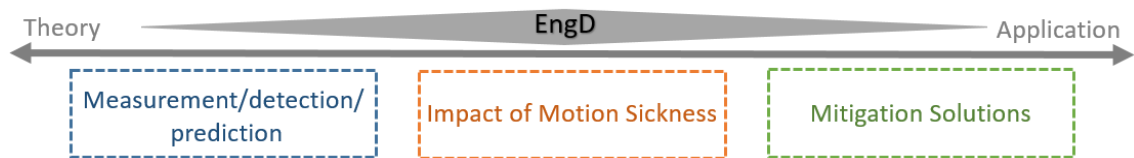


Figure 7 Modified Framework of Identified Future Research

The framework above differs somewhat from that presented in the literature review summarised in Submission 2, as both the field and this research project have developed since its initial conceptualisation. Figure 7 helps to present and justify the scope for this EngD project – sitting in-between theory and application. The theory based fundamental research can be more exploratory in nature and tends to be associated with academic research. Whereas the applications traditionally tend to be more where industry focused research and development lies. The scope of the EngD is therefore represented by the grey diamond, where the bulk of the effort is in understanding and contextualising the impact of motion sickness and future automotive technologies. This positioning also allows for some significant work to be carried out either side of this centre point - both adding to the fundamental knowledge as well as the application of knowledge to industry. The six submissions (besides Submission 2 – the literature review) can be mapped onto this framework presented in

Figure 7 where they form three Projects - A, B and C as per Figure 6. A brief overview of the portfolio of submissions is given.

2.1.1 PROJECT A – MOTION SICKNESS AND HUMAN PERFORMANCE (SUBMISSIONS 3 AND 4)

Project A looks at motion sickness and human performance, it sits within the category of ‘impact of motion sickness’ as defined in the framework presented in Figure 7. One of the immediate concerns highlighted within the literature review (Submission 2) was the relatively undefined extent to which motion sickness affects human performance. This was of concern due to the nature of simulator-based user trials, and the propensity for driving simulators to induce motion sickness for some users. Submission 3 looked to see how motion sickness affects various areas of human performance and looked to conclude on how performance, and therefore user trial results, may be impacted if motion sickness is a factor for participants. An experiment was devised using 51 participants, each using a simulator for up to 30 minutes and the impact of motion sickness on various areas of human performance was measured. The outcomes for Submission 3 were very interesting for understanding the transferability of simulator data to the ‘real-world’. Following up on the simulator study, a ‘real-world’ study using the pods from the UK AutoDrive project was devised, and this is presented in Submission 4.

Within Submission 4, the same experimental procedure is followed as in Submission 3 – the simulator study, although this time a further 17 participants were assessed whilst taking part in a ‘highly automated’ driving ‘pods’ trial, rather than a driving simulator study. This trial confirmed that the pods did not induce any significant motion sickness (in this trial) – and as a validation for results in submission 3 where performance was affected by motion sickness – no decrement to performance was observed following the pod trials.

The summary of the two trials which make up Project A, provide insights into the transferability of simulator-based user trial data to real-world as well as bring into context the effect of motion sickness on human performance. This brings with it interesting considerations for automated vehicles and performance degradation because of motion sickness in an automated vehicle is discussed.

2.1.2 PROJECT B – REDUCING MOTION SICKNESS SUSCEPTIBILITY (SUBMISSIONS 4 AND 5)

Project B looks at a new method for reducing susceptibility to motion sickness, is comprised of Submission 4 and 5, and primarily sits within the category of ‘applications’ as defined in the framework presented in Figure 7. However, this project also contributes significantly to the scientific literature through the more fundamental

understandings of motion sickness, which sits further to the left of Figure 7. One of the interesting findings presented in Submission 3 was the relationship observed between motion sickness and visuospatial skills. Upon examination of the data, and building further on the literature already discussed in Submission 2, it was hypothesised that motion sickness susceptibility could be reduced through improving one's visuospatial skills. Project B set out to explore this hypothesis with a two-part experimental design.

Submission 5 explores, through a simulator study, if through training visuospatial skills it is possible to reduce motion sickness susceptibility, a first for the academic literature. Submission 5 presents a novel visuospatial training tool, and shows how using this training tool participants (n=20) were able to improve visuospatial performance. Subsequently, and most significantly, it was shown how this increased visuospatial performance was responsible for a significant reduction in motion sickness susceptibility experienced within the driving simulator (measured as simulation sickness).

Considering the importance of the findings presented in Submission 5, both for the fundamental understanding of motion sickness and the industry application of a potential motion sickness management method, Submission 6 looked to replicate this study in the 'real-world'. Using a further 22 participants, a user trial was designed to mimic that of the trial presented in Submission 5, but using an on-road driving task as the motion sickness inducing task. This study somewhat mimicked the conditions of a fully automated vehicle where the occupant sat as a passenger whilst being driven. This user trial again showed how the novel visuospatial training tool was successful in improving visuospatial performance, and importantly showing how this improved visuospatial performance was responsible for a significant reduction in motion sickness severity for participants. Submission 6 therefore validated the findings presented within Submission 5 and showed the real-world application for a visuospatial training tool for the management of motion sickness. Further data was presented within this submission around the effect this reduced motion sickness had on cognitive workload when completing a basic reading task.

Project B concludes on these two user trials, presents the data as well as a discussion about the implications of this finding. Further, an ideation workshop was conducted and methods of exploitation of this new knowledge have been presented – adding to the business case support for this project.

2.1.3 PROJECT C – THE MEASUREMENT OF MOTION SICKNESS (SUBMISSIONS 7 AND 1)

Project C primarily sits within the category of 'measurement / detection/prediction' as defined in the framework presented in Figure 7, and combines outputs submitted at the beginning and the very end of this EngD portfolio.

The roots of Submission 7 were again based upon the findings presented in the literature review (Submission 2), where this project looked to see the extent to which the physiological measures of Electro Dermal Activity (EDA) and skin temperature were useful as a measure of real-time motion sickness severity. This project idea stemmed from the confusion evidenced within the literature presented in Submission 2 where the utility of objective motion sickness measures was often argued. Using the user trials presented in submissions 3, 5 and 6 physiological data was collected for later analysis – hence it is presented at the end of the portfolio, upon completion of all these trials. There was a significant interest from the sponsoring company (JLR) to identify useful physiological metrics on which motion sickness can be inferred where at that time, JLR researchers were planning on using EDA and skin temperature to measure motion sickness. This submission looked at real-time measurement of motion sickness (objectively and subjectively) and showed that it is impractical to use these physiological measures as real-time motion sickness measures by themselves. Within submission 7, recommendations were made on how motion sickness could perhaps be measured using a mixed-methods approach, where this allowed for the re-consideration of the data collection model presented in Submission 1.

Submission 1, was completed at the beginning of this EngD, and looked at problems within JLR’s Self-learning Car (SLC) project. This submission summarised the issues which were being experienced with the SLC system and proposed a new model through which data can be collected to better inform a machine learning system to enable reliability. The SLC team was disbanded soon after the completion of this submission and therefore the context in which the model was developed is less useful for this theme of motion sickness. However, the model itself remains relevant and is of testament to the appropriately scoped research in that its utility goes beyond its original purpose. This model may be applied to the measurement and perhaps prediction of motion sickness onset – exemplifying ‘architectural innovation’. The model is extracted and its implementation is discussed and explored within this project.

2.1.4 SUMMARY OF THE PORTFOLIO PLAN

In summary of the portfolio plan, it is possible to revisit the frameworks presented in Figure 6 and Figure 7, combining the two to conclude upon the scope of this EngD. This has been presented below in Figure 8:

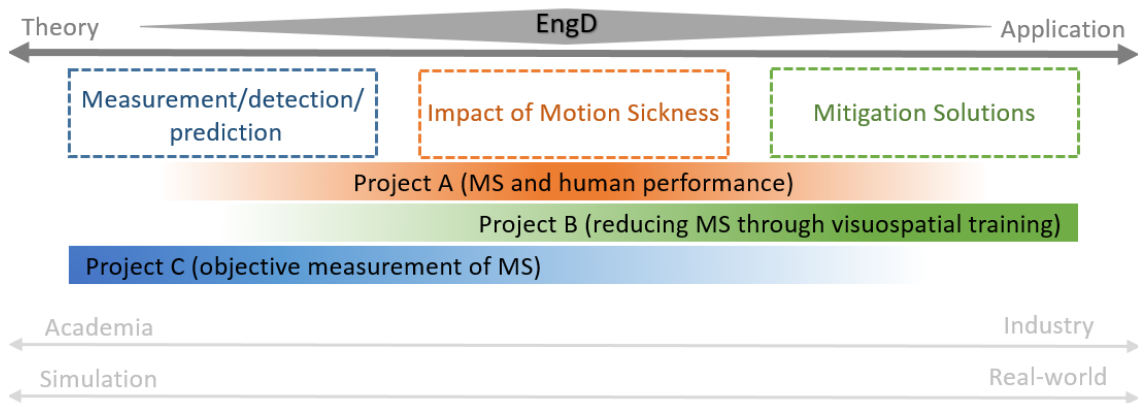


Figure 8 Innovation Report Summary of Scope

No individual project is constrained to just one area in the scope of motion sickness research, where all span the spectrum from fundamental theory-based research to industry-ready applications in some manner. However, the three projects presented within this Innovation Report do lend themselves to be mapped loosely within the framework and evidence how this research has attempted to cover the spectrum of research opportunities. The purpose of Figure 8 is to show the scope of the research conducted for this EngD, with a fundamental aim to bridge the gaps between academia and industry. The section highlighted in blue on the left of Figure 8 (measurement / detection / prediction) encompasses the study of physiological measures and their correlation to motion sickness. In the middle (orange), is the impact of motion sickness, and is focused on the performance and subjective discomfort that motion sickness brings. Finally, mitigation solutions to the right (green) covers strategies for reducing motion sickness without drug or hormonal manipulation (i.e., non-invasively). All of these themes will be explored primarily in an automotive context, but each offer transferability for their application to the wider field.

As more of a point of interest, two further scales have been added to the bottom of the framework presented in Figure 8. In general, it is understood that the research topics towards the left of the spectrum lend themselves to academic research, and to the right, industry research – as previous explained. But also interesting for this EngD is the applicability of simulation as a research method for studies further to the left of the spectrum, where real-world studies are more suited to those further to the right. This is of consequence for this EngD project, which looks to cover simulator-based research transferability between many aspects of the projects included.

2.2 AN INTRODUCTION TO THE PROJECT SPONSOR

Jaguar Land Rover (JLR) are a British automotive OEM (Original Equipment Manufacturer) and home of the two previously independent brands of Jaguar and Land Rover. The two brands both strongly target the luxury / premium car market. Although the traditional primary focus of the two brands has been sports cars (Jaguar) and off-road capable vehicles (Land Rover), the defining characteristic of their overarching business model is certainly one of luxury and quality. More recently, it seems JLR are positioning themselves as a lifestyle company, whereby you might 'buy in' to the brand for the overall experience rather than just the product, their 2019 tag line on their company website speaks to this ambition:

Jaguar Land Rover: "Creating experiences people love for life" (Jaguar Land Rover, 2019)

It is this focus on the premium/luxury market and experience 'creation' around their brand that helps define the scope set out for this EngD. It also uncovers the driving force behind this research project, which looks overall to make the JLR experience the best it can be for its customers.

When this EngD began in September 2015, JLR were attempting the development of a Self-Learning Car (SLC) system, which aimed to learn user engagement patterns with distinct in-vehicle systems (such as heated seats, radio media and climate control). There were no new features within the vehicle, but rather the automation of these existing features was the innovative step JLR were making to continue their premium vehicle development, and create the new experience for their customer. The challenge faced by JLR at the time was in finding a way to accurately predict the users' routine based on data it could collect from the user. This challenge was the primary aim of this initial EngD conception. The SLC project was taken away from the research department and handed over to mainstream engineering, the SLC research team was disbanded and the scope of this EngD project therefore adapted and changed.

Looking towards the future of the automotive industry, with increasing levels of automation on the horizon, JLR were keen to better understand some of the human factors concerns with automation within vehicles. At the time, the scope from JLR was broad with no fixed direction to research. This played to the strengths of the EngD aim and the challenge was, considering future mobility, to create a meaningful impact to JLR's future vehicles whilst enabling the ethos of "creating experiences people love for life". An initial consideration from the original SLC project was to explore the possibility of driving simulator-based SLC user trials, and how transferable these studies would be to real-world applications. One consideration from this was the propensity for people to become motion sick during studies (specifically, simulator sick) which gave the

consideration for the first project looking to understand if there was a human performance consideration. Expanding this line of study, it was conceived that motion sickness could be an issue for current, and certainly future automated JLR vehicles. The concept of motion sickness was discussed with JLR, and it was agreed that there was good scope to help shape their future vehicles by better understanding the relationship between motion sickness and future automotive technologies. Such a project is well suited to JLR as a car company who are keen to develop value-adding and experience enabling technology for their target market in the premium automotive sector. When this project began, the JLR research department had limited competency within the field of motion sickness management for driving simulators or automated vehicles.

3 REVIEWING THE SUBJECTS OF AUTOMATED VEHICLES AND MOTION SICKNESS

Although the research aims, objectives and themes have already been presented – to enable clarity of this Innovation Report, the aims and objectives were primarily concluded upon after the initial literature review (Submission 2). The literature covering motion sickness, automated vehicles and the combination of the two was of significant interest and importance for this EngD and an introduction to the subjects are now presented where the aims and objectives are further justified. This literature has been explored in greater detail in Submission 2, and as a result of this contextualisation and exploration of the subject a publication was created looking at the potential disparity between automated vehicle expectation and realistic outcomes (Smyth, Jennings, & Birrell, 2019).

3.1 AN INTRODUCTION TO AUTOMATED VEHICLES

The premise of increasing automation within a vehicle is to reduce the requirement for manual driving interaction from a human driver. Common lay phrases used to refer to automated vehicles include ‘self-driving vehicle’, ‘driverless vehicles’ and ‘autonomous vehicles’.

3.1.1 TERMINOLOGY

There are different levels of automation to classify automated vehicle technologies and the most recent, and most useful, scale is supplied by the Society for Automotive Engineers (SAE) and presented below in Figure 9:

Level	Name	Narrative definition	DDT		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	OEDR		
Driver performs part or all of the DDT						
0	No Driving Automation	The performance by the <i>driver</i> of the entire DDT, even when enhanced by <i>active safety systems</i> .	<i>Driver</i>	<i>Driver</i>	<i>Driver</i>	n/a
1	Driver Assistance	The <i>sustained</i> and ODD-specific execution by a <i>driving automation system</i> of either the <i>lateral</i> or the <i>longitudinal vehicle motion control</i> subtask of the DDT (but not both simultaneously) with the expectation that the <i>driver</i> performs the remainder of the DDT.	<i>Driver and System</i>	<i>Driver</i>	<i>Driver</i>	Limited
2	Partial Driving Automation	The <i>sustained</i> and ODD-specific execution by a <i>driving automation system</i> of both the <i>lateral</i> and <i>longitudinal vehicle motion control</i> subtasks of the DDT with the expectation that the <i>driver</i> completes the OEDR subtask and <i>supervises</i> the <i>driving automation system</i> .	System	<i>Driver</i>	<i>Driver</i>	Limited
ADS (“System”) performs the entire DDT (while engaged)						
3	Conditional Driving Automation	The <i>sustained</i> and ODD-specific performance by an ADS of the entire DDT with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to <i>intervene</i> , as well as to DDT performance-relevant system failures in other vehicle systems, and will respond appropriately.	<i>System</i>	System	<i>Fallback-ready user (becomes the driver during fallback)</i>	Limited
4	High Driving Automation	The <i>sustained</i> and ODD-specific performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to <i>intervene</i> .	<i>System</i>	<i>System</i>	System	Limited
5	Full Driving Automation	The <i>sustained</i> and unconditional (i.e., not ODD-specific) performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to <i>intervene</i> .	<i>System</i>	<i>System</i>	<i>System</i>	Unlimited

Figure 9 Summary of Levels of Driving Automation (SAE International, 2018)

‘DDT’: Dynamic Driving Task.

‘OEDR’: Object and Event Detection, Recognition, Classification, and Response

‘ODD’: Operational Design Domain

For the purposes of this research and Innovation Report, SAE Levels 2 to 5 (as per Figure 9) are of most interest and will further be discussed:

At SAE Level 2 (partial automation), in defined scenarios the vehicle will allow the driver to relinquish control of both lateral and longitudinal driving inputs to the automation system. However the driver must remain attentive to the driving task at all times, and overall, responsibility for the vehicle still lies with the driver.

At SAE Level 3 (conditional automation) the vehicle can take control of all aspects of driving in defined scenarios (or ODD’s), however, the system requires the user to regain control of the vehicle at any time, following a notice period.

At SAE Level 4 (high automation) the vehicle can control all aspects of the driving task within specific ODD’s but will allow the user to take control of the vehicle if they so choose – although there is no requirement to do so. This is where the line between ‘driver’ and ‘passenger’ begins to blur as the user can choose to be either.

At SAE Level 5 (full automation), the vehicle will control all aspects of the driving task and there will be no availability for the occupant to take over the DDT. In such a

vehicle, there would not be any traditional driving controls such as a steering wheel or pedals.

As somewhat of a summary to the definitions above, the term Autonomous Vehicle (sometimes abbreviated to 'AV') relates to an SAE Level 5 full driving automation vehicle. Pods, such as the ones created by RDM group (RDM Group, 2017) and as used in recent research (Burns, Oliveira, Hung, Thomas, & Birrell, 2019) look physically like a Level 5 vehicle (with no manual driving controls), although they are designed to operate in specific ODD's therefore they are classified as Level 4 vehicles according to the SAE. The term 'Automated Vehicle' relates to vehicles with Level 3, 4 or 5 capability (i.e., conditional to full automation). Other commonly used terms such as 'self-driving' vehicle and 'driverless' vehicle, whilst presumably refer to a Level 5 fully autonomous vehicle, have fallen into disuse in recent academic literature due to their lack of specificity and should therefore be avoided.

3.1.2 CURRENT STATE-OF-THE-ART

Although the overall goal of many automotive OEMs is full driving automation (SAE Level 5) there are a number of technical and legislative barriers to cross before this technology is ready. Until then it is likely vehicles will be released with increasing levels of automation, until full autonomy can be achieved. As of 2019, there is already evidence of this path to full automation with companies such as Tesla (AutoPilot), Cadillac (Super Cruise), Volvo (pilot Assist) and Nissan (ProPilot Assist) amongst others all releasing SAE Level 2 vehicles. A subjective review of these current systems has been published (Olsen, 2018) and presents a good overview of the various systems and implementations of this technology. A key thing to note about Level 2 vehicles is the responsibility for the driver to remain attentive to the driving task at all times. The way in which this is executed differs between vehicles where, for example, Tesla requires hands on the steering wheel at all times and Cadillac monitors eye fixation behaviour.

Looking at SAE Level 3 systems, Audi has released their 'Traffic Jam Pilot' system in their 2019 A8 model vehicle, which claims to operate under the defined requirements for a Level 3 system and can control all aspects of the driving task (DDT) up to a speed of 37mph. As of 2019 there are no commercially available Level 4 or 5 vehicles on the market.

3.1.3 UTILITY OF AUTOMATED VEHICLES

There are myriad benefits to automated driving systems, and the increased safety that these technologies are likely to bring is possible even in the lower levels of automation. Initial estimates studying ADAS systems and 'low levels of automation' show the potential for this technology to reduce light vehicle crashes by at least 32.99% per year and crashes for heavy trucks by at least 40.88% per year (Yue , Abdel-

Aty, Yina , & Ling, 2018). However, considering Levels 4 and 5 it is expected this reduction in collisions would be drastically greater. Morgan Stanley have previously predicted a US\$488 billion saving per year for the US economy due to the reduction in road traffic accidents due to Level 4 or Level 5 vehicles (Morgan Stanley, 2013). They based this figure on the reporting that 90% of road traffic accidents are related to human error (World Health Organisation, 2004) (p.10) – so without the driver, they expect a reduction of 90% in road traffic accidents. The logic behind this calculation may be disputed, but the argument for increased safety is established enough and the specifics of exact figures is not necessary for this EngD research.

Looking past safety, there are many more benefits to this technology, particularly at the higher levels (SAE Levels 4 and 5) where the driver can relinquish control to the automated system completely. Such systems will enable transportation for those who cannot drive a traditional vehicle due to age, health, disability etc. and thus has the ability to significantly enhance inclusivity in mobility. Also within these vehicles (SAE Levels 4 and 5) comes the ability to engage in non-driving related tasks for extended periods. A Level 3 vehicle may also allow for some engagement – although tasks may be restricted by the requirement to regain control of a vehicle if needed. Some tasks often envisaged for these vehicles include reading, watching films, working and socialising, amongst others. A survey conducted by insurance company StateFarm in 2016 (State Farm, 2016) looked to understand what people want to do within a vehicle that can drive itself (referring to SAE Levels 3, 4 and 5), given the premise that self-driving technology would free up their time to engage in other activities. With a sample size of 961 they reported 45% of people would be more willing to read texts, 36% would be more willing to access the internet, 21% would be more willing to watch movies and 19% would be more willing to read a book (StateFarm, 2016). Findings are also reported around the trust of automated vehicles, and it is expected that these figures presented above would likely increase as trust in the technology and willingness to ride in such Level 3, 4 and 5 vehicles increases. The breakdown of responses from this StateFarm survey is presented below in Figure 10.

“How much more, or less, likely would you be to engage in the following activities when the vehicle is driving itself compared to when you are driving the vehicle yourself?”

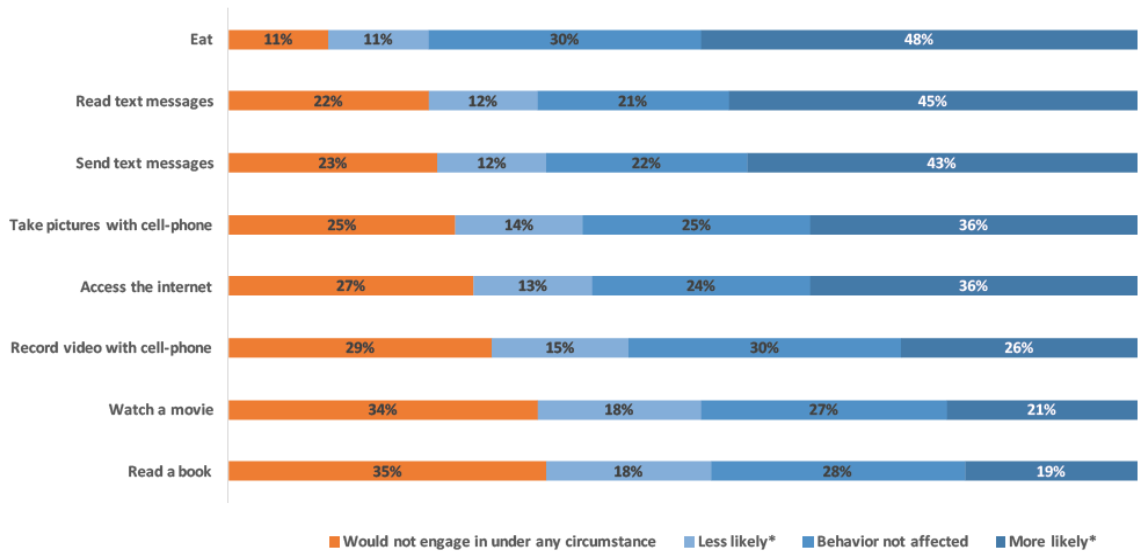


Figure 10 What People Want to Do in a Level 3, 4 or 5 Automated Vehicle.

This concept of productivity in vehicles is well supported by automotive OEM’s, many of whom have published concepts of what they believe are possible use cases for self-driving vehicles. The image previously presented in Figure 4 which showed Mercedes-Benz’s F015 automated vehicle speaks to this consideration and expectation for increased productivity in vehicles with all occupants engaging in a work based task. Many others are also advertising similar possibilities for future automated vehicles – two of which are presented below:



Figure 11 Rinspeed XchangeE Automated Vehicle Prototype (Rinspeed, 2014)



Figure 12 Volvo Automated Vehicle Prototype (Volvo, 2019)

As proposed in these concepts, there appears to be a great opportunity to transform driving time into time spent doing many other activities when riding in an automated vehicle. Further to these leisure activities presented above, there is also scope for vehicles to become mobile offices as people can complete work-based activities whilst in their automated vehicle. This is particularly true for Levels 4 and 5 automated vehicles, but may also be possible, to some extent, for Level 3 vehicles. A recently OnePoll survey with a sample size of 2000, revealed how 27% of the population would want to engage with work related activities whilst commuting in an automated vehicle (Lofthouse, 2017), although the full research article has not been published. Again, this figure is likely to increase as trust and willingness to ride in such vehicles increases. Further to this consumer pull, there may also be an industry push for work-orientated productivity in future automated vehicles. Morgan Stanley have estimated that the ability to work within an automated vehicle could bring US\$508 billion per year to the US economy (Morgan Stanley, 2013) (p.50). A smaller figure, but again in support of the concept of completing work-based tasks in automated vehicles predicts a potential US\$220 billion per year benefit to the US economy linked to increased productivity (Montgomery, 2018).

3.2 AN INTRODUCTION TO MOTION SICKNESS

Humans have been documenting motion sickness as early as 800 BC according to one text (Huppert, Benson, & Brandt, 2017) which explores the historical documentation of the condition. It is still a condition which humans suffer from today. Motion sickness, or 'kinetosis' can be experienced in a broad array of scenarios, such as on a boat (seasickness), in a car (car sickness), in a simulator (simulator sickness), or on a plane (airsickness) etc. Many of these definitions include motion sickness experienced when

in a mode of transport, therefore another common phrase covering these is 'travel sickness'. Although all of these terms and more fall under the umbrella term of motion sickness (MS).

3.2.1 THEORIES OF MOTION SICKNESS

The cause(s) of motion sickness are still, to this day not fully agreed upon, with even the most established theories sometimes disputed. The most commonly referenced theory of motion sickness is the Sensory Conflict Theory (Reason & Brand, 1975). To understand this theory, it must first be understood that there are three primary ways of perceiving motion:

- The Visual system – a person can infer motion using their eyes to track movement, light or parallax
- The Vestibular system – balance organs within the inner ear which are responsible for sensing self-motion
- The Somatosensory system – an area and therefore function of the brain which can infer motion based on movement of limbs and pressure on the body etc.

The sensory conflict theory argues that mismatches between or within visual, vestibular or somatosensory inputs cause motion sickness. This theory holds the most weight in our present understanding of motion sickness where nearly all motion sickness incidences involve at least some form of conflict between these senses (Bles, Bos, de Graaf, Groen, & Wertheim, 1998) and therefore, it is most commonly observed. Some criticism of this theory is found within the literature, where it is argued that because "only a small subset of intermodal patterns of stimulation is associated with motion sickness" sensory conflict cannot necessarily predict motion sickness (Stoffregen & Riccio, 1991) (p.188).

As somewhat of a response to the criticism of the sensory conflict theory, a new theory of motion sickness was proposed - the Postural Instability Theory (Riccio & Stoffregen, 1991). This theory explains how motion (physical or perceived) can disrupt the natural postural sway pattern of an individual, resulting in the inability to accurately understand 'centre of gravity' and therefore inability to maintain postural control. This theory was proposed as an alternative to sensory conflict theory and is presented as a challenge to the sensory conflict theory (Stoffregen & Riccio, 1991) where they argue that prolonged postural instability is the cause of motion sickness (Riccio & Stoffregen, 1991) (p. 205). This theory was investigated initially by (Warwick-Evans & Beaumont, 1991) through a comparison of the postural instability theory to sensory conflict theory. Through attempting to remove postural control as a factor of the experimental design, the results of their study (where all participants became motion sick) indicated that reducing demands of postural control did not reduce motion sickness onset or severity. This study provided evidence on which to debate

the validity of the postural control theory. A further study using two conditions to control postural stability further disproves the hypothesis of the postural stability theory (Warwick-Evans, Symons, Fitch, & Burrows, 1998) whilst providing further evidence to support the sensory conflict theory. More recently, the theory of postural control is being considered less of a cause of motion sickness, and more as a precursor to motion sickness (Stoffregen, Hettinger, Hass, Roe, & Smart, 2000) (Stoffregen & Smart Jr., 1998) (Guerraz, Gianna, Burchill, Gresty, & Bronstein, 2001). It may not be postural instability that is necessarily causing motion sickness, but it does often precede motion sickness, agreeing there is a relationship between motion sickness and postural instability – but not a direct causation.

Sopite Syndrome (Graybiel & Knepton, 1976) is also commonly discussed in relation to motion sickness subjects. Sopite syndrome is a condition related strongly to sensations of fatigue and mood changes in relationship to motion (observed and perceived). One of the subcategories of the MSAQ is sopite-related symptoms, again attesting to the link between this and motion sickness. However, sopite syndrome is not a causal theory of motion sickness, rather their relationship is such that they occur due to similar stimuli (motion), therefore in similar domains and at similar times.

3.2.2 CLASSIFICATION OF MOTION SICKNESS TYPES

Considering the various reference terms for motion sickness (car sickness, seasickness, virtual reality sickness etc.) along with the explanation of motion sickness theories it is useful to classify motion sickness states based on the presence of physical motion. The presence of motion and different motion cues are argued to be of importance in the understanding of motion sickness onset (Stoffregen & Riccio, 1991). A useful differentiating characteristic of motion sickness-inducing scenarios is those which involve ‘afferent’ and ‘efferent motion’. Where afferent motion accounts for when “objects are moving in the environment” (i.e., when observing object movement) and efferent motion accounts for “movements of the eyes, body or head” (i.e., self-movement) (Kapoula & Thanh-Thuan, 2006) (p.438). It is afferent motion which also leads to the concept of ‘vection’ or the self-illusion of motion which is of consequence for sensory conflict theory and therefore motion sickness (for more onvection see (Palmisano, Allison, Schira, & Barry, 2015)). Given this reliance on motion (or lack thereof) for identifying motion sickness ‘type’, it is useful to categorise the three motion-related categories of motion sickness:

Table 1 Classification of Motion Sickness ‘States’ Based on Motion

Classification	Examples of motion sickness state
1. Motion is seen but not felt (afferent motion present) (referred to as VIMS)	E.g., Space-sickness, virtual reality (VR) sickness, simulator sickness (fixed base)
2. Motion is felt but not seen (efferent motion present)	E.g., Car sickness, seasickness, airsickness
3. Motion is seen (efferent) and felt (afferent) but the two do not correlate	E.g., Simulator sickness (moving base) or when using VR equipment or watching a film in a moving environment

3.2.3 MOTION SICKNESS SYMPTOMOLOGY

The subjective sensations of motion sickness are uncomfortable and undesirable, where common symptoms include nausea, sweating, headaches and, in severe cases, vomiting. The symptomology is somewhat explained through the evolutionary hypothesis (Treisman, 1977) which explains how the brain rationalizes the conflict in sensory inputs (as per sensory conflict theory) to be the result of ingesting a poison. Therefore evolutionary responses to self-sustain result in the characteristic sweating, burping and vomiting which are used to push toxins out through the skin, get rid of gas build up, and empty the stomach contents in case poison has indeed been ingested. The symptomology of motion sickness is somewhat dependent on the incidence of onset, where VIMS (visually induced motion sickness) related cases result in more visual discomfort, but afferent motion scenarios tends to result in more nausea related conditions. As a good explanation of this, two widely used subjective grading criteria for motion sickness - the Simulator Sickness Questionnaire (SSQ) by (Kennedy, Norman, Berbaum, & Lilienthal, 1993) and the Motion Sickness Assessment Questionnaire (MSAQ) (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001) measure many motion sickness symptoms and therefore provide a good insight into the types of symptoms related to motion sickness. Where the SSQ is more useful for afferent motion environments, it is interesting to see a greater emphasis on visual system-related symptomology, compared to the MSAQ.

3.2.4 WHO IS AFFECTED BY MOTION SICKNESS

It is understood that everyone is susceptible to motion sickness except those with complete loss of labyrinth function (i.e., those who are completely deaf or have a vestibular dysfunction) (Chung, Howard, & Money, 1991) (Kellogg, Kennedy, & Graybiel, 1965). The U.S Library of Medicine report that as many as one in three people are highly susceptible to motion sickness (U.S. National Library of Medicine, 2019). Looking at car sickness specifically it is understood that around 60% of the

population has experienced some nausea from car travel, whereas about a third has vomited in cars before the age of 12 (Griffin, 1990).

Motion sickness severity and onset frequency vary between demographics also, where it is known females are more susceptible than males (Jokerst, et al., 1999) (Flanagan, May, & Dobie, 2005) where the effect is even more pronounced when menstruating or pregnant. Because of this, and other factors, it is understood that the main reason for the gender difference in motion sickness susceptibility is related to sex hormones (Matchock, Levine, Gianaros, & Stern, 2008) where those with higher androgen levels report fewer incidents of motion sickness and those with higher levels of oestrogens report more motion sickness incidences (Hausmann, Slabberkoorn, Van Goozen, Cohen-Kettenis, & Gunturkun, 2000). There is also some differentiation between mechanisms for visually determining motion between the genders (Schouten, Troje, Brooks, Van Der Zwan, & Verfaillie, 2010) which can result in higher motion sickness for efferent motion scenarios (VIMS) for women.

There is also evidence to suggest that ethnicity has a role to play in susceptibility, where in general "Asian people are more susceptible than those of European or African origin" (Klosterhalfen, et al., 2005) (p.1051). Highlighting also how genetics too have a significant role to play in motion sickness susceptibility (Stern, et al., 1996). Further to gender and ethnicity, age also known to have an effect on motion sickness susceptibility, the direction of which is relatively well understood for children. It is known that infants and very young children are immune to motion sickness (Golding J. F., 2006) where susceptibility begins around the age of 6 or 7 (Reason & Brand, 1975), peaking towards the ages of 9 to 10 (Turner & Griffin, 1999) before a subsequent decline during teenage years. For adults however, there is greater confusion, with some claiming motion sickness increases with age (Golding J. F., 2006) (p.71), and others claiming motion sickness decreases with age (Turner M. , 1999). In this earlier paper (Turner M. , 1999) it is explained how familiarity and experience with travel modalities affects motion sickness independently of age. This study (with 3256 participants) provides a stronger argument for the potential age effect in adulthood where the other studies had not considered travel experience as a factor. A greater exploration of age has been given in the literature review (submission 2) where it was concluded that it is not possible to draw robust conclusions about the effect of age (for adults) on motion sickness without an understanding of past travel experience. The exploration of age effects is still of interest and worth exploring in dedicated, fundamental studies, however it will not be the focus of this more applied EngD research. In consideration of the project sponsors motivations, the involvement of children was omitted from this EngD research and there was no motivation to add to the literature discussing the fundamental age effects.

No correlation between the ‘Big Five’ personality traits (extraversion/introversion, agreeableness/antagonism, conscientiousness/lack of direction, neuroticism/emotional stability and openness/closeness to experience) and motion sickness susceptibility have been observed (Nieto & Golding, 2006).

3.3 THE RELATIONSHIP BETWEEN MOTION SICKNESS AND AUTOMATED VEHICLES

Upon the understanding of motion sickness onset and the expected use cases of automated vehicles, it is possible to bring the two subjects together to understand why this technology may increase motion sickness for many people. The main reasons have previously been classified into three key areas (Diels C. , 2014) (p. 303) which has been built upon to help create the classification list below, presented in no particular order:

Table 2 Reasons why Automated Vehicles May Cause More Motion Sickness

Classification	Associated SAE Levels
1 Change of role from active driver to passive occupant	Levels 2, 3, 4 and 5
2 Propensity to engage in non-driving related tasks	Levels 3, 4 and 5
3 Automated vehicle design changes	Level 3, 4 and particularly 5

3.3.1 CHANGE OF THE ROLE OF THE DRIVER

The ability to understand current and upcoming motion is related to the Postural Instability Theory (Riccio & Stoffregen, 1991) where understanding motion is key in effective postural control management. Although the exact theory linking the postural control theory to increased motion sickness through the removal of driving as a task is complicated by the disputes around the validity of the postural control theory itself (Warwick-Evans & Beaumont, 1991) (Warwick-Evans, Symons, Fitch, & Burrows, 1998). However, the reasoning for the increase of motion sickness onset remains. When a driver is no longer required to input lateral and/or longitudinal control there is a reduced ability to anticipate motion and change(s) in acceleration. This phenomenon is known as the ‘Profound Helplessness Reaction’ or, ‘Loss of Control Theory’. This is built upon findings that aircraft pilots in control of the plane do not suffer motion sickness when the rest of the crew do (Geeze & Pierson, 1986), and vehicle drivers do not suffer sickness when driving, despite suffering from motion sickness when being a passenger (Howard & Templeton, 1966) (p. 136) amongst others. A useful text exploring this relationship between control and motion sickness is provided by (Lublow & Rolnick, 1991) who show that through control over a motion task, there is a decreased likelihood of motion sickness onset.

Using the above findings in an automotive context provides an explanation as to why relinquishing control to an automated driving system may increase the chance of motion sickness onset. From SAE Level 2 automation onwards there are significant driver inputs 'taken over' by the car, but it is likely that this effect will be most significant in Levels 3, 4 and 5 where both lateral and longitudinal control is handled by the vehicle simultaneously.

3.3.2 NON-DRIVING RELATED TASKS

It is fairly well established that automated vehicles (specifically Levels 3, 4 and 5) will increase the freedoms to engage in non-driving related activities. Some of which have been discussed in the previous sections where survey data reports people want to engage with their consumer electronic devices such as mobile phones, watch films, read books and complete work-based tasks amongst others. All of these tasks increase eyes-off-road time and therefore the theory of sensory conflict (Reason & Brand, 1975) is of importance. Figure 13 below shows a 'first person view' of an on-road Level 3 or 4 vehicle mock-up for an occupant both driving the vehicle, and engaging in a reading task (a realistic use case for an automated vehicle).



Figure 13 Example of Sensory Conflict in a Conditionally Automated Vehicle

As seen in the image to the left in Figure 13, when driving a traditional vehicle (e.g., SAE Level 0, 1 or 2) the majority of the visual field (highlighted in purple) is of the outside world. Therefore, the visual system is able to detect motion, which will match the somatosensory system and the vestibular system. Given this ability to sense both afferent and efferent motion there is a minimal chance of motion sickness onset in this scenario. However, with the image to the right of Figure 13, the occupant is now reading a book and the majority of the visual field is therefore static with only a limited ability to gain visual information about motion (again, highlighted in purple). In this second scenario (right) the occupant's visual system, registering no motion, will be in conflict to their somatosensory and vestibular system(s). As a result of no afferent motion cues, but still detecting the efferent motion, there is a sensory conflict and motion sickness onset is likely. Although this example is given when reading a book,

the effect is transferable to any task which requires the occupant to take their eyes off the road. Given this, it is discussed and agreed that (considering non-driving related activities in an automated vehicle) “all envisaged use cases can be predicted to increase the risk of motion sickness” (Diels & Bos, 2015) (p. 14).

3.3.3 AUTOMATED VEHICLE DESIGN CHALLENGES

Some concepts for automated vehicles have previously been presented – such as those shown in Figure 4, Figure 11 and Figure 12. It is somewhat expected that future automated vehicles are likely to move away from traditional vehicle design – particularly at the higher SAE levels of automation where traditional driving controls are of less importance. There is further affordance to change vehicle design where there is less reliance for a ‘driver’ to be attentive to the road in the traditional forward-facing seat in front of a large windscreen. As the vehicle takes control of more of the DDT (Dynamic Driving Task) there is a reduced need to stick to these traditional vehicle layouts, and as the desire for non-driving related tasks increases comes the pull to re-design vehicles to allow these other activities. Even with recent ADAS technology, such as parking assists (rear-view cameras, 360 cameras, parking sensors and even self-parking) there has been a slow shift towards reduced need for the driver to have views around the outside of the vehicle. Such technology has afforded the design of DLO’s (daylight openings) to change from being designed with a utilitarian approach, to more of a stylistic approach as is evidenced in many modern vehicles. It is not possible to draw a direct correlation between the increase in technology and reduction in DLO size, but the willingness to change vehicle design is evident.

It is likely that without the consideration of motion sickness, future automated vehicles may want to reduce DLO size, place display screens in the way of DLOs, include a host of new HMI’s (human machine interfaces) in new locations and enable flexible seating (including rearward facing seats). Explanations of why motion sickness will be increased in such designs is evident when combining the above two sections where it is understandable that many of these design choices will limit the ability to predict upcoming motion, manage postural sway, and increase the risk of sensory conflict. It is well established in the motion sickness literature that rearward facing seating should be avoided, but for the first time in an automotive context research showed empirically that rearward facing seating increases the incidence and severity of motion sickness (Salter, Ciels, Herriotts, Kanarachos, & Thake, 2019).

Research published alongside this EngD project (as somewhat of an output from the literature review in Submission 2) further argued the need for motion sickness considerations in the design of future automated vehicles and went on to propose some design recommendations (Smyth, Jennings, & Birrell, 2019). As part of this publication, a categorisation table was developed to break down considerations for motion sickness in automated vehicles – see Table 3 below.

Table 3 Categorising Areas of Motion Sickness Management

Category	Explanation/ Examples
1 – Occupant characteristics	E.g., a person’s natural susceptibility to motion sickness - including demographic differentiation, habituation, clothing, etc.
2 – Interior design	E.g., the design of the cabin including seat layouts, display locations, user interface design, DLO’s, climate control etc.
3 – Vehicle design	E.g., size, height, vehicle dynamics, suspension etc.
4– Activity	i.e., the activity of the person inside the vehicle such as working. E.g., reading, texting on a mobile phone, looking out the window etc.
5 – Driving	E.g., the driving style, speed, acceleration profiles, route motion path etc.

This above table is useful for considering not only physical design but also system design, specifically in relation to category 5 Driving. A full discussion of the impact of automated vehicle design is given in Appendix 1.

3.3.4 WHO WILL GET MOTION SICK IN AN AUTOMATED VEHICLE

Of course, without widespread use of automated vehicles in the present day it is not possible to report on exactly how many people experience (or will experience) automated vehicle motion sickness. However, given the knowledge of how motion sickness is caused and how automated vehicles are intending to be used, a few papers have attempted to gain an estimation on the scale of the issue. One such paper looking at motion sickness onset likelihood for adults riding as passengers in a fully automated vehicle found that 37% of Americans, 40% of Chinese, 53% of Indian people would “experience an increase in the frequency and severity of motion sickness” (Slivak & Schoettle, 2015) (p.5) referring specifically to severe motion sickness. They went on to add that the actual figure might be greater depending on in-vehicle activity and the design of the vehicle. This paper also did not consider more mild cases of motion sickness so again, these figures could be greater still considering all levels of motion sickness.

People surveyed in studies such as in the paper by Slivak, cited above, will have varying levels of trust and acceptance of automated vehicles. Research looking at how trust and situational awareness affects secondary task performance indicated that as trust increases, situational awareness for non-driving-related task completion does too (Peterson, Robert, Yang, & Tilbury, 2019). This indicates that as trust and familiarity within automated vehicles increases, so might peoples engagement with non-driving related tasks. Considering this, it is likely that predictions on how many people will get sensory conflict – induced motion sickness may increase as trust with automated vehicles increases. The increased likelihood of occupants completing non-driving

related activities is one significant reason why motion sickness onset may be more frequent in automated vehicles.

There is no reason to believe that the demographics of motion sickness sufferers will change much, where those who are more pre-disposed to motion sickness currently will likely also be those who are susceptible to motion sickness in an automated vehicle. One thing that is known however, is the strong effect of habituation on motion sickness. Therefore, people who ride often as passengers in traditional vehicles and those who regularly engage in reading, text messaging, work related, or other eyes-off road tasks whilst in a vehicle would, in theory, be more 'prepared' (considering habituation) for the automated vehicle experience. Further, as experience with automated vehicles grows and people use them more frequently, it is perceivable that people may habituate themselves to the experience, gradually increasing their ability to complete eyes-off-road tasks as their experience and habituation increases. However, habituation is somewhat less understood in environments with intermittent exposure (e.g., road vehicles) compared to that of boats or planes, so it is not possible to conclude on the precise effect this may have at present.

3.4 SUMMARY OF THE LITERATURE - PROBLEM IDENTIFICATION

In summary of the previous three sections introducing motion sickness, automated vehicles, and the relationship between the two, the issue of motion sickness and automated vehicles is contextualised. It is understood that motion sickness is likely to be a factor for many users of automated vehicles, especially so if completing non-driving related tasks as many claim they want to do. Even for those who do not claim to want to complete productivity based tasks in a vehicle, with such significant estimates for productivity gains in automated vehicles it seems possible that future employers may expect productivity from their staff as part of a job role.

The implications of motion sickness are relatively well understood considering subjective discomfort – where many people have first-hand experience with the uncomfortable symptoms of motion sickness. Other factors are less understood, where more work needs to be done to understand the impact of motion sickness in relation to the automotive industry considering how, for example, cognitive performance may be impacted. The impact of motion sickness is of consequence for simulator-based user trials as well as automated vehicle use so this must be explored within this research. Further to the impact, methods of reducing or managing motion sickness also needs to be addressed, where existing methods should be summarised and a new method(s) will be explored. If it is likely that many automated vehicle users will experience motion sickness further work is needed in finding mitigation strategies.

Finally, the measurement of motion sickness is of importance for both research and the day-to-day use of automated vehicles to be able to manage, and one day perhaps predict, motion sickness onset.

The problems identified are of interest to the field in general, considering the gaps in the literature and the problem identified, but also align well with JLR's objectives as the sponsoring company.

4 OVERARCHING METHODS

Before the three core projects of this EngD are presented, a few overarching notes on methodology are given. Some measures and methods are used in many of the user trials which make up this EngD, therefore an introduction and explanation of these is given now which applies to all incidences in which these methods are applied.

4.1 SIMULATION SICKNESS QUESTIONNAIRE (SSQ)

The Simulation Sickness Questionnaire (SSQ) (Kennedy, Norman, Berbaum, & Lilienthal, 1993) is perhaps the most common method of measuring motion sickness experienced in a simulator (i.e., simulation sickness). It is comprised of 16 items, which allow participants to rate their severity for each symptom on a 0-3 scale ranging from none (0) to severe (3). The results from this questionnaire allow for a total motion sickness score output and can also be broken down into three subcategories, which include nausea (N), oculomotor (O), disorientation (D). The formula for calculating these categories relies on the selection of questionnaire items associated with each category and multiplying these by a calculated factor weighting as laid out in the original paper (Kennedy, Norman, Berbaum, & Lilienthal, 1993). The total score is calculated using the sum of all weighted scores and multiplying by another factor weighting as explained by Kennedy. In Submissions 3 and 4 total SSQ score was calculated by summing the calculated subcategories before applying a total factor weighting (t_s) to their sum, resulting in a score that was larger, by a factor of ~ 14 , than the original method set out by (Kennedy, Norman, Berbaum, & Lilienthal, 1993). The conclusions derived from the statistical outputs remain unchanged. For the rest of the research the total score calculation followed the same protocol as the original publication. A screenshot of the SSQ as used throughout this EngD research is given below in Figure 14:

SIMULATOR SICKNESS QUESTIONNAIRE
Kennedy, Lane, Berbaum, & Lilienthal (1993)**

Instructions : Circle how much each symptom below is affecting you right now.

1. General discomfort	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
2. Fatigue	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
3. Headache	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
4. Eye strain	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
5. Difficulty focusing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
6. Salivation increasing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
7. Sweating	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
8. Nausea	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
9. Difficulty concentrating	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
10. « Fullness of the Head »	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
11. Blurred vision	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
12. Dizziness with eyes open	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
13. Dizziness with eyes closed	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
14. *Vertigo	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
15. **Stomach awareness	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
16. Burping	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea

Figure 14 Simulation Sickness Questionnaire (SSQ)

The SSQ is very useful for the measurement of motion sickness in a simulator, and as seen, includes a consideration for the measurement of oculomotor discomforts as well as a dedicated oculomotor subscale. This is important for simulator use where the inclusion of large display screens and dependence on efferent motion cues often induce oculomotor discomfort. To derive the total score as well as the subcategory scores the original author provides weightings to be applied. These weightings are included to provide ease of comparability when plotting results on a graph.

4.2 MOTION SICKNESS ASSESSMENT QUESTIONNAIRE (MSAQ)

Looking for motion sickness assessment measures for more ‘real-world’ motion sickness the Motion Sickness Assessment Questionnaire (MSAQ) was used (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001). This questionnaire comprises of 16 items whereby participants rate their subjective severity of each symptom on a scale of 1 (not at all) to 9 (severe). The results of this questionnaire allow for the calculation of a total score alongside four subscales including Gastrointestinal (G), Central (C), Peripheral (P) and Sopite-related (SR). Total score is calculated as a percentage of total points scored, similarly the subscales are calculated as a percentage taking into account the number of items associated with each subscale. The screenshot below shows the original design of the questionnaire, however the questionnaire used in this

EngD used a modified layout whereby the scale from 0-9 was presented alongside each questionnaire item for ease of use.

MOTION SICKNESS ASSESSMENT QUESTIONNAIRE (MSAQ).

Instructions. Using the scale below, please rate how accurately the following statements describe your experience

Not at all Severely

1—2—3—4—5—6—7—8—9

1. I felt sick to my stomach (G)	9. I felt disoriented (Q)
2. I felt faint-like (C)	10. I felt tired/fatigued (S)
3. I felt annoyed/irritated (S)	11. I felt nauseated (G)
4. I felt sweaty (P)	12. I felt hot/warm (P)
5. I felt queasy (G)	13. I felt dizzy (C)
6. I felt lightheaded (C)	14. I felt like I was spinning (C)
7. I felt drowsy (S)	15. I felt as if I may vomit (G)
8. I felt clammy/cold sweat (P)	16. I felt uneasy (S)

Note. G; Gastrointestinal; C: Central; P: Peripheral; SR: Sopite-related.

Figure 15 Motion Sickness Questionnaire (MSAQ)

There is a slight error made in the formulas given in the original MSAQ (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001) which appears to be a typing error. The calculation for ‘central’ should also include the questionnaire’s item 9 ‘I felt disoriented’ which has mistakenly been given the subscale reference as ‘Q’.

4.3 FAST MOTION SICKNESS SCALE (FMS)

Both of the above methods of motion sickness assessment are implemented directly after an exposure to a motion sickness related task and capture the subjective scores at the time directly after exposure. A method of measuring subjective motion sickness in ‘real-time’ is also of use where motion sickness can be tracked and measured throughout a motion sickness exposure. A method for measuring this is given by (Keshavarz & Hecht , 2011) who present a ‘Fast Motion Sickness Scale’ (FMS). This scale requires participants to report their motion sickness on a scale of 0 (none at all) to 20 (frank sickness). An explanation is given to participants whereby their consideration to motion sickness symptoms should “focus on nausea, general

discomfort, and stomach problems” (Keshavarz & Hecht , 2011) (p.418). There are a few ways in which the FMS score can be calculated for overall discussion, including taking the mean score of all scores given, the peak score given or the final score given. The authors recommend the FMS peak score as the most useful metric of overall motion sickness severity for a scenario. This scale was used for two reasons. Firstly, there was already familiarity with this tool within the sponsoring company, therefore results could be disseminated effectively and it provided the option to compare results if required. Secondly, where it was understood that comparisons of ‘real-time’ motion sickness to physiological measures would be of interest, the scale from 0-20 allowed a precise rating. Other scales such as the ‘misery scale’ (MISC) (Bos, MacKinnon, & Patterson, Motion Sickness Symptoms in a Ship Motion Simulator: Effects of Inside, Outside, and No View., 2005) has also proven to be of great utility in recent literature, although the MISC but utilises less precise rating scale of 1-7, making it less precise, albeit perhaps more simple for participants.

4.4 EMPATICA E4 PHYSIOLOGY WRISTBAND

In addition to measuring subjective motion sickness in many of the user trials completed as part of this research, physiological measures were also recorded. The utility of physiological measures are often disputed considering motion sickness, and this argument will be explored within the research summarised in Project C of this Innovation Report. However, as the physiology equipment was used in multiple studies a brief explanation is given. The Empatica E4 wristband (Empatica Inc. , 2016) is a non-invasive wrist mounted device used to collect physiological data including heart rate (and derivations thereof), skin temperature, electrodermal activity (EDA) and motion. It requires no electrolyte gel and mounts on the wrist with no significant expectation of discomfort. . Evidence of its utility has been shown in recent publications such as (Betancourt, Dethorne, Karahalios, & Kim, 2017) and (Melnicuk, Birrell, Crundall, & Jennings, 2017). An image of the E4 is presented below in Figure 16:



Figure 16 Empatica E4 Wristband

4.5 THE 3xD SIMULATOR

The '3xD Simulator' is a drive-in, driver-in-the-loop driving simulator located at WMG at the University of Warwick, UK (The University of Warwick, WMG, 2016). This was used for all of the simulator studies conducted for this EngD. An image of the simulator is presented below:



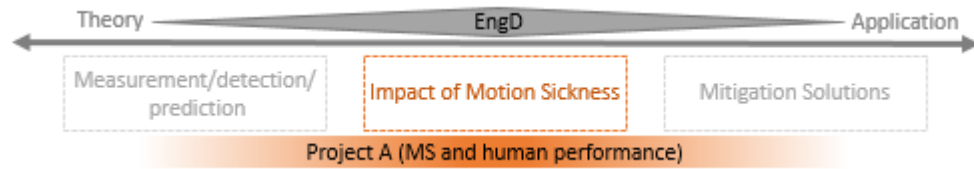
Figure 17 3xD Simulator

This simulator features a 360-degree screen providing a seamless projection of the created world from all viewing angles when inside the vehicle. The BUC (built up chassis) used within all experimentation was a Range Rover Evoque as photographed above. For all research, all driving related controls are linked to the simulation so the driver has complete control over the steering, braking and acceleration of the vehicle. Temperature can be controlled within the vehicle and a camera is used inside to monitor participants. There is a 2-way radio system allowing communication between the participant and the researcher in the control room.

5 MOTION SICKNESS AND HUMAN PERFORMANCE (PROJECT A)

This project stemmed from the literature review discussed in Submission 2 where much of the background literature is presented and discussed. The two user trials which make up this project were written up as separate submissions and presented as Submission 3 and Submission 4 for ease of documentation (see the portfolio plan in Figure 6 for further details). The results from Submission 3 and as presented in this

section have been used for two publications. The first explored the binary effect of motion sickness on human performance (Smyth, Birrell, Mouzakitis, & Jennings, 2018) and the second looked for a scale to the observed effect (Smyth, Jennings, Mouzakitis, & Birrell, 2018). The results from Submission 4 were used internally within JLR for validation of the UK AutoDrive user trials.



5.1 BACKGROUND

Driving simulators are very useful tools for developing and testing new technology and have many benefits. The immediate benefit is that of safety – particularly when the technology involves interaction of the driver where, without understanding the potential risks of the technology such as distraction, invasiveness or influence on driving behaviour on-road trials should be avoided. A driving simulator provides a safe environment in which to test prototype technology where, in the worst instance the driver cannot come to physical harm if they make a driving error. Further benefits that are particularly useful for scientific research are the controllability and repeatability that driving simulators offer. In a simulated environment, the researcher can have complete control over all conditions including (but not limited to), road layouts, events and traffic. This allows for greater validity when testing technology in specific use cases and allows for the creation of many varied scenarios to test the new technology. With this controllability comes another benefit – which is repeatability. In many instances, particularly when looking for variations between or within a demographic set it is imperative that everyone receives the same ‘stimulus’ (dependent variable) on which their response (the independent variable) can be measured. In a driving simulator example, it is possible to test technology in exactly the same environment and scenario multiple times. This is not possible in the ‘real-world’ where it would be near impossible to orchestrate the same events to happen in the same way multiple times and factors such as changing traffic conditions, weather and external events etc. will all limit the repeatability of the study. This ability to create repeatability between trials also highlights the benefit of testing time that simulators can bring. With the ability to run scenarios one after the other a driving simulator offers a great time saving benefit where on-road studies may take much longer to set up and run.

The list of benefits discussed above is not exhaustive and there are many more benefits to driving simulators. However, there are of course some drawbacks of this technology. The most frequently discussed challenge is that of transferability of data

collected in a simulator to 'real-world' applications. There are many aspects to this challenge of transferability – many of which are dependent on specific trials. For example, a study measuring headway as the independent variable (i.e., distance maintained between the driver's car and the car in front) may want to consider distance perception disparity between the simulator and the real-world. A study measuring eyes-off-road time might consider risk perception where participants may be more likely to have extended eyes-off-road time if they do not perceive physical danger of a driving error. One particular challenge however, which spans across almost all simulator studies, is the propensity to experience motion sickness in a driving simulator. It is known that motion sickness onset is an unpleasant physical experience and often manifests in nausea, sweating, dizziness, fatigue and sometimes even vomiting (amongst other symptoms). However, aside from these subjective discomforts, there is also the possibility that motion sickness may influence human performance and thus affect the validity of user trial results. Further to this, the consequence of motion sickness on performance may have further implications for the automotive industry as a whole where motion sickness is often experienced in car travel (car sickness) and is likely to be experienced also in future automated vehicles.

5.2 INTRODUCTION

As previously discussed, it is possible that motion sickness can be experienced in a simulator where the visual system can gain information on efferent motion, but without any afferent motion to match, sensory conflict is likely. This is true in both fixed and moving-base simulators where even those which have motion may not be able to replicate the expected physical motion as the occupant might expect so the disparity between the visual, vestibular and somatosensory system still remains. Below illustrates why sensory conflict is likely in a driving simulator:



Figure 18 Motion Sickness in a Driving Simulator

Looking at Figure 18 above it is clear to see why sensory conflict may be likely in this scenario. The majority of the visual field is sensing motion (highlighted in purple) whilst the vestibular and somatosensory systems are detecting no motion, hence a conflict is likely. In fact, it is not uncommon in driving simulator trials to see around 25% of participants end the study early due to severe motion sickness as a 'rule of thumb'. Looking at actual data, one study showed it is possible to have 50.3% of participants drop out of a user trial (Reed, Diels, & Parkes, 2007). Another study reported 52 out of 88 participants dropped out of a simulator study due to motion sickness (59%) (Matas, Nettelbeck, & Burns, 2015). A meta-study of such MS looking at multiple user trials (Balk, Bertola, & Inman, 2013), reported the highest dropout rate in one trial was 71% (pp. 259), where the mean drop-out percentage was 14% between the 9 user trials this paper reviewed. The results from all these studies only speak to drop-outs - it is expected that many more people will experience at least some degree of simulation sickness in a driving simulator even though it is not severe enough to make them drop out.

Considering the likelihood of motion sickness onset in a driving simulator, there is good reason to further investigate the effect of such sickness on human performance. There is limited literature directly discussing the effect of motion sickness on driving simulator user trial data, so the literature was explored with a wider scope looking for any motion sickness state and its relationship to human performance. Firstly, a tank simulator study from 1995 reported that "simulator sickness does degrade training effectiveness for some trainees" (p.36) (Lampton, Kraemer, Kolasinski, & Knerr, 1995) where the training effectiveness is not a transferable measure. Lampton and Kraemer go on to advise that simulator users should not drive a physical vehicle directly after the simulator exposure due to their understanding the performance would be degraded. This recommendation is commonly found in the literature, for example, one driving simulator research paper recommended that motion sickness "can affect performance after the simulator experience" (p.795) (Brooks, et al., 2010). Where they reference "problems with hand-eye coordination or postural instability that could interfere with the real-world task of driving home" (p.795) see also (Jones, Kennedy, & Stanney, 2004) and urged participants not to drive immediately after the study. This recommendation was based on the findings that use of virtual environments "could directly affect visuo-motor coordination" (p.29), where virtual environments can induce similar motion sickness effects to other motion sickness prone activities (Stanney, Kennedy, Drexler, & Harm, 1999).

One study looked at a job-related cognitive task (exact task is unspecified) and found that when motion sick (seasickness) the inability to complete the task increased from 5% to 60% (Bos J. E., 2004). This decrease in cognitive function was supported by another paper (Colwell, et al., Human Performance Sea Trial QUEST Q-303), which was part of a larger seasickness project showing how cognitive task performance decreased

with increased motion sickness symptoms. This project (Quest 303 trial) is perhaps one of the most useful series of experiments in this area where a three-phase seasickness experiment saw participants assessed in pre-exposure over four days whilst the boat was docked at harbour. This was followed by an exposure phase of eight days at sea with varying sea conditions (and therefore varying motion sickness states) and finished with a one-day post-exposure phase with the ship anchored in sheltered waters. The project was written up in more depth in an internal report (Bos, et al., 2008) which explains how researchers assessed cognitive performance using the Vigilance and Tracking Test (VigTrack) (Valk, Simons, Struyvenberg, Kruit, & van Berge Henegouwen, 1997) alongside the Multi-Attribute Task Battery (MAT) (Comstock & Arnegard, 1992). The first assessment tool (VigTrack) was originally designed for aeroplane pilots, where the test was designed to relate to specific tasks pilots were expected to be able to perform. Therefore the use of this measurement in a seasickness trial may not be useful for specific job-based task completion, however it should still give a useful report on human performance when studying pre-exposure and exposure scores. The task, despite being validated by its authors in other studies, doesn't appear to be a purely cognitive task as there is a heavy reliance on visual tracking of an object on a computer screen. Thus, it is likely visual performance also will impact test results. No attempt to address visual implications or counter them was discussed.

Looking then for any relationship between visual performance and motion sickness one study looked at visual acuity (i.e., the ability to perceive detail) where a Dynamic Visual Acuity test was used as previously developed (Toet & Bos, 2002). In this study they found "consistent behaviour: in all tests sick subjects showed worse acuities" (p.22) (Bos, et al., 2008). This was written up in a separate report which concludes "a highly significant effect of seasickness on acuities" (Bos, Hogervorst, Munnoek, & Perrault, 2008) (p.1). Further research by NASA looked to improve task performance ability by reducing motion sickness. Although they did not report specific measures used to record task performance (as it was related to job task) they did find it was possible to increase task completion ability significantly by reducing motion sickness (Stroud, Harm, & Klaus, 2005) with a speed increase of 12% and decrease in errors over two conditions of 39% and 34%.

In summary of the literature, it is shown that motion sickness affects human performance in a number of ways – specifically when looking at job completion. There is a need therefore to understand to what extent various fundamental areas of performance are affected by motion sickness (where many of the cited texts are related to specific work-task related activities). Being able to understand the effect of motion sickness on performance will provide a better insight to the transferability of simulator data to real-world where it is known that people are likely to feel at least some level of motion sickness in a simulator. The research question is therefore set:

Does simulation sickness affect human performance?

The benefit of such a study is of further interest to the automotive industry however, where this Innovation Report has already detailed reasons why future automated vehicles may induce motion sickness for a considerable percentage of the population. There is added interest to begin to consider if someone is motion sick in an SAE Level 2, 3 or 4 vehicle is it likely that their performance will be degraded and therefore will this have an impact on their ability to monitor or regain control of the vehicle. This is of interest as it is understood that non-driving related tasks (such as reading, or watching films) may be desirable in automated vehicles and these tasks are likely to induce motion sickness in vehicle occupants. Although motion sickness may be avoided through the choice not to engage in these tasks, it has already been discussed in this Innovation Report that future employment may require work-based tasks where motion sickness may be unavoidable. Although for this study, the research question does not extend to automated vehicle applications, the concept remains for discussion and adds further justification for the importance of understanding this link between motion sickness and performance.

The hypothesis of this study is that human performance is reduced when experiencing motion sickness.

5.3 METHOD

To answer the research question a two-part user trial was devised. Phase 1 will take part in the 3xD simulator at the University of Warwick, and Phase 2, will take part in the RDM SAE Level 4 pods as part of the UK AutoDrive project in Coventry, UK (UK Autodrive, 2019).

5.3.1 HUMAN PERFORMANCE ASSESSMENT

In order to answer the research question concerned with the relationship between motion sickness and human performance it must first be established what 'human performance' is for the purpose of this study. There are hundreds of specific driving tasks that could be measured and with future automated vehicles, there are many more undefined actions that may be expected of a driver/occupant. It would not be practical to measure all driving related performance measures. The limitation of some of the previously cited works was in regards to their transferability where many performance metrics were specific to a unique work-based task and therefore do not necessarily inform on any potential relationship with another task. It was decided that fundamental human performance should be measured which includes visual ability, cognitive ability and physical ability – where auditory ability was omitted as it is not

necessary for driving. The Venn diagram in Figure 19 below maps out the areas of performance to be assessed where the intersections of are also highlighted.

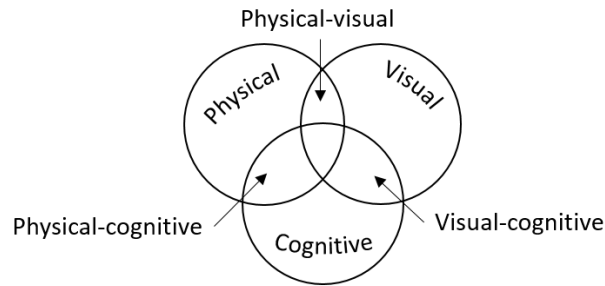


Figure 19 Human Performance Diagram

Using the above diagram to measure the six areas of human performance it is possible to apply the findings to any task which falls into one or more of the categories above. For example, although this trial will not directly measure the affect of motion sickness on comprehension of road signs, the results from the visual-cognitive section may lend themselves to this application. It is hoped that many driving tasks can be mapped to this diagram, therefore allowing for an understanding of motion sickness for many tasks, rather than looking at single specific driving tasks themselves. Table 4 below gives some examples of what type of task could be ‘mapped’ to the fundamental abilities to be explored:

Table 4 Examples of Driving-Related Tasks

Performance area	Example of driving-related task
Visual	<ul style="list-style-type: none"> Identifying road signs Reading in-vehicle notifications Identifying obstacles
Physical	<ul style="list-style-type: none"> Dexterous interaction with out-of-sight HMI or HMI when not looking directly at it Physical manipulation of vehicle controls
Cognitive	<ul style="list-style-type: none"> Situational awareness of environment Route planning Appraisal of danger
Physical-Visual	<ul style="list-style-type: none"> Interaction with HMI (Human Machine Interface) or in-vehicle controls (hand/eye coordination)
Physical-Cognitive	<ul style="list-style-type: none"> Interaction with variable controls (such as rate of braking or acceleration) Emergency driving manoeuvres (reaction time in emergency braking)
Visual-Cognitive	<ul style="list-style-type: none"> Identifying upcoming dangers Predicting traffic flow (for example, when approaching a junction) Estimating distances for braking consideration

To assess the areas of human performance set out in Figure 19 six individual tests were needed. There were a few criteria, which the tests should meet:

- These tests should be pre-designed, pre-validated and used in other published research to ensure transferability, validity and reliability
- Each test should take no longer than 60-seconds to complete (<six minutes for the entire set) so they can be completed before motion sickness recovery, where subjective sickness can decline rapidly within the first 5-10 minutes (Goulding & Stott, 1997).
- They should have no 'learning effect', so that after the initial practice with the task, performance should not get better with repeat exposure
- They should represent the category which they are assigned (as per Figure 19), isolating the specific ability without requiring abilities from other areas of performance

Through an extensive review of the literature six tests were found, one for each of the areas of performance presented in Figure 19 which are presented below:

Test 1 - Visual performance: A visual acuity (VA) ETDRS LogMar test chart was used whereby participants would use only their dominant eye, standing at a set distance and read out the letters presented on the chart. They were scored on the total number of letters read. Visual Acuity (VA) is the ability to perceive detail and is quick and easy to administer. There are many other visual abilities that could be measured such as depth perception, flicker fusion, stereopsis etc. however, all these take longer than 60-seconds to administer and require specialist equipment. It must be noted that when referring to 'visual ability' this project is just referring to visual acuity. A screenshot of the test is shown below:

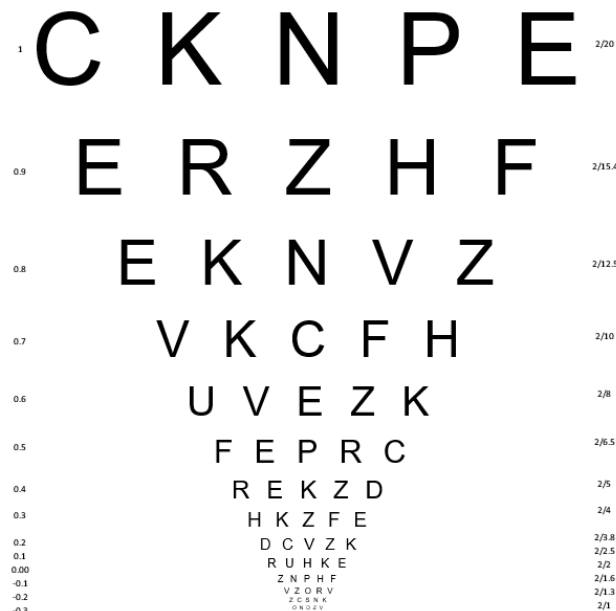


Figure 20 Visual Acuity Test

Test 2 - Physical performance: A card turning test was extracted from the 'Jebson Taylor Hand Function Test' (Raad, 2012). This test is used to measure physical skill and

dexterity in its original design. The cards used were 3" by 5" index cards as required by the standardized test. The cards were white and set on a dark grey table. Although there is visual ability required to identify the cards it is considered the visual requirements are extremely low where the cards are clearly identifiable, of sufficient contrast and size and would be used by people who are able to drive so it is assumed eyesight in normal conditions will not be a problem. As explained in the Jebson Taylor Hand Function Test, participants were scored on the time taken to turn over all cards for both their dominant and non-dominant hand independently. An image of someone completing the test is shown below:



Figure 21 Card Turning Test (UAB OTCLASS, 2014)

Test 3 - Cognitive performance: A 'Paced Visual Serial Addition Test' (PVSAT) was used, which is a visual version of an n-back test (for n-back see (Kane, Conway, Miura, & Coleflesh, 2007)). A visual version was preferable where ordinarily this test is given audibly, however, without the knowledge of audible skills, ability to distinguish accents for participants and hearing variability between participants a visual test was preferred. Numbers (from 1-10) were presented on a screen and participants had to add the current number to the previously shown number (i.e., 1-back) and give the answer verbally before the next number appeared. A 200pt font size with black text on a white background was used and the numbers were presented on a Microsoft Surface Pro 4 with a display screen of 31cm. It is believed the clear representation of the numbers is sufficient to isolate cognitive performance by reducing any effect of visual performance. Participants were scored on the number of correct answers. An example of the test is given below:

- if the first number is 3 the participant doesn't answer.
- if the second number is 5 the participant answers 8 (3+5)
- if the third number is 9 the participant answers 14 (5+9) etc.

A screenshot of the display screen is shown:



Figure 22 N-Back Test

Test 4 – Visual-cognitive performance: A modified mental rotation test (MRT) was used (Peters M. , et al., 1995) whereby a ‘target’ 3D shape was presented on paper to the participant with four other shapes, their task was to identify which two of the shapes matched the target shape, despite being rotated into a different orientation. The test usually takes upwards of three minutes to complete however, to reduce the time requirements just four questions were extracted from the full test and participants had to complete the four questions as fast as possible. This deviation from the standard test reduces the transferability of the results to other studies using an MRT test, but due to time restrictions it was a necessary compromise. Participants were scored on completion time and the number of correct answers (i.e., if they gave the two correct shapes per question). Two example questions are given below where the target shape is highlighted by a thick border and the two correct answers for each question (i.e., those which match the target shape) are highlighted by red circles for illustrative purposes:

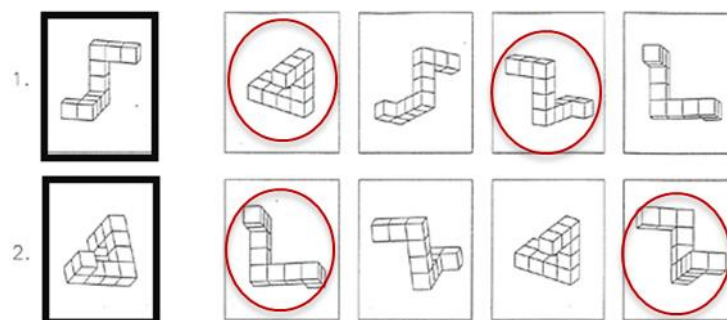


Figure 23 Mental Rotation Test (MRT)

Test 5 - Physical-visual performance: The Perdue Pegboard (Radd, 2014) was used to measure physical-visual performance. This test requires the physical dexterity and visual skill of locating pins in small holes. There are a few ways in which this test can be administered including constructing pins with washers and spacers. However, the basic version of just placing the pins in the holes was chosen as it was quicker to administer. Participants were tested with their dominant and non-dominant hand independently and were scored on the number of pins they put in the holes in the time given of 60-seconds. An image of the test being completed is shown below:



Figure 24 Perdue Pegboard (OPC Health, 2018)

Test 6 – Physical-cognitive performance: A reaction time test was used whereby a large traffic light was displayed on the Microsoft Surface Pro 4 screen, When the bottom green light illuminated (within a random length of time between 1 and 6 seconds) the participants had to press a physical button on a wired computer mouse. The amber light does not illuminate in this test. This test depended on cognitive processing speed and the physical response to press the button. Again, there was a visual aspect to this test, however, the traffic light was very large so easy to identify and given the spatial layout of a traffic light (familiar for all participants who all had a driving license) they will be able to identify the change with minimal visual skill. Participants were timed for five consecutive repetitions and their score was derived from the average of the five measurements. A screenshot of the test is shown below:

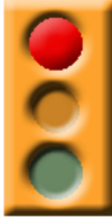

Test Number	Reaction Time	The stoplight to watch.	The button to click.
1	0.33		
2	0.306		
3	0.315		
4			
5			
AVG.	0.317		

Figure 25 Reaction Time Test (Allen, n.d.)

A summary of the six tests chosen to assess the human performance areas (as identified in Figure 19) is given below in Table 5.

Table 5 Tests of Human Performance

Test number	Test area	Test name
Test 1	Visual	ETDRS LogMar Visual Acuity
Test 2	Physical	Jebson Taylor Hand Function – Card Turning
Test 3	Cognitive	Paced Visual Serial Addition Test - PVSAT
Test 4	Visual-Cognitive	Mental rotation test
Test 5	Physical-Visual	Perdue Pegboard test
Test 6	Physical-Cognitive	Reaction time

For Phase 1 of this study, the battery of six tests will be given to participants a total of three times each. For that reason, Tests 1, 3 and 4 (as per Table 5) were created three times each, each including a different set of questions so the participant did not see the same questions more than once. Each time the battery of tests were given, the order in which they were received was randomised. The first exposure to the tests is to teach the participants how to complete the test. The researcher will explain all instructions and give the participant a chance to try the tests– repeating the same test if required until familiar with the process. The second time they complete the tests will be to measure baseline performance in a non-motion sick state. The third time they complete the tests will be after a motion sickness exposure where their motion sickness will also be measured and the difference between their baseline scores and ‘motion sick’ scores will be studied.

For Phase 2 of this study only the cognitive and cognitive-physical tasks were used (Tests 3 and 6 as per Table 5). There was a significant time restriction as this trial was running alongside the JLR UK AutoDrive user trials so only a total of seven minutes available for data collection (including questionnaires etc.). These two tests were chosen after Phase 1 was complete as they were identified as being particularly interesting considering motion sickness.

5.3.2 PROCEDURE FOR PHASE 1 – A SIMULATOR STUDY

For Phase 1 of this two-part study design the participants will use the 3xD driving simulator where motion sickness (specifically, simulation sickness) will be measured. 51 participants were recruited for this user trial using a convenience sampling technique. There was limited opportunity to collect pre-trial information for screening participants. Use of the motion sickness susceptibility questionnaire (MSSQ) (Golding J. F., 1988) in the trial itself was considered but omitted to ensure participant engagement time was kept under 60 minutes as requested within the guidelines from the BSREC committee. Participants were required to be aged between 18 and 65 and have normal or corrected to normal eyesight to take part. Upon arriving at the simulator at their agreed timeslot the trial was explained to them, they read through the participant information leaflet, signed the consent form and completed a demographics questionnaire. They were then trained on how to complete each of the

six human performance tests before their baseline scores were recorded. Participants were given a Simulation Sickness Questionnaire (SSQ) to complete to identify any baseline symptoms (such as if participant had a pre-existing headache or fatigue) so this could be filtered out from post-exposure scores. Participants were also asked to wear the Empatica E4 wristband and their physiology was tracked throughout the study.

Participants were introduced to the 3xD simulator and given full instructions on how to operate the vehicle. The vehicle cabin was maintained at a stable 21 degrees Celsius throughout the study. The route was designed specifically for this user trial and began with an 8-minute familiarisation run, which consisted of a straight road at a constant speed (30mph). The concept of a familiarisation run is supported by (Reed, Diels, & Parkes, 2007) and this is considered an ethically appropriate way to begin a simulator-based study to reduce the chance of immediate severe motion sickness. The main test route followed directly on from the familiarisation route where gradual bends and changes in speed were slowly introduced. The route consisted of a mixture of country, rural and motorway roads and takes approximately 30-minutes to complete. The final 10-minutes of the route were particularly challenging with increasingly complex bends and junctions which were designed to challenge participants who have a particularly low susceptibility to motion sickness. Throughout the route, automated 'sat-nav' style instructions were played through the in-car speakers to the participant so everyone took an identical route. Multiple speed signs ensured participants completed the drive at a similar pace and road blocks ensured that only one route was possible to follow – although the researcher monitored driving progress throughout.

Whilst driving the simulator, participants were able to speak to the researcher through the 2-way radio system whilst the researcher sat in the control room. Participants were asked once every minute to rate their motion sickness as per the FMS design (Keshavarz & Hecht, 2011). Participants were reminded at the beginning of the driving scenario that if any time they felt too unwell and wanted to end the study they should say so right away and the driving task can be stopped. If the researcher noted a particularly severe increase in FMS scores or a participant appeared to be getting more uncomfortable the researcher prompted the participant to consider if they were fit to continue. There was no specific criteria used to classify a 'severe increase' in FMS score. It was expected that scores would gradually increase, but if this increase became uncharacteristically high for that given individual, the researcher would ask the participant if they were fit to continue.

At the end of the drive, participants came back to the control room (connected to the main simulator) and immediately completed the battery of six tests again, in a randomised order. All tests were completed within 6-minutes of the scenario ending. After this, another SSQ was given where participants were asked to rank their motion

sickness between ending the driving scenario and until this point. Even if participants asked to end the driving early, they were still eligible to complete the six tests and SSQ as long as they were happy to do so, as the length of driving was not a variable of interest, rather their motion sickness state was of interest. All participants were reminded that if they feel unwell, to stay and recover as long as necessary and to not drive a car for at least 1 hour after the simulator exposure, and until they feel well enough to do so. This user trial was approved by the University of Warwick Biomedical & Scientific Research Ethics Committee (BSREC) with the reference: (REGO-2017-2090).

A photo of a participant taking part in the study is shown below in Figure 26 (with permission given by the participant to publish this photo).

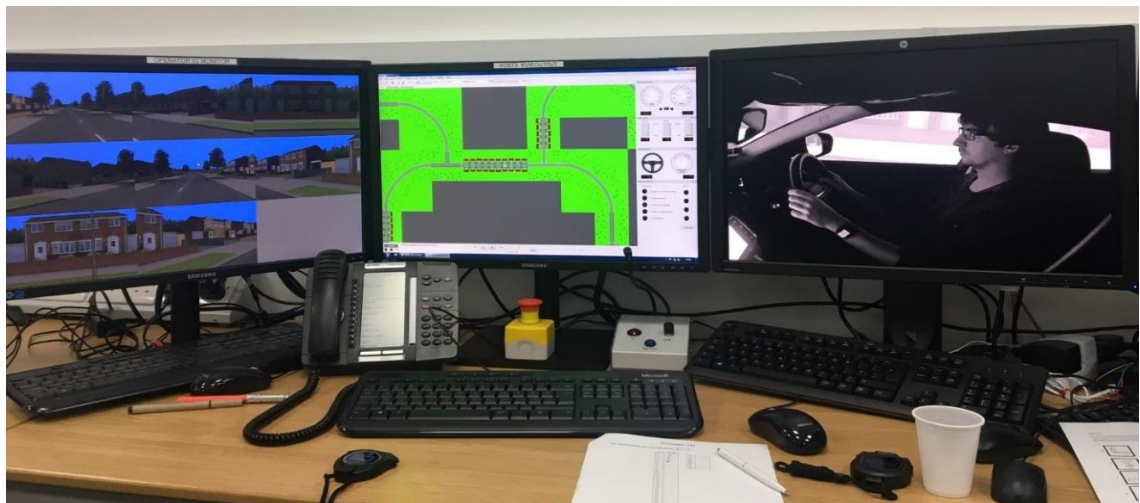


Figure 26 Human Performance Simulator Study (Phase 1) From the Control Room

An example of what the participant might have seen whilst in the vehicle is also shown below in Figure 27:



Figure 27 Human Performance Simulator Study (Phase 1) Inside the Simulator

5.3.3 PROCEDURE FOR PHASE 2 – A ‘REAL-WORLD’ STUDY

Phase 2 used the UK AutoDrive trials (AK Autodrive, 2018) on which to collect additional data using 17 participants - none of whom had completed the simulator study in Phase 1. For this trial, the overall trial design was already set out by the JLR research team. Given this, there was no chance to contribute to the trial design and the study had to be written around the existing research plan. 7-minutes were given for data collection for this motion sickness study. When participants arrived at the facility they were given the SSQ to complete to capture any baseline conditions. Although the MSAQ would have been more appropriate for this ‘real-world’ study, it was important that results would be transferable to the simulator study in Phase 1 so the SSQ was a necessary comprise. The SSQ has been used in on-road studies successfully previously (Salter, Ciels, Herriotts, Kanarachos, & Thake, 2019) so it was still deemed an appropriate tool. After completing the baseline SSQ, participants were then introduced to the cognitive and cognitive-physical tests as previously explained and as presented in Table 5 Tests of Human Performance. They had a chance to learn how to complete the tests and then baseline scores were measured where the tests were given in a random order.

The self-driving pod exposures formed the core of the user trial for the organisers, this process saw participants sitting in the self-driving pod for 8-minutes whilst the pod drove around a test facility. Participants were not allowed to complete any task inside the pod (use their phone, read a book etc.) so were asked to just sit and observe the ‘scenery’. After the 8-minutes, participants exited the pod and completed a questionnaire about trust, sitting in a waiting room whilst another participant was in the pod. This cycle of 8 minutes in the pod, 8 minutes out was repeated four times. The total number of exposures to the pod was four, with a total time in the self-driving pod being 32-minutes. The test track was based within an approximately 24m by 34m warehouse and the pod followed a pre-programmed route through the track turning, braking and accelerating autonomously. The pod travelled at 2.5m/s (approx. 5.6mph) on the straights and slowed to 2m/s (approx. 4.5mph) for the corners. An image of a pod as used in this trial is shown below in Figure 28:



Figure 28 RDM UK AutoDrive Pod

Also shown below is an approximate layout of the warehouse where the user trial was conducted.

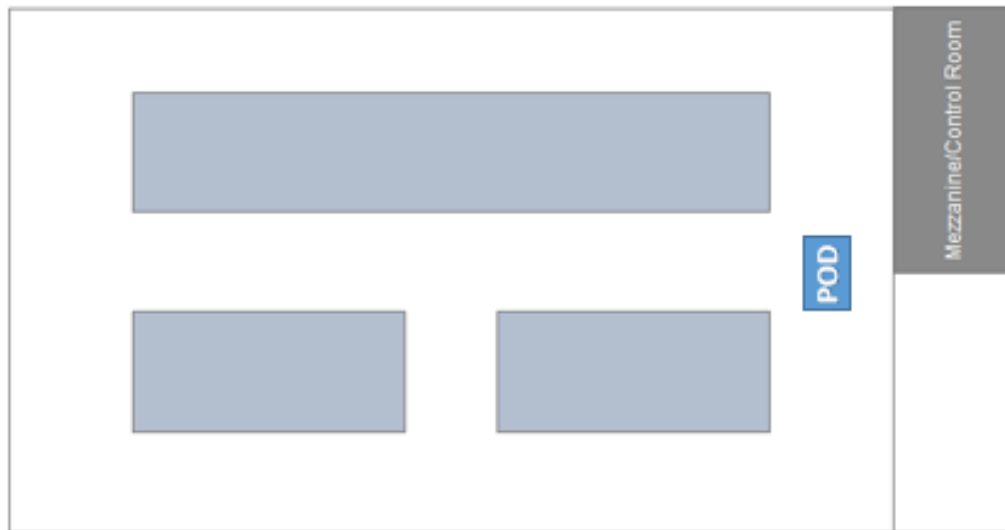


Figure 29 Layout of Test Facility

No photos of the pods or test facility were allowed at the time of testing and no dimensions or measures of test circuit or vehicle dynamics could be collected.

After the final pod exposure participants came to the control room and immediately completed the two performance tests (cognitive and cognitive-physical) in a random order and completed another SSQ to give comparative results. Although participants completed the performance assessments only at the end of all four exposures (with gaps in-between each exposure), it is understood that total motion sickness recovery is greater than 8 minutes and certainly not less than 10 minutes (Goulding & Stott, 1997), so residual effects in-between exposures would be expected to 'carry over'. This, although not an ideal experimental procedure was the best achievable methodology considering the practical limitations of this collaborative research.

The hypothesis of this experiment was that if motion sickness was induced, this would be responsible for a reduction in human performance

5.3.4 DATA ANALYSIS

The statistics package SPSS (version 26) was used for analysis of results where people who dropout of the driving scenario due to motion sickness as a group were compared to those who completed the entire drive. This grouping method is an effective way of categorising motion sickness objectively whilst ensuring the outcomes of analysis will be practical to inform the overall research question. Mixed ANOVA's were the primary method of analysis, but were supported by further t-tests, one-way ANOVAs, Welsh ANOVAs, Sign tests and Wilcoxon Signed-Rank tests, where appropriate. In all cases

significance levels are reported, but the threshold of 95% significance ($p \leq 0.05$) is being used.

5.4 RESULTS

5.4.1 PHASE 1 – A SIMULATOR STUDY

51 participants took part in Phase 1 of this user trial, including 27 males and 24 females. The minimum participant age (measured using age ‘brackets’) was 22 ± 4 years, with a maximum age of 49 ± 4 years, a mean age of 31 and a standard deviation of 10.13. Exact reporting on ages is not possible where age groups were used. In total, 45% of participants ended the study early due to MS (N=23), including 26% of males (N=7) and 67% of females (N=16). These participants are referred to as ‘dropouts’ and make up ‘Group 2’. Group 1 participants include all the participants who completed the full driving scenario and were not severely motion sick. All dropouts still completed the post-driving the SSQ and six performance tests. SSQ scores were collected and calculated to give a ‘total’ score and a score for the three subcategories (‘nausea’, ‘oculomotor’ and ‘disorientation’). An exploratory analysis was conducted where scores were reported for ‘pre-driving’ (i.e., scores reported before the driving task) and ‘post-driving’ (i.e., the scores reported directly after the driving task) including mean and standard deviation (SD) and this is presented below in Table 6.

Table 6 Exploratory Analysis of the Subscales of the SSQ

SSQ Category	Pre-Driving		Post-Driving	
	Mean	Pre-Driving SD	Mean	Post-Driving SD
Nausea	3.18	7.05	44.71	32.74
Oculomotor	6.66	11.39	33.44	21.66
Disorientation	2.95	7.38	52.68	42.8
Total	3.667	4.701	35.166	23.287

As seen, motion sickness was increased across the group where, on average, simulator use caused a total motion sickness score of 31.499. Table 7, below now looks at delta scores (i.e., change in sickness) for Group 1 (those who completed the driving) and Group 2 (those who dropped out due to sickness). All delta (Δ) scores for statistical analysis were calculated on an individual basis (post score minus baseline score) before the mean was taken for the group.

Table 7 Motion Sickness for Group 1 and Group 2

SSQ Category	Group 1 Δ		Group 2 Δ Mean	Group 2 SD
	Mean	Group 1 SD		
Nausea	22.279	30.221	62.856	30.376
Oculomotor	33.308	35.809	71.416	42.658
Disorientation	25.989	21.581	29.661	21.910
Total	23.232	21.244	41.557	19.740

Looking at the SSQ scores comparatively between those who completed the driving (Group 1) vs those who dropped out (Group 2) a one-way ANOVA reveals significance for three of the four SSQ categories. Where dropouts had a significantly higher Δ Total SSQ score ($F=10.009$, $p=0.003$), Δ Nausea score ($F=16.453$, $p<0.001$), and Δ Oculomotor score ($F=12.305$, $p<0.001$). However there was no significant difference between those who completed the driving scenario and dropouts for the Disorientation subscale ($F=0.361$, $p=0.551$). Average motion sickness scores for each group has been shown below in Figure 30. The notation * denotes a 95% confidence significant difference, and ** a 99% confidence and the error bars indicate the standard deviation.

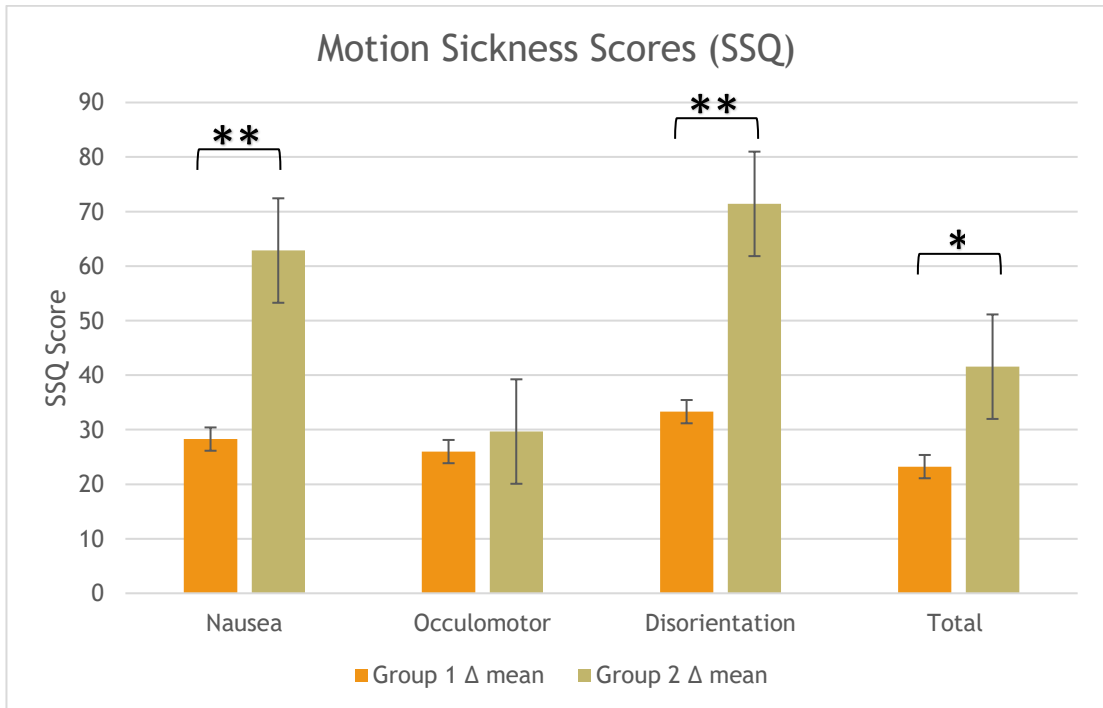


Figure 30 Motion Sickness Scores for Group 1 and Group 2

An exploratory analysis of the six human performance tests was conducted - each denoted by a number from 1 to 6 – as per Table 5. Tests 2 and 5 scores were recorded for both dominant and non-dominant hands independently (where the participant was

required to report on their dominant hand). The results are presented in Table 8 below:

Table 8 Exploratory Analysis of Human Performance Scores

Test Number		Pre-Driving Mean	Pre-Driving SD	Post-Driving Mean	Post-Driving SD
1 (Visual)	Score	1.055	0.093	1.056	0.09
2 (Physical)	Dominant	3.813	0.617	4.025	0.737
	Non-Dominant	4.015	0.835	4.289	0.81
3 (Cognitive)	Score	18.196	1.184	17.569	1.769
4 (Visual-Cognitive)	Score	3.157	1.027	3.235	0.971
	Time	79.821	43.789	74.878	43.738
5 (Physical-Visual)	Dominant	16.039	1.673	15.529	1.641
	Non-Dominant	14.765	1.531	14.471	1.419
6 (Physical-Cognitive)	Average Time	0.3	0.038	0.324	0.056

It was shown previously that participants who dropped out (Group 2) reported significantly higher total motion sickness scores compared to those who completed the study (Group 1). To explore the scores visually, seven graphs are presented to show the scores before (pre) and after (post) simulator exposure for both the non-motion sick group (Group 1) and the motion sick group (Group 2). A note has been added below each graph to explain the implication of an increased score, where the implication of a decrease score is opposite. The notation * denotes a 95% confidence significant difference, and ** a 99% confidence and the error bars indicate the standard deviation.

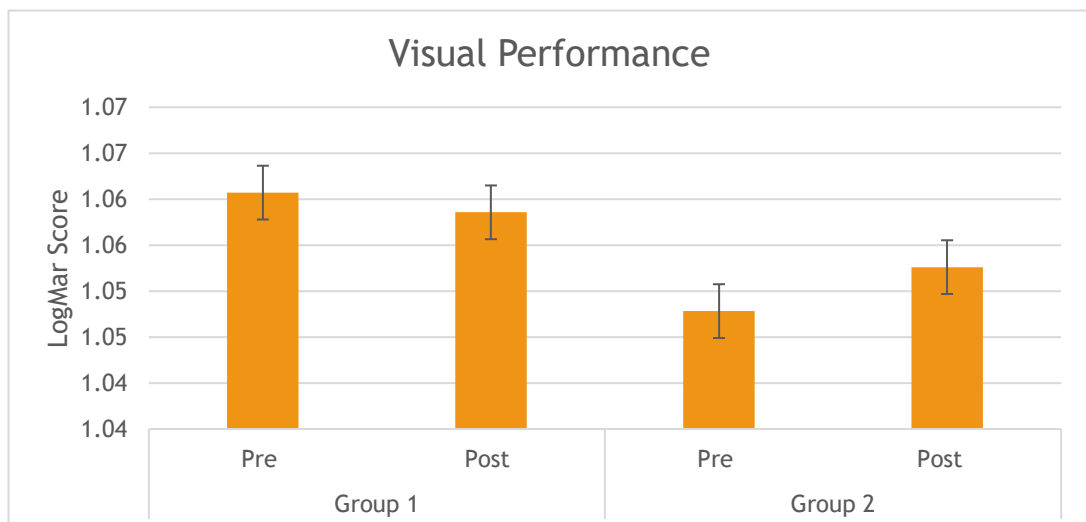


Figure 31 Visual Performance (Test 1) note: an increase in LogMar score indicates an improved performance

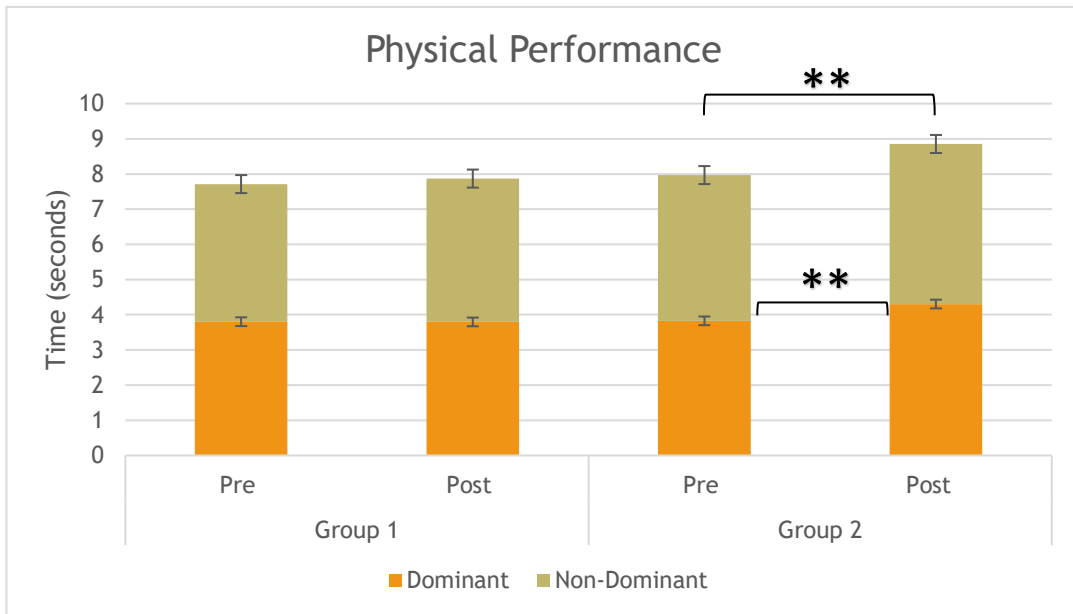


Figure 32 Physical Performance (Test 2) note: an increase in time indicates a reduced performance

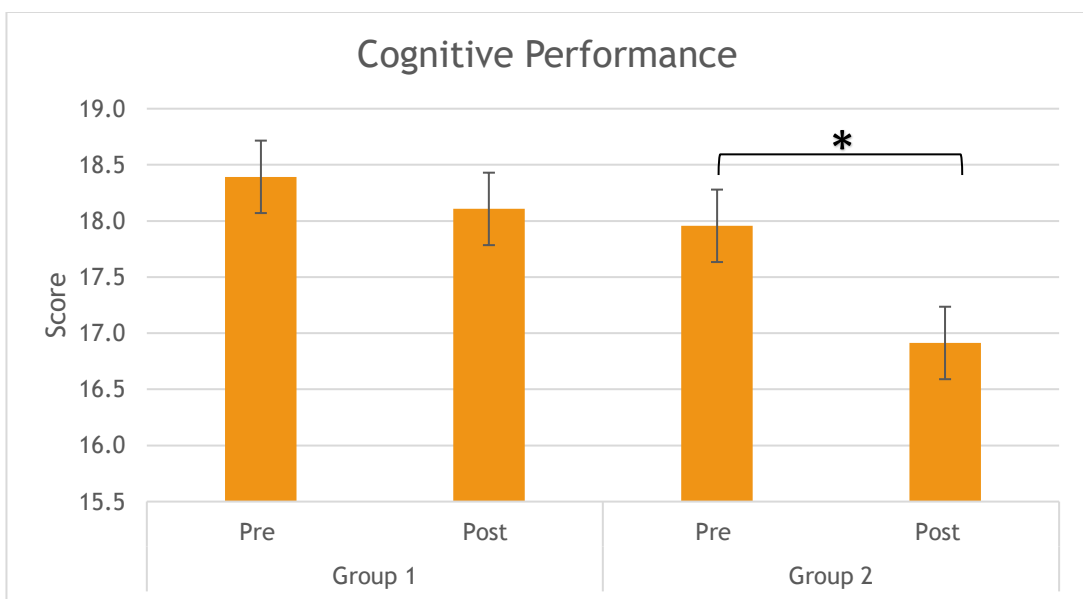


Figure 33 Cognitive Performance (Test 3) note: an increase in n-back score indicates an improved performance

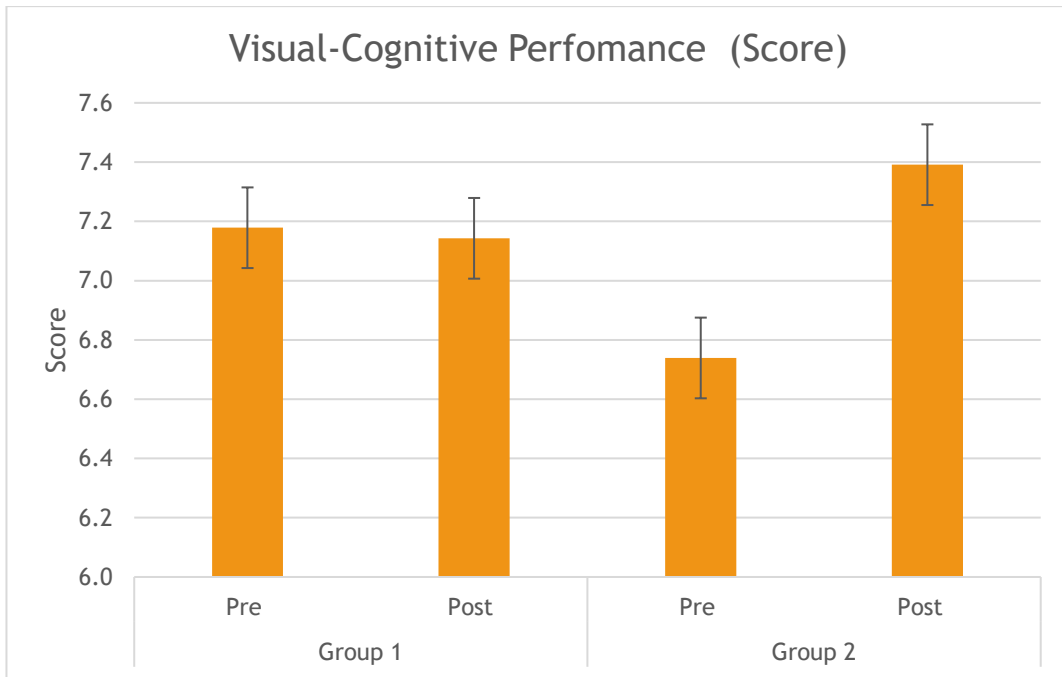


Figure 34 Visual-Cognitive Performance Score (Test 4) note: an increase in score indicates an improved performance

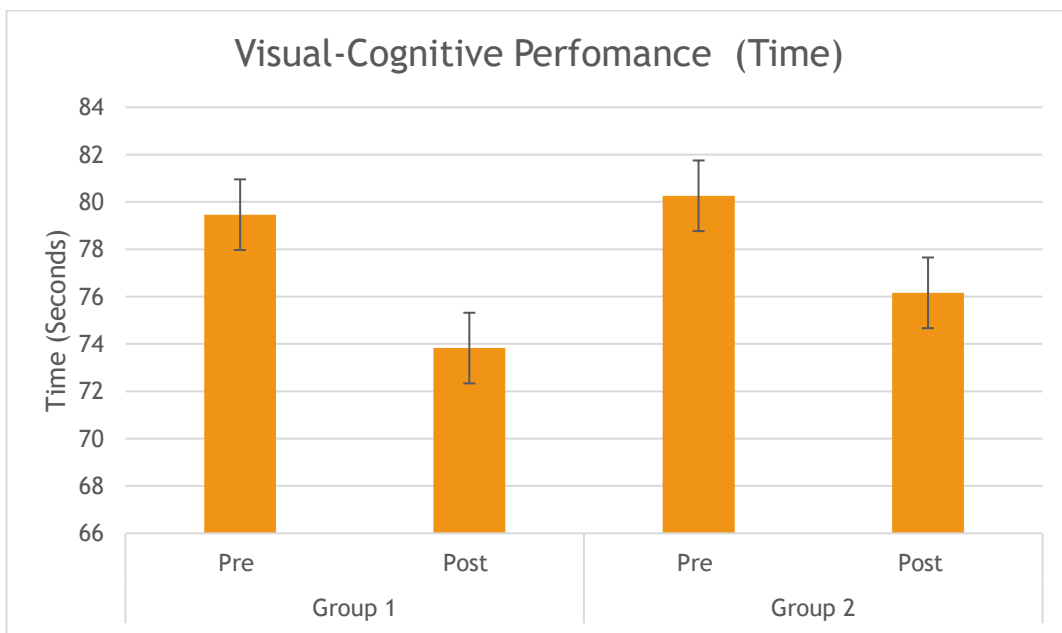


Figure 35 Visual-Cognitive Performance Time (Test 4) note: an increase in time indicates a reduced performance

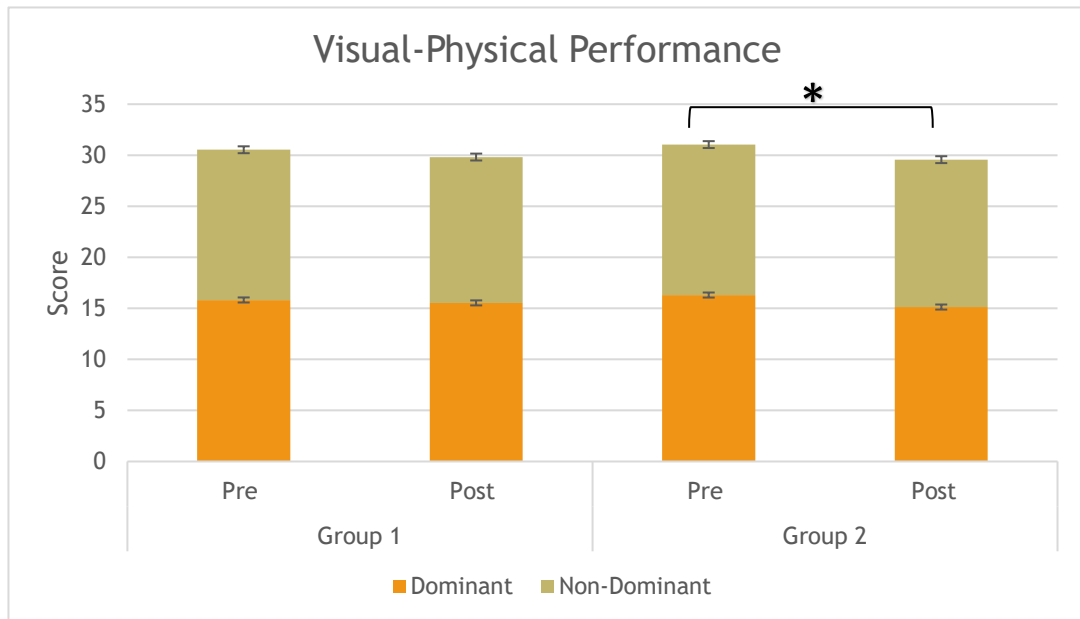


Figure 36 Physical-Visual Performance – (Test 5) note: an increase in score indicates an improved performance

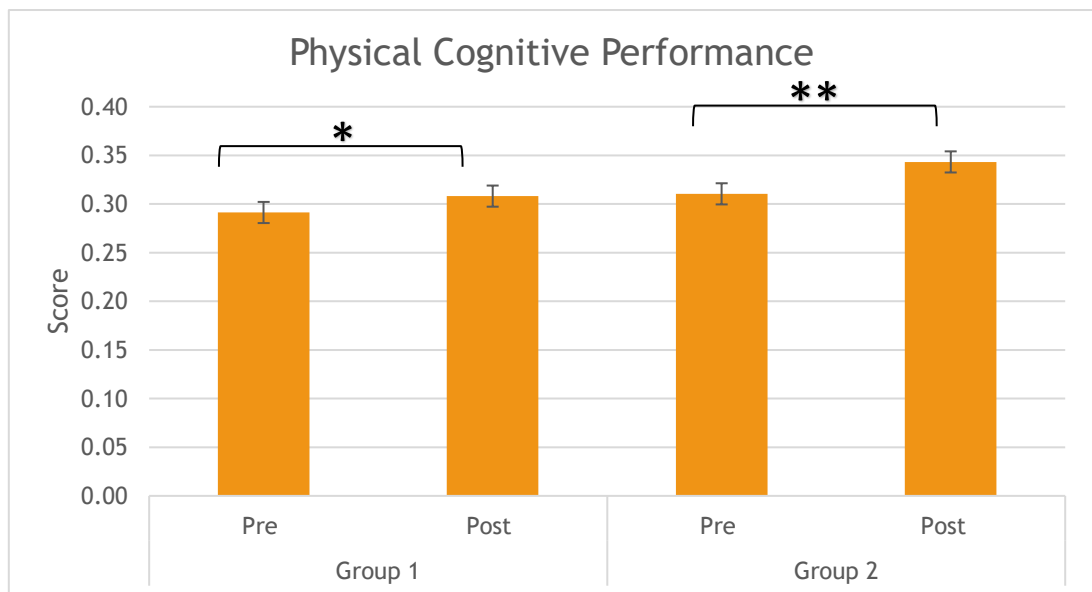


Figure 37 Physical-Cognitive Performance (Test 6) note: an increase in time indicates a reduced performance

Looking at the above figures, visually, there appeared to be some differences in abilities between Group 1 and Group 2's pre-exposure (i.e., baseline) performance scores. To understand if there was a difference, a mixed ANOVA was conducted. The exploratory statistics below present only the pre-exposure (baseline) scores for the two groups:

Table 9 – Group 1 vs Group 2 Pre-Exposure Performance Scores

	Groups	Mean	Std. Deviation	N
1 Visual	Group 2	1.0478	.06681	23
	Group 1	1.0607	.11055	28
	Total	1.0549	.09277	51
2 Physical (dominant)	Group 2	3.8261	.66436	23
	Group 1	3.8021	.58695	28
	Total	3.8129	.61675	51
2 Physical (non-dominant)	Group 2	4.1426	.97678	23
	Group 1	3.9104	.69869	28
	Total	4.0151	.83489	51
3 Cognitive	Group 2	17.9565	1.49174	23
	Group 1	18.3929	.83174	28
	Total	18.1961	1.18355	51
4 Visual Cognitive (Score)	Group 2	3.0870	1.04067	23
	Group 1	3.2143	1.03126	28
	Total	3.1569	1.02708	51
4 Visual Cognitive (Time)	Group 2	80.2596	21.77686	23
	Group 1	79.4611	56.25164	28
	Total	79.8212	43.78945	51
5 Visual Physical (non-dominant)	Group 2	14.7391	1.38883	23
	Group 1	14.7143	1.60686	28
	Total	14.7255	1.49771	51
5 Visual Physical (dominant)	Group 2	16.3043	1.29456	23
	Group 1	15.8214	1.92553	28
	Total	16.0392	1.67285	51
6 Physical Cognitive	Group 2	.3105	.04089	23
	Group 1	.2913	.03286	28
	Total	.2999	.03757	51

Box's test for equality of covariance matrices ('M test'), showed that with an M value of 74.440 and a p value of 0.073 we can reject the null hypothesis (with a 0.05 significance threshold) and assure reliability in a mixed ANOVA analysis where the data meets the assumption of a multivariate normal distribution.

Assuring Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated a mixed ANOVA with repeated measures with a Greenhouse-Geisser correction was used to understand if there was a difference between mean performance baseline scores between the groups (Group 1 and Group 2). There was no

main effect for group observed between baseline test scores ($F(1, 49) = 0.006$, $p = 0.936$).

Following this precursory analysis, the data was then explored to see if there was a difference between the change of performance scores of Group 1 and Group 2 participants where motion sickness is the differentiator between the groups. This will give an indication as to the effect of motion sickness on human performance, where dropping-out of a user trial is a good indicator that someone is motion sick. A mixed ANOVA was conducted for each performance test. Although there were only six performance areas, test 2 and test 5 tested both dominant and non-dominant hands independently and thus 9 analyses were completed.

Test 1 visual performance. There was no significant main effect for pre vs post test score $F(1, 49) = 0.290$, $p = 0.866$ for the entire group of participants. Further, there was no significant main effect between the groups $F(1, 49) = 0.145$, $p = 0.705$. There was no interaction between pre and post test scores and group $F(1, 49) = 0.198$, $p = 0.658$. These results show that performance remained unaffected after simulator use, and this was true for both the motion sick group (group 2) and the non-motion sick group (group 1).

Test 2 physical performance (dominant hand). There was as a significant main effect observed for pre vs post test score $F(1, 49) = 15.308$, $p < 0.001$. There was no main effect between the groups $F(1, 49) = 2.288$, $p = 1.137$. Following the significant main effect of pre vs post, there was also a significant interaction between pre/post and group $F(1, 49) = 16.251$, $p < 0.001$. The estimated marginal means showed how Group 2 (motion sick) took significantly longer to complete the card turning task (pre vs post exposure) indicating a decreased physical performance for the motion sick group (group 2). The estimated marginal means have been plotted below to show the direction, where an increase in score shows an increased time to complete the task, thus a poorer performance.

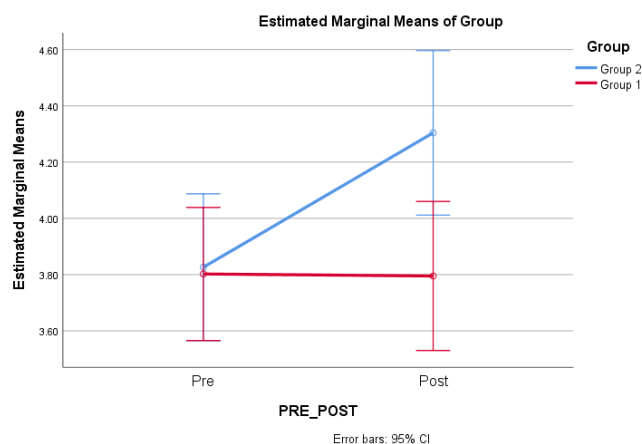


Figure 38 Test 2 Physical Performance (dominant hand) Error bars: 95% CI (Group 1 Non-Motion Sick, Group 2: Motion Sick)

Test 2 physical performance (non-dominant hand). There was as a significant main effect observed for pre vs post test score $F(1, 49) = 11.282, p = 0.002$. There was no main effect between the groups $F(1, 49) = 2.800, p = 0.101$. There was no significant interaction between pre/post and group $F(1, 49) = 2.032, p = 0.160$. The estimated marginal means plot below shows that although time taken to complete the task increased after exposure for the entire sample, the difference in scale between the motion sick and non-motion sick group was not significantly different showing that the classification for motion sickness (dropout vs non-dropouts) did not impact the scale of performance change. The estimated marginal means have been plotted below to show the direction, where an increase in score shows an increased time to complete the task, thus a poorer performance.

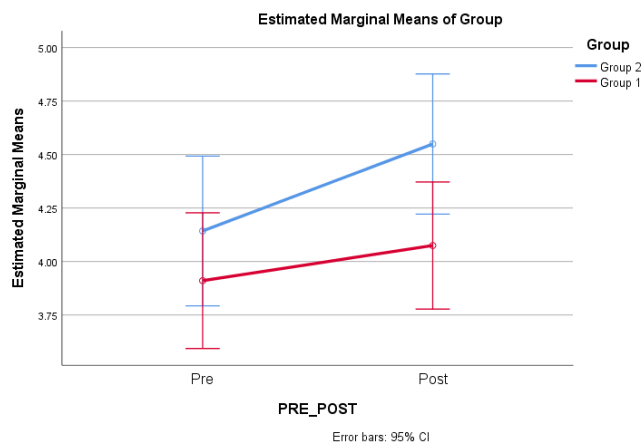


Figure 39 Physical Performance (non-dominant hand) Error bars: 95% CI (Group 1 non-motion sick, Group 2: Motion Sick)

Test 3 Cognitive performance

There was a significant main effect between exposures $F(1, 49) = 11.155, p = 0.001$. There was also a significant main effect of group $F(1, 49) = 5.114, p = 0.028$. The interaction effect was not significant at a confidence threshold of 0.05, where $F(1, 49) = 3.918, p = 0.053$. This result shows that performance was degraded for both groups and they were affected to different extents. However, the lack of an interaction shows again the scale of performance degradation was not well characterised by the motion sickness classification. The estimated marginal means have been plotted below to show the direction, where a decrease in score indicates a poorer performance.

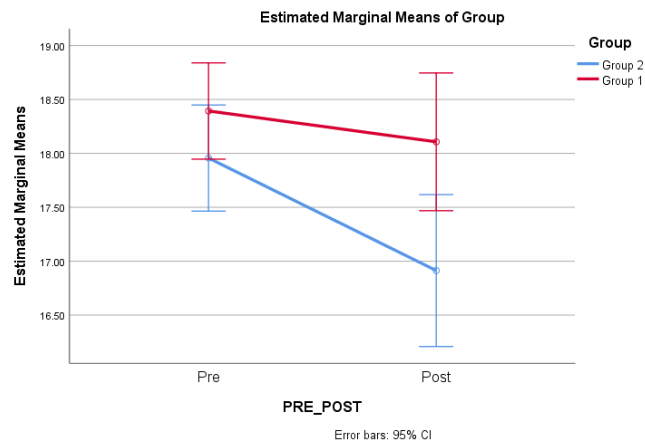


Figure 40 Cognitive Performance Error bars: 95% CI (Group 1 Non-Motion Sick, Group 2: Motion Sick)

Test 4 visual cognitive performance (score)

There was no main effect observed for pre vs post exposure, $F(1, 49) = 0.409$, $p = 0.525$ nor was there a difference observed between the sickness groups. $F(1, 49) = 0.260$, $p = 0.873$. Further, there was no interaction observed $F(1, 49) = 1.258$, $p = 0.267$, all of this indicates that performance was not affected through simulator use or motion sickness.

Test 4 visual cognitive performance (time to complete)

Similar to the visual-cognitive score analysis there was no main effect for pre vs post, $F(1, 49) = 2.920$, $p = 0.094$, between the groups $F(1, 49) = 0.017$, $p = 0.898$, or interaction $F(1, 49) = 0.073$, $p = 0.789$. This shows how performance (i.e., the time to complete the task) was not affected through simulator use or motion sickness.

Test 5 Visual Physical performance (non-dominant)

There was no main effect observed between assessments $F(1, 49) = 2.562$, $p = 0.116$ or between groups $F(1, 49) = 0.073$, $p = 0.789$. Further, there was no interaction observed $F(1, 49) = 0.074$, $p = 0.787$ indicating that simulator use and motion sickness did not impact performance for the non-dominant hand.

Test 5 Visual Physical performance (dominant)

Looking at the dominant hand scores, there was a main effect observed between tests (pre vs post) $F(1, 49) = 9.910$, $p = 0.003$. However there was no significant group main effect $F(1, 49) = 0.010$, $p = 0.920$, or interaction $F(1, 49) = 3.670$, $p = 0.061$. The estimated marginal means have been plotted below to show the direction, where an decrease in score indicates a poorer performance.

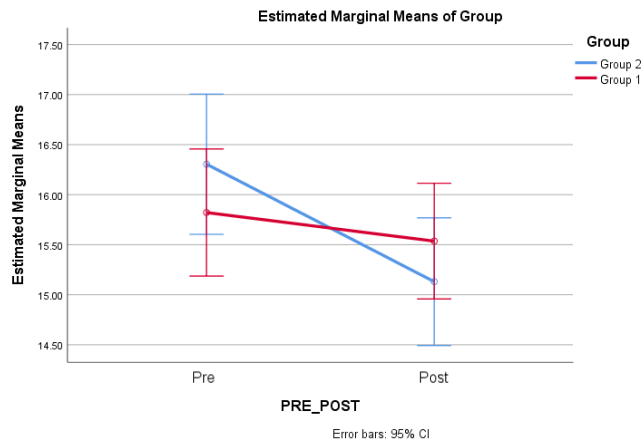


Figure 41 Visual Physical Performance (dominant hand) Error bars: 95% CI (Group 1 Non-Motion Sick, Group 2: Motion Sick)

Test 6 physical cognitive performance

For the physical cognitive performance a strong main effect between the pre and post test was observed $F(1, 49) = 33.727, p < 0.001$. There was also a main effect of group observed $F(1, 49) = 5.006, p = 0.030$. However, there was no interaction $F(1, 49) = 3.494, p = 0.068$. This shows that simulator use negatively affected both groups, and with a difference between the groups, motion sickness was a compounding negative factor for group 2. However, the lack of interaction again hints that the grading criteria of motion sick vs not motion sick was not entirely effective for predicting the scale of performance change. The estimated marginal means have been plotted below to show the direction, where an increase in score indicates a longer reaction time and thus a poorer performance.

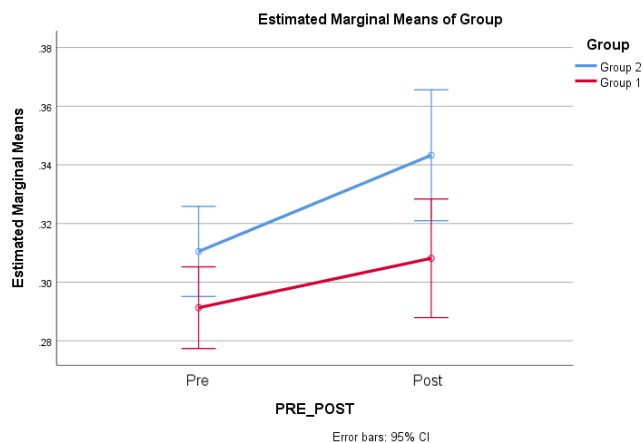


Figure 42 Physical Cognitive Performance Error bars: 95% CI (Group 1 Non-Motion Sick, Group 2: Motion Sick)

The mixed ANOVA is a very thorough analysis, allowing the variance across the groups to be taken into account for each analysis. However, for consistency between submissions within this EngD research, further analysis was also done through splitting the groups and analysing them in comparison to one another. These outputs are useful to consider as a post-hoc analysis for where there was a significant main effect of pre

vs post exposure in the previous mixed ANOVA. The paired (pre and post) data sets were not normally distributed and symmetry was not observed in the data from Test 3, Test 4 (time and score), Test 5 dominant and Test 6. Therefore, data was analysed using the Sign Test for the non-symmetrical results and the Wilcoxon Signed-Rank Test for the symmetrical results. The output is presented below in Table 10 where all significant findings are highlighted in yellow and directional arrows (↑, ↓) have been included next to significant results to show if this difference was an improvement (↑) or reduction (↓) in objective performance.

Table 10 Analysis of Dropouts and Complete Scores (where ** indicates 99% confidence)

Test Number	Score	Group 1 Pre vs. Post	Group 2 Pre vs. Post
1 (Visual)	Score	Z=-0.428	Z=-0.404
2 (Physical)	Dominant	Z=-0.162	Z=-3.101** ↓
	Non-Dominant	Z=0.054	Z=-2.660** ↓
3 (Cognitive)	Score	p=0.804	p=0.004 ↓
4 (Visual-Cognitive)	Score	p=0.791	p=0.118
	Time	p=0.265	p=0.523
5 (Physical-Visual)	Dominant	p=1.000	p=0.004 ↓
	Non-Dominant	Z=-0.857	Z=-1.182
6 (Physical-Cognitive)	Average Time	p=0.003 ↓	P<0.001 ↓

As shown above in Table 10 there is a significant difference in many performance scores for Group 2 participants (i.e., those who dropped out due to motion sickness) where performance was statistically decreased for Physical ability (Test 2), Cognitive ability (Test 3), dominant hand Physical Visual ability (Test 5) and Physical-Cognitive ability (Test 6). For the ‘complete’ participants (i.e., those who didn’t drop out due to severe motion sickness there was no change in their abilities in any test other than the Test 6 which showed a significantly reduced Physical-cognitive ability, which used a reaction time test.

The previous analysis methods have looked at motion sickness as a binary state – by comparing those who had to drop out of the study (Group 2) vs. those who were able to complete the full driving scenario (Group 1). Within the mixed ANOVA method it was shown that, through a lack of interaction in some tests, the grouping classification was not always an appropriate indicator for the difference in scale of performance change between groups. It was interesting therefore to see if there is a scale to the effect where it’s possible that motion sickness severity as ascertained from the SSQ may correlate to performance degradation. Participants were split into three equal groups of 17 participants, based on individual MS (motion sickness) severity where group 1 contained participants with the lowest Δ(delta) SSQ scores, group 2 consisted of the next 17 participants and group 3 consisted of the final 17 participants with the

greatest Δ SSQ scores. An ANOVA showed a significant difference between the three groups' SSQ scores ($F=36.882$, $p<0.001$). An exploratory analysis of the groups (considering motion sickness) is given below in Table 11

Table 11 Descriptive Statistics of MS Severity Groups

Group	Mean Delta SSQ Total	Standard Deviation
1 (n=17)	9.460	6.219
2 (n=17)	27.500	6.194
3 (n=17)	57.539	15.199

Now, Table 12 below presents the mean performance delta scores for the three groups, where delta scores were calculated for each individual, before an average of each group was taken.

Table 12 Descriptive Statistics of Performance for MS Severity Groups

Performance area	Group	Mean	Std. Error	Standard Deviation
Test 1 Visual	1	0.0056	0.01312	0.05565
	2	0.0119	0.01376	0.05504
	3	-0.0141	0.01303	0.05374
Test 2 Physical (dominant)	1	0.0556	0.05774	0.24498
	2	0.2288	0.15137	0.60547
	3	0.3606	0.12984	0.53533
Test 2 Physical (non-dominant)	1	0.0922	0.10543	0.44729
	2	0.2969	0.15609	0.62435
	3	0.4435	0.17436	0.71891
Test 3 Cognitive	1	-0.1111	0.29024	1.23140
	2	-0.8750	0.40697	1.62788
	3	-0.9412	0.30281	1.24853
Test 4 Visual Cognitive (Score)	1	0.2778	0.23990	1.01782
	2	0.1250	0.20156	0.80623
	3	-0.1765	0.31196	1.28624
Test 4 Visual Cognitive (Time)	1	-5.8050	3.66316	15.54146
	2	-0.5550	4.35667	17.42669
	3	-8.1612	6.34660	26.16772
Test 5 Visual Physical (non-dominant)	1	0.2222	0.36654	1.55509
	2	-0.2500	0.26615	1.06458
	3	-0.8824	0.34173	1.40900
Test 5 Visual Physical (dominant)	1	0.1667	0.27116	1.15045
	2	-0.6875	0.39496	1.57982
	3	-1.0588	0.42418	1.74895
Test 6 Physical Cognitive	1	0.0141	0.00372	0.01576
	2	0.0398	0.00981	0.03923
	3	0.0198	0.00744	0.03067

The above raw mean data indicates there may be a difference between the groups across a few of the performance scores. Box Plots of the performance change between the groups have been included in Appendix 4 to explore any visual relationship.

Using a Levene Test for Homogeneity of Variance it was found that data within Test 2 (Physical) and 6 (Physical-Visual) exhibited significance where $F(2,48)=4.667$, $p=0.014$ and $F(92,48)=4.255$, $p=0.02$ respectively. The Welch ANOVA will be used for analysing Test 2 and 6. The data within tests 1, 3, 4 and 5 met all assumptions so a one-way ANOVA was used. The result of the ANOVA found no statistical significance between the three groups in Tests 1, 3, 4 or 5 where $p>0.05$ in all cases. Using the Welch ANOVA no statistical significance was found for Test 2 where $p>0.05$. However, for Test 6 (physical-visual) statistical significance was found $F(2,27.168)=3.468$, $p=0.046$. For Test 6 the Scheffe post-hoc analysis showed a statistically significant difference between group 1 and 2 ($p=0.035$) and group 2 and 3 ($p=0.026$), however there was no difference between groups 1 and 3 ($p>0.05$), indicating a lack of linear relationship between the groups.

Another approach used to better understand if there was a relationship between severity of motion sickness and scale of performance change was to analyse the data at a group level using a linear regression. Initially, the multiple correlation coefficient R value at 0.588 does not indicate great quality of the prediction of test score change as the dependent variable. Further, the coefficient of determination (R^2) value of 0.345 indicates that the independent variable of motion severity change explains just 34.5% of the variability of the performance change. The overall ANOVA within this test shows that the change in test score was significantly related to motion sickness state $F(9,41)=2.402$, $p=0.027$. However, all but one of the individual tests proved to be insignificant in themselves where $p>0.05$. For the cognitive test (N-Back, Test 3) significance was observed where $p=0.027$. Overall this output of the linear regression further examples the overall negative effect of motion sickness on human performance, but does not provide evidence for the subjective motion sickness scores as a useful predictor for the scale of performance change ($R^2=0.345$) across tests.

5.4.2 PHASE 2 - A 'REAL-WORLD' STUDY

A further 17 participants took part in the RDM pod user trial which was used for Phase 2, none of these participants had completed the simulator study in Phase 1 of this project. All participants completed the driving scenario with no dropouts. Motion sickness scores for 'PRE' SSQ (baseline) and 'POST' SSQ (after use of the pods) along with 'PRE' (baseline) and 'POST' N-Back (cognitive) and reaction time (cognitive-physical) scores are presented in Table 13 below

Table 13 Exploratory Analysis of SSQ and Human Performance (Pre and Post)

	N	Minimum	Maximum	Mean	Std. Deviation
PRE_SSQ_TOTAL	17	0.000	18.7	3.3	4.746
POST_SSQ_TOTAL	17	0.000	11.2	2.9	3.379
PRE_REACTION	17	0.226	0.352	0.299	0.0341
POST_REACTION	17	0.267	0.394	0.317	0.0381
PRE_NBACK	17	14.000	19.000	17.823	1.333
POST_NBACK	17	15.000	19.000	17.117	1.495

To see how motion sickness scores changed after exposure to the pods, the delta (i.e., change in) scores were assessed. The SSQ scores has been presented as delta total, as well as for its three sub-categories of nausea ('N'), oculomotor ('O'), and disorientation ('D'). The descriptive statistics are presented below in Table 14:

Table 14 Exploratory Analysis of The SSQ Subcategories

	N	Minimum	Maximum	Mean	Std. Deviation
DELTA_N	17	-9.50	9.50	1.117	4.608
DELTA_O	17	-22.70	22.70	-0.447	9.833
DELTA_D	17	-27.80	13.90	-0.817	7.724
DELTA_TOTAL	17	-11.2	11.2	-0.440	5.101

As seen in Table 14, every measure was slightly decreased after exposure to the pods except in the nausea scale. It appears that the pods did not induce any motion sickness. To assess if the use of the pod affects motion sickness it was first necessary to check for normality in the data so the appropriate statistical test could be executed. The Shapiro-Wilk test was used where the null hypothesis is that the data is normally distributed. In all cases $p < 0.05$, so the null hypothesis of the Shapiro-Wilk must be rejected and it can be concluded that the data is non-normally distributed. Given the lack of normality in the data, a non-parametric test was required. The data was then assessed for symmetry, whereby the Sign Test could be used for the non-symmetrical results and the Wilcoxon Signed-Rank Test for the symmetrical results (as all other assumptions of each test were met). To check for symmetry, the delta scores (i.e., the difference between the paired data pre vs. post) was used and box plots created. Conclusively, none of the data was observed to be symmetrical so the Sign Test was used. A statistical analysis using the Sign test shows that there was no significant change in motion sickness total score ($p=0.727$), nausea ($p=0.625$), oculomotor ($p=0.774$), or disorientation ($p=0.727$)

Looking now at the performance scores, there was no statistically significant change between the pre and post N-Back scores assessing cognitive ability ($Z=-1.270$, $p=0.204$)

where $p > 0.05$. However a t-test revealed there was a significant increase in cognitive-physical ability between pre-exposure ($m=0.299$, $SD=0.034$) and post exposure ($m=0.317$, $SD=0.038$) $t(16)=-2.251$, $p=0.039$.

It is now possible to explore if the statistically significant change in reaction time score was related to any fluctuation in motion sickness using an ANOVA. Despite the lack of significant change between pre and post motion sickness scores and N-Back scores, it is still worth presenting the data to aid discussion and give comparison to the results presented in the first simulation-based user trial in Phase 1. There was no statistical significance between delta SSQ total (i.e., the change in total SSQ score) and delta cognitive-physical score as determined by the one-way ANOVA ($F=0.967$, $p=0.493$). Likewise, there was no significance shown between delta total SSQ and delta cognitive score ($F=1.1998$, $p=0.159$) where $p > 0.05$ in both instances. Looking also for any significance between the delta SSQ subscale scores and the two performance measures there too was no significance shown where delta nausea vs. delta reaction showed ($F=0.205$, $p > 0.05$) and delta N-back showed ($F=0.701$, $p > 0.05$). Delta oculomotor vs. delta reaction showed ($F=1.200$, $p > 0.05$) and delta N-Back showed ($F=1.218$, $p > 0.05$). Finally, delta disorientation vs. delta reaction showed ($F=2.564$, $p > 0.05$) and delta N-Back showed ($F=3.016$, $p > 0.05$).

5.5 DISCUSSION

Firstly, looking at Phase 1 of this project, dropout rates in the simulator were higher than a usual 3xD simulator study, with 45% ($n=23$) participants asking to end the study early. It is thought that the driving route design had the biggest impact on participant dropouts and the track was designed to be challenging considering motions. It is noteworthy that every participant reported at least some motion sickness as measured by the SSQ proving that no one was immune to motion sickness.

Previous literature discussed the effect of different demographics on motion sickness, such as gender (Jokerst, et al., 1999), age (Golding J. F., 2006) and driving experience (Turner M. , 1999) amongst others. These relationships did not form part of the research question so analysis is retained within Submission 3.

Looking to the key findings, it was shown that motion sickness affects various areas of human performance. Motion sickness in this instance was considered as a binary state. For those who did complete the drive (Group 1) they were classified 'not motion sick', whereas those who asked to end the drive early due to sickness (Group 2) were classified as 'motion sick' and referred to as 'dropouts'. This method has previously successfully been used in the published literature where dropping out is an accepted classifier for motion sickness state (Bertin, Collet, Espie, & Graf, 2005). There is

currently no validated method for categorising motion sickness states other than strictly by the SSQ scale, where there are no thresholds on which to infer states of 'motion sick' or 'not motion sick'. To assess human performance across the entire range of scores many participants would be needed each at similar motion sickness states. Therefore, with the modest sample size, and no real thresholds, the propensity to drop out of the drive was used as the defining characteristic to classify motion sickness. Four of the six areas of human performance (as per the Venn diagram in Figure 19) were shown to be negatively affected by motion sickness. Looking at the human performance diagram it can be amended to identify the areas shown to be negatively affected by motion sickness and is presented below where the red area identifies the area as being negatively affected by motion sickness:

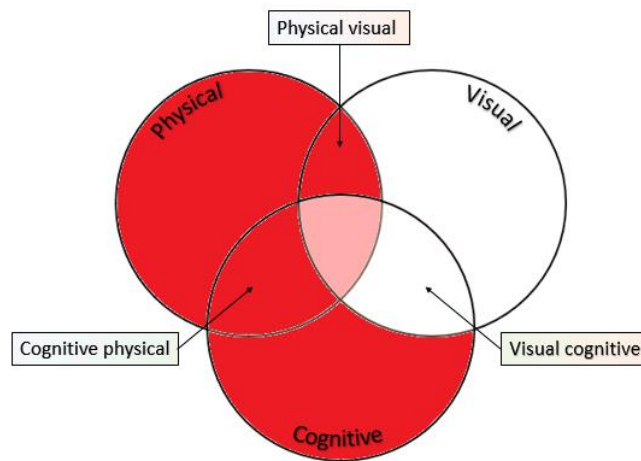


Figure 43 Modified Human Performance Diagram

Considering Visual Acuity (VA) previous literature suggests motion sickness (seasickness in their case) had a negative effect on VA (Bos, et al., 2008). However, the results found in this simulator trial should be considered as non-conclusive. It was noticed early on in the user trial that there may be some darkness adaptation benefiting participants. The control room where the VA test took place is much brighter than the simulator and there was no ability to change the lighting in either the simulator or the control room. It is likely that participants, after spending time in the dark simulator were dark adapted, then, when coming back to the control room for the post-exposure tests they benefited from being dark adapted and being tested in a better lit environment. This justification is supported by the literature where it has been shown multiple times how dark/light adaption has a significant affect on VA that dark/light adaption has a significant affect on acuities (Hecht, Haig, & Chase, 1937) (Graham & Cook, 1937) (Campbell, Harrison, & Vertigen, 1950). Unfortunately because of this inability to control lighting conditions, it is not possible to make any conclusions on the relationship observed between VA and motion sickness in this user trial.

Secondly, looking at the visual-cognitive assessment which consisted of a modified Mental Rotation Test (MRT), no significant change was observed. Contrary to the hypothesis, the group average score increased (insignificantly) from ($m=3.157$, $SD=1.027$) to ($m=3.235$, 0.971). The time taken to complete the test (measured in seconds) showed no significant change either, although the raw data showed a slight decrease from ($m=79.82$, $SD=43.78$) to ($m=74.87$, $SD=43.73$), albeit statistically insignificant. Curiously, as shown in Figure 34 it seems that scores increased more for dropouts (i.e., those who were motion sick) than for those who completed the drive (i.e., those who were not motion sick) – this was opposite to the expected effect. Upon some brief further reading it was found that the ‘skill’ of spatiality, assessed using the MRT, has an interesting relationship with motion sickness. For example, one study showed that those who scored lower at spatial ability tasks reported greater numbers of historic bouts of motion sickness (Levine & Stern, 2002) This relationship is continued to be discussed and explored within Project B of this Innovation Report.

Looking at all of the other areas of human performance it was shown that Group 2 had significantly reduced cognitive ability, physical ability, physical-cognitive ability and physical-visual ability. These findings are difficult to compare to the literature, as many previous projects used specific work-related tasks on which to assess performance, thus it is unknown what specific areas of human performance were affected in other experiments. One aforementioned project did find a negative relationship between cognitive skills and motion sickness (Bos, et al., 2008) when using the Vigilance and Tracking Test (VigTrack) (Valk, Simons, Struyvenberg, Kruit, & van Berge Henegouwen, 1997) alongside the Multi-Attribute Task Battery (MAT) (Comstock & Arnegard, 1992). However, these tests both rely on other abilities, such as visual ability. Therefore the data presented in this simulator study, is in agreement with the conclusion set out by (Bos, et al., 2008) but adds to our understanding of this relationship, where cognitive ability was more isolated in this project.

Looking to the results found in Phase 2 of this study, using the RDM pods there was no motion sickness being induced for participants. However, despite there being an observed decrease in physical-cognitive scores, there is no evidence that this relationship was linked to motion sickness (where there was none). As one possible explanation for the reduced physical-cognitive scores observed after the exposure to the pods, it is thought that the temperature was of influence. The outside temperature on the three days of the user trial was conducted had lows of 5 degrees, 1 degrees and -1 Degrees Celsius and the trials took place in a non-heated warehouse. Participants all wore insulated jackets to counter the cold, but their hands were exposed. It is expected that when arriving at the facility and completing the first round of assessments they were in a normal state considering temperature. However, after 40-minutes in this cold warehouse it was possible that their motor skills were slowed due to the cold. There is much research correlating cold temperatures to decreased hand

performance (such as (Clark, 1961)), although no skin temperature readings were taken to validate the temperature as a reason for the decreased physical-cognitive performance so this explanation remains speculative. Another possible explanation is that the onset of Sospite Syndrome could affect reaction time as previously observed (Lawson & Mead, 1998), however there was no measure taken to measure sospite syndrome, so again, it is not possible to draw a reliable conclusion. Overall, with motion sickness not being a significant factor for these pod trials in Phase 2, and no relationship observed between motion sickness and human performance, this trial did help validate the validity of simulator study where no change in motion sickness showed no significance to any change in performance. Taking the findings that motion sickness does affect human performance as measured in the simulator study it is of benefit to the UK AutoDrive trials that no significant motion sickness was observed as this helps to validate the findings they will take away from the project.

The implications of motion sickness affecting human performance is very interesting for further automotive technologies. Firstly, it highlights the importance of data handling for simulator-based user trials where it is not advisable to use user trial data for participants who have to drop out of a study due to motion sickness as it is proven that this level of motion sickness significantly affects their performance and therefore their data is not-representative of their usual abilities. At this stage it can be concluded that if participants are not asking to end the study early (therefore 'not motion sick' by this binary classification system) their results (for the most part) are representative of their usual abilities, and therefore this adds to the validity of simulator-based user trials. It was shown however that even for those who completed the driving task, their physical-cognitive ability did significantly decrease where their reaction time (measured in seconds) increased from ($m=0.3$, $SD=0.038$) to ($m=0.324$, $SD=0.056$). A few papers look at reaction time in simulator environments such as (Guzek, Jurecki, Lozia, & Stanczyk, 2006) and (Guzek, et al., 2012) and both confirm that reaction time is affected negatively through simulator use. The exact reason why is described in these reports in relation to specific driving tasks, rather than a change in fundamental ability. It is possible that Sospite Syndrome (Graybiel & Knepton, 1976) could be a factor which is a complex condition related to drowsiness and fatigue related to motion exposure. This usually is of consequence when experiencing physical motions but it is possible that the perceived sensation of self-motion experienced in the simulator throughvection could induce similar sensations which may induce sospite syndrome. Previous research has explored the onset of Sospite Syndrome in simulators and details how this fatigue and drowsiness related syndrome is indeed a factor for vehicle simulators where there is no physical motion (Lawson & Mead, 1998). No data collected to assess participants for sospite syndrome symptoms (as this research was solely interested in motion sickness). However it is conceivable that it may have had a role to play in the observed reduction in physical-cognitive ability in the pod trials – but this can not be proven.

Within this project (specifically Phase 1 where more data was collected), it was also considered if there was a scale to the effect of motion sickness and human performance. This, although not the primary research question, was of interest considering the impact of performance degradation. It has already been discussed that when looking at motion sickness as a binary measure (sick or not sick) a difference has been observed between the two group's performance scores. However, it is interesting to explore how one might go about understanding if there is a scale between motion sickness severity and performance change. As a brief insight, Table 11 presents an exploratory method for splitting participants into lowest, highest and those in the middle of severity scores – dividing the group equally into three as more of an 'exploratory' approach. It was shown how the grouping of participants using SSQ data, assigning participants based on their subjective motion sickness severity into three groups (low, medium, high) showed no changes. The implication of this highlights the utility of the binary method used for grouping sick / not sick participants in this study (using dropouts as the grouping variable). A linear regression was also conducted to further explore this relationship, but again did not support any linear relationship between the scale of motion sickness and the scale of performance degradation.

In order to provide a more reliable analysis of a linear relationship it would be necessary to first collect a much larger range of motion sickness data. The largest score measured by the SSQ in this user trial was 71.1, whereas the largest total motion sickness score achievable would be 224.4 indicating this experiment observed only up to 31% of the range of possible SSQ data. An experiment to better understand if there is a linear relationship might involve identifying motion sickness severity score targets as 'groups', and subjecting participants to a motion sickness stimulus until they reach a common group threshold. A comparison between groups of participants each at a discrete level of subjective motion sickness would then show, more robustly, if there is a linear relationship between the scale of motion sickness severity and the scale of performance degradation.

This consideration highlights two limitations on the ability to conclude on any linear relationship – firstly, there is no validated method of splitting SSQ severity into groups there may be a better way to interpret this subjective data. Secondly, all participants were constantly reminded they can end the study if they feel too sick. It is likely this data set has not captured the full extent of motion sickness severity, where if participants were required to endure the motion sickness inducing task for longer a greater state of motion sickness would be measured and a greater range of data may reveal a significance between subjective score and performance. However, due to ethical considerations and concern for participant wellbeing no one was subjected to any more motion sickness than they opted to tolerate. Use of the motion sickness susceptibility questionnaire (MSSQ) (Golding J. F., 1988) may have provided a useful

method of categorising participants and collecting data from a broad demographic considering susceptibility and it is unfortunate this data was not collected.

Overall, and besides the simulator transferability questions, considering the impact of motion sickness on performance (simulation sickness in this instance) these findings, and that which was explored in the literature, may have significant implications for future automated vehicles. The propensity for automated vehicles to induce motion sickness is quite well established in the literature and summarised in this Innovation Report. It is now seen (both in this experiment and the background literature) that motion sickness can reduce human performance in a number of ways. If, for example in a SAE Level 3 vehicle, the user is experiencing motion sickness, and thus their performance is degraded, it is possible that their ability to regain control of the vehicle may be deteriorated. There is no agreement yet about the time between a Level 3 vehicle asking the user to regain control, and the time in which the user is required to take control. However, in one well cited report a 10-second handover request is recommended (Melcher, Rauh, Diederichs, Widlroither, & Bauer, 2015). Considering subjective motion sickness recovery, for the most part, takes 15-30 minutes there is perhaps an implication for the timeline of vehicle handover. If automated vehicle induced motion sickness is affecting performance, it may not be advisable to hand over control of a vehicle within this 10-second time frame. Further, in a Level 4 vehicle, if the occupant is experiencing motion sickness they may decide to regain control of the vehicle as a method of self-help, where 'controllability' and driving a vehicle is a known way to minimise motion sickness onset (Howard & Templeton, 1966). However, if the user is motion sick to the degree of no longer being able to tolerate the environment (similar to 'dropouts' in this project's experimentation) it is possible that the users' cognitive, physical and other performance areas will also be reduced – the extent to which this has a safety implication is not known, but worthy of consideration. These concerns have not been directly addressed in an automated vehicle instance, so no precise conclusions can be drawn, but the consideration of this has been highlighted for the first time, and the need for further research has been identified and justified.

Considering also the previously discussed use cases of automated vehicles, it is apparent that productivity is a significant influencer on the appeal of these vehicles. Morgan Stanley have estimated that the ability to work within an automated vehicle could bring US\$508 billion per year to the US economy (Morgan Stanley, 2013) (p.50) – clearly identifying the possibility of productivity in an automated vehicle. It was also discussed that many of these work-related tasks would induce the likelihood of motion sickness meaning people may not want to be productive. Further to this, it is now proven that motion sickness can negatively influence various areas of performance – this may further limit the productivity benefits expected. Going back to the literature it was shown in a seasickness trial how work task-related performance suffered significantly when motion sick (Bos J. E., 2004), and the experiment presented here

confirms these findings. This starts to bring into question the true ability to be productive in an automated vehicle. This, as a potential issue is worsened still when considering how different demographics are more affected than others considering motion sickness – so it is likely this productivity concept may be rather limited considering inclusivity. This inclusivity consideration was further discussed in a recent paper (Smyth, Jennings, & Birrell, 2019), which has been included in Appendix 1.

5.6 CONCLUSION

Motion sickness has been shown to be a significant negative influencer on four of the six human performance categories highlighted for this study: including, cognitive ability, physical ability, physical-cognitive ability and physical-visual ability. The test results from the visual ability and visual-cognitive ability remain inconclusive from this trial due to uncontrollable light conditions concerning visual skills, and external variables of spatial awareness ‘training’ and simulator exposure for the visual-cognitive skill. It was also shown that physical-cognitive skill (reaction time in this case) was negatively affected not only by motion sickness, but by simulator use in general as well as pod use. This is expected to be related to sopite syndrome, although this was not measured so cannot be reliably concluded upon. It does highlight however cause for concern of the transferability of reaction-time measures from simulator data to ‘real-world’ applications. If future reaction-time based research is completed in a simulator (3xD or otherwise) it is recommended that Sopite Syndrome is measured and perhaps a baseline reaction time assessment is given alongside the primary task to compare reaction time differences between simulated and real-world. All other areas of performance are considered to be transferable from simulator to-real-world if participants are not experiencing motion sickness which makes them drop out. It is advised that if participants do drop out of a study all of their data should be omitted from the study where the validity of their performance is not assured.

The RDM pods were shown in this specific user trial to not be an influencer on motion sickness and more explanations as to why this is the case is given in Submission 4, where vehicle speed, and inability to complete secondary tasks were thought to be of most significance.

This project, using original data and supported by the background literature has identified the need for future research around the safety of vehicle handover scenarios for future automated vehicles – specifically SAE Level 3 and 4 vehicles. Motion sickness induced performance degradation may impact the safe ability for someone to regain control of a vehicle. Further to this safety concern, bringing into consideration the idea of productivity in automated vehicles, this research highlights a possible limitation to productivity goals - such as predicted by (Morgan Stanley, 2013).

This project has also allowed for an opportunity to provide useful impact to the sponsoring company- JLR. Through the literature review presented in Submission 2, and the simulator-based user trial as discussed (and presented in Submission 3) a 'best practice' guide was created for JLR research staff who will run future user trials. This document is summarised into a one page handout and was designed to be easy to follow to ensure maximum validity of future JLR studies as well as minimise participant dropouts and ensure participants are taken care of appropriately considering motion sickness. The latest copy of this is presented in Appendix 2. Further, as a summary of the project on the UK AutoDrive project a 1-page summary was also completed for the JLR staff (See Appendix 3). This was used to show that motion sickness was not a significant factor for their user trials, adding validity to their research findings and providing useful information about the usability of these pods considering motion sickness. The findings around performance degradation provided a useful insight into the issue of motion sickness for automated vehicles and helped scope future research plans for JLR as a result.

5.6.1 FUTURE RESEARCH

Although this research project has made many contributions, some further questions and areas of interest for future research have been raised. As a brief summary these have been noted below:

- The extent to which motion sickness affects specific driving tasks in a simulator should be addressed (such as lane keeping, apprehension of danger, headway etc.) to ensure transferability of trials containing those variables.
- Impact of motion sickness compared (using identical performance measures) to other common driver states such as fatigue
- Areas of visual performance should be addressed in a more controlled environment.
- A method for categorising or grouping motion sickness severity states using the SSQ should be examined.
- Consideration of vehicle handover implications with regards to motion sickness should be further explored
- The effect of motion sickness and/or simulator use and the mental rotation test should be further explored
- The impact of Sospite Syndrome on automotive technology (simulators and automated vehicles) should be further explored.

5.6.2 LIMITATIONS

This project was effective in addressing the primary research question, but had a few limitations that are important to note. As an overall point it is first worth mentioning that although the term 'motion sickness' is used, the specific form of this sickness was 'simulation sickness'.

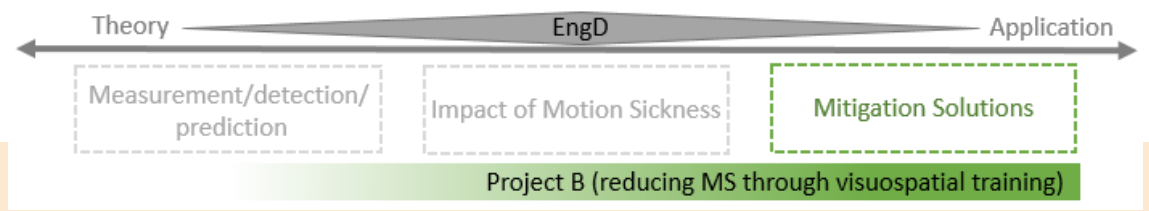
Firstly, the categorisation method of human performance only allowed for one test per performance area, where in fact there are many. For example, visual skills can relate to visual acuity, depth perception or night vision etc. Cognitive skills could include processing, working memory or long term memory etc. For this experiment, only one test was allocated to test each area of performance. This was done to ensure the tests could be completed before motion sickness subsided, but due to this, some wider information on each area of performance is missing.

The grouping method of motion sickness severity was based on a binary classification related to the objective measure of dropping out or completing the trial. This was effective for addressing the research question, but leaves further questions about the linear relationship of motion sickness and performance which this data is not entirely suitable to address. Subjecting participants to a motion sickness stimulus to the point that they reach a specific level of sickness would allow for better grouping of participants for analysis. Further, as a limitation to the data set, only relatively moderate sickness was captured, where participants were advised to end the study if they became too unwell. This limits the breadth of data available and the maximum motion sickness score collected was 71.1, out of a total possible score of 224.4. This does not limit the applications of the primary research question, but hinders understanding about the linear relationship.

Considering the follow up trial in the 'RDM pods', motion sickness was expected to be very low given the experimental design, and this was bared out in the data. This limits the utility of the data collected to directly show 'real-world' comparability. The extraneous conditions, and the lack of control over experimental design and temperature etc. is a significant limitation of this section research.

6 VISUOSPATIAL TRAINING AND MOTION SICKNESS (PROJECT B)

This project was conceived through the exploration of the results from Project A and a deep review of the literature. Some of this background literature was added to the Literature Review presented in Submission 2. This project was a two-part study, beginning with simulator trials followed by on-road trials. These two phases are written up as Submissions 5 (simulator study) and 6 (on-road study) as shown in Figure 6. This project identified a new way of reducing motion sickness susceptibility through training visuospatial skills. JLR (the sponsoring company) placed an embargo on this project to restrict a journal publication where they want to protect the intellectual property associated with the findings. Therefore, no publications have been made as of August 2019 and discussions over future publications are ongoing.



This Innovation Report has established the issue of motion sickness onset for future automated vehicles and vehicle simulators for developing new technology. Of course, the reduction of motion sickness considering onset frequency and overall severity is something that would be of great benefit to the automotive industry as a whole. There are a few methods through which motion sickness can be managed. These have been categorised as part of this EngD (see Table 3) and the publication (Smyth, Jennings, & Birrell, 2019) which has been included in Appendix 1. As part of this categorisation for motion sickness countermeasures, some previous design-based methods were considered and this has been discussed in the literature review as seen in Submission 2. Many design recommendations for automated vehicles have been summarised in (Diels & Bos, 2015) which include methods for reducing the onset of sensory conflict through ensuring outside views in the direction of travel. Later research looked at the location of display screens finding that indeed, those which allow maximum peripheral vision to the motion can reduce sickness (Diels C. , Bos, Hottelart, & Reilhac, 2016). A sea-sickness study concerned with HMI (Human-Machine Interface) design looked at the utility of presenting artificial horizons on display screens with some success (Bos, Houben, & Lindenberg, 2012).

Other methods of reducing motion sickness in automated vehicles which are recently being explored include the use of Bone Conducting Vibration (BCV) headsets which use vibrations to disturb the signals between the vestibular system and the brain,

essentially 'masking' the afferent motion. The effectiveness of these methods is hard to establish in the current literature and is a relatively new development. It is expected that, if effective, it is only a short-term solution however. Something that one might want to use for a short drive where motion sickness is likely, but not for extended periods. Other methods of reducing motion sickness in an automated vehicle include the use of Virtual Reality (VR) headsets (e.g., (California, United States of America Patent No. US 2018/0089901 A1, 2018)) which look to provide the afferent motion cues to match the efferent motion being experienced. Again, there is no literature discussing the effectiveness of this method, but one question is raised – the acceptability of wearing a VR headset throughout a journey. It is thought to be unlikely people will want to wear a VR headset throughout a car journey. A slightly less intrusive method presents designs for glasses which project light in the periphery vision to help infer motion cues see (University of Michigan Regents, 2018) although again, no data has been published to attest to the success of this method.

Drugs such as scopolamine have been shown many times to be effective in reducing motion sickness (Sherman, 2002), (Wood, Manno, Wood, Manno, & Redetzki, 1966) and (Schmäl, 2016). However, not only do these drugs limit habituation (Wood C. D., et al., 1994) (p.632), they also bring many side effects such as drowsiness and fatigue which last for many hours and affect day-to-day tasks which limit the application of medication. Medication is thought to be a very useful method of elevating motion sickness for 'one-off' applications (such as when on a cruise ship for recreation), however long term use is not advisable.

Despite there being various methods discussed, all are limited by specific use cases. For example, for HMI based solutions, one has to be actively engaging with the HMI. If someone wants to work on a personal electronic device such as a phone, tablet or laptop (as is common for work-related tasks) they will not benefit from the in-car design implementations. Considering wearables, the user has to be actively wearing them every time they travel, this is unlikely to be desirable. For medication it is unlikely someone can use prescription motion sickness medication for a commute to work and then have a productive day on account of the fatigue-inducing side-effects. All of these solutions are limited further when considering future Mobility as a Service (MaaS) concepts which see ride sharing and multi-vehicle mobility solutions where specific mitigation strategies may not be possible in a ride-sharing scenario and design may differ from vehicle to vehicle. Consideration needs to be given to methods of reducing personal susceptibility to motion sickness, in a non-invasive, non-drug related and non-vehicle-design dependent way which will reduce motion sickness across any use case.

In Project A (presented also as Submissions 3 and 4) an interesting effect was observed between simulator use and the mental rotation test (MRT). It was found here that

participants average MRT score and completion time after simulator exposure was statistically unchanged (see Figure 34 and Figure 35). This was despite the fact that many participants were suffering from motion sickness and other areas of performance were decreased – including cognitive ability. Initial exploration of these results and some literature started to reveal a possible relationship between mental rotation ability and natural motion sickness susceptibility. Further research into the relationship between the MRT and motion sickness was needed.

6.2 INTRODUCTION

Mental rotation is an aspect of visuospatial ability – a relatively well-studied subject in itself. Looking to the literature for more information about visuospatial skills, the most prominent, and widely discussed area is surrounding gender variability in visuospatial ability. Many studies highlight how, on average, males have an improved ability in visuospatial tests over females. For example, one study measuring the difference between males and females highlighted gender differences among a variety of visuospatial tasks –identifying particularly large sex differences specifically in the MRT (mental rotation test) (Linn & Petersen, 1986). Other research has confirmed these findings also finding males outperforming females in the MRT abilities (Peters, Chrisolm, & Laeng, 1995) and other visuospatial tasks including water level tests and rod and frame tests (Robert & Ohlmann, 1994) and (Scholl, 1989). Using the water level test combined with a card rotation test, this gender difference and direction is again confirmed by (Sigorella, Jamison, & Krupa, 1989) where they went on to highlight how “sex, self-concept, and spatial activities made significant direct contributions to the prediction of spatial performance” (p. 1). Across a variety of tests, and research projects the same gender effect is revealed multiple times and it can be concluded that gender has a significant role to play in natural visuospatial performance.

This gender difference is immediately of interest where this EngD research has identified in a previous simulator trial (presented as Project A and in Submission 3) how a far greater number of females dropped out of the simulator study due to motion sickness than males. So it also becomes apparent that there is a gender difference in motion sickness susceptibility. This is not a new finding, in fact the literature is very clear on this gender effect considering motion sickness - for example (Jokerst, et al., 1999), (Flanagan, May, & Dobie, 2005), (Dobie, McBride, May, & Dobie, 2001) and (Matchock, Levine, Gianaros, & Stern, 2008). This relationship is well established where not only is this gender effect observed when specifically looking for it, as in the above studies, but has been observed in a variety of motion sickness studies including studies assessing airsickness (Lindseth & Lindseth , 1995), seasickness, (Grunfeld & Gresty, 1998) and car sickness (Turner & Griffin, 1999).

It is shown that females score lower at visuospatial performance tests, and experience more motion sickness. Conversely, males score higher at visuospatial tests and experience less motion sickness. One factor linking these two relationships can be found in research discussing the effect of sex hormones on both visuospatial skills and motion sickness. It has been previously shown how oestrogen (female sex hormone) fluctuations throughout the menstrual cycle influence spatial ability, where females perform worse at spatial tasks when menstruating (Silverman & Phillips, 1993). It has also been shown how fluctuations in female sex hormones throughout the menstrual cycle affects motion sickness susceptibility (Hausmann, Slabberkoorn, Van Goozen, Cohen-Kettenis, & Gunturkun, 2000).

Given the nature of these findings it starts to become possible to consider that there is an underlying relationship between visuospatial ability and motion sickness susceptibility. Further to the findings presented in Project A and Submission 3, it is interesting therefore to consider if through improving visuospatial ability it is possible to reduce motion sickness susceptibility. Some research discusses the effect of hormone manipulation on visuospatial ability (Van Goozen S. , 1995). However, hormone manipulation is to be avoided for this application, and two research questions (RQ's) are highlighted:

RQ1 - Is it possible to improve visuospatial ability through non-invasive training tasks?

RQ2 - Does increasing visuospatial ability decrease motion sickness susceptibility?

6.3 METHOD

To address the two research questions it was decided that a two-part user trial would take place. The first trial will be a simulator-based study, which is useful for a low-cost, quick, controlled and safe way to assess RQ2. Further, it is possible that the interesting effect between simulator use and visuospatial performance (as measured by the MRT) was linked to the visually intensive simulator environment. Following the success of the simulator trial as Phase 1, an on-road study will take place to further answer RQ2 by providing information on the applicability of findings to 'real-world' motion sickness – this on-road part will be presented as Phase 2.

6.3.1 DEVELOPING THE VISUOSPATIAL TRAINING PACK

In order to answer RQ1 it is necessary to develop a method of training visuospatial ability. There were no useful academic publications advising on the training of visuospatial skills in a non-invasive manner, therefore a slightly more experimental

approach was needed, guided by common practice rather than scientific literature. There were found to be many sources online providing training platforms for training visuospatial ability for people who want to prepare for recruitment aptitude tests – where some tests similar to the MRT are commonly present. Many sources online advocate (through their conception and design) that repeat exposure to, and practice with these tasks can improve ability. Therefore, a training pack was to be developed which included many visuospatial tests and through repeat exposure and practice with these tests it was conceivable that participants could improve their visuospatial ability. It was not practical to create entirely new visuospatial tests and training tasks, therefore online resources were used to create a novel assemblage of pre-existing visuospatial tests which would be used as the training pack. A few considerations were needed before deciding on the format for a training regime. Firstly, it was decided that the training tasks needed to be printable pen and paper tasks so that participants could be given a hard copy – thus controlling the variable of screen size and effects of VDU (Visual Display Units) if this was an online training task.

Next, it was considered that for both phases (simulator and real-world) participants would provide a baseline motion sickness susceptibility score, complete the training pack, and then give a comparative motion sickness score. Therefore, the training pack should be long enough to ensure that habituation to the baseline motion sickness exposure was not an issue between the two exposures, but short enough to ensure participants do not withdraw from the study due to frustration of a long training period. Consulting a motion sickness expert (Diels C. , 2018) it was thought that 14-days would be long enough to ensure habituation to the motion sickness task (used for a baseline measure) would not be a factor for the second exposure. Although the literature is sparse, 14-days does seem appropriate, where one study recommends that when looking to habituate someone to a motion sickness task, repeat exposure should take place within one week (Kennedy, Jones, Lilientha, & Harm,, 1993). Further supportive evidence to attest to one week as suitable time for habituation to the task to subside is found in (Dunlap, 2000). The effect of time taken to train on the effectiveness of the visuospatial training was unknown, but it was hoped that 14-days should provide enough time to see some training effect if indeed possible.

To assemble the training pack, 14-days' worth of training tasks were needed. For practicality sake, it was decided that training should last around 15-minutes per day where it was unlikely that participants would want to take part if the training tasks took up too much time. Three main sources for training tasks were found which included website dedicated to testing and training spatial abilities (amongst other traits for aptitude test preparation) (IndiaBix, 2009), a book published about mechanical and spatial aptitude (Learning Express, 2001) and an US army flight aptitude test document (Wiener, 2005). Training tasks were selected within these

sources, primarily based on the supportive information given by (Voyer, Voyer, & Bryden, 1995) around visuospatial training. Table 15 below gives an outline of each test chosen to be included in the training pack as well as the source.

Table 15 Tests Used for Visuospatial Training Pack.

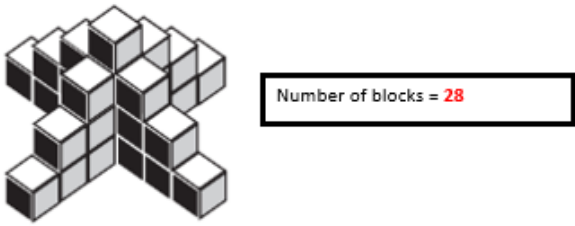
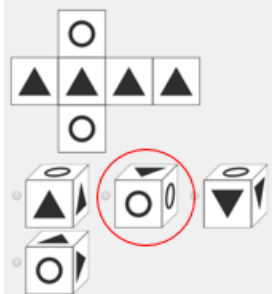
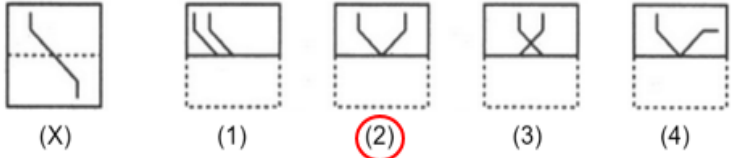
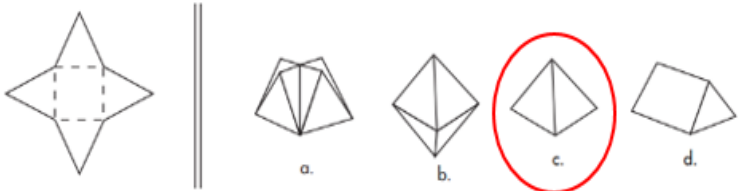
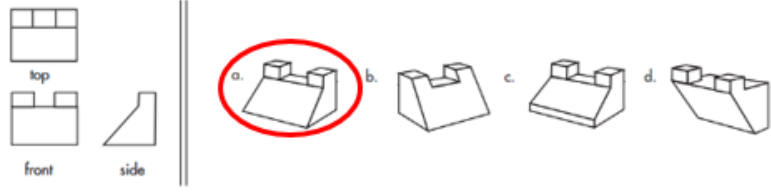
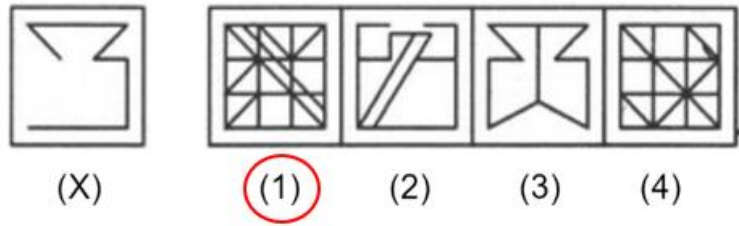
Day	Test name	Description of training task	Source
1	Image analysis	A selection of shapes is given along with four assembled shapes. Participants imagine constructing the pieces and choose which answer resembles the sum of all their pieces.	(IndiaBIX Technologies, 2009)
2	Paper folding task 1	A target shape is presented on imaginary transparent paper. Four possible answers are given with the paper folded in half, participants have to fold the shape in their head to work out which folded shape matches the target shape.	(IndiaBIX Technologies, 2009)
3	Perdue Spatial test	A shape is presented in two orientations. The participant has to work out how the shape has been rotated. They are then presented with another shape which they have to mentally rotate in a similar way to the first shape and work out which answer has the same orientation	(Bodner & Guay, 1997)
4	Block counting	A complex 3D shape is shown, made up of many uniform blocks. The participant has to work out the number of blocks present, imagining the side of the shape that isn't visible.	(Learning Express, 2001)
5	Unfolded cube test	An unfolded cube is presented with images on each face of the cube. Four assembled cubes are then presented with images on each side. The participant has to imagine assembling the cube to decide which one of the four options is not possible.	(123Test, 2018)
6	Paper folding task 2	The same test as 'paper folding task 1', but with a different set of questions.	(IndiaBIX Technologies, 2009)
7	Understanding patterns	A 2D pattern (with fold lines) is presented along with a series of four 3D shapes. Participants have to imagine the pattern being folded and decide which shape it will make when 3D.	(Learning Express, 2001)
8	Spatial analysis task	Participants are given an engineering drawing of a shape with views from the top, side and front. They have to imagine these 2D shapes as a 3D object and decide which one of the four possible answers is	(Learning Express, 2001)
9	Embedded images 1	A line diagram is shown along with four much more complex line diagrams. The participant needs to find the original diagram within one of the four complex diagrams and report where it is	(IndiaBIX Technologies, 2009)
10	Rotated blocks	Participants have one 'target shape' and five other shapes. The participant needs to report which one of the five shapes is the same as the target shape (but rotated in a different orientation)	(Wiener, Part 14 ROTATED BLOCKS, 2005)
11	Mixture of tests	Tests comprise of a mixture of block rotations, paper folding, shape rotations, pattern identification, shape assembling, and gears and pulleys,	(Psychometric Success, n.d.)

12	Embedded images 2	The same test as 'Embedded images 2', but with a different set of questions.	(IndiaBIX Technologies, 2009)
13	Matching pieces and parts	A shape is presented along with five smaller shapes. Participants have to decide which two of the five smaller shapes can be assembled to make the original shape.	(Learning Express, 2001)
14	Rotated shapes	Participants have one 'target shape' and four other shapes. The participant needs to report which one of the four shapes is the same as the target shape (but rotated in a different orientation)	(Learning Express, 2001)

To give an example of the type of questions within the training tasks highlighted in Table 15, an example of one question from each day's training is presented below in Table 16:

Table 16 Examples of Training Tasks

Day	Test Name	Example question
1	Image analysis	
2	Paper folding task 1	
3	Perdue Spatial test	

4	Block counting	
5	Unfolded cube test	
6	Paper folding task 2	
7	Understanding patterns	
8	Spatial analysis task	
9	Embedded images 1	

10	Rotated blocks	
11	Mixture of tests	
12	Embedded images 2	
13	Matching pieces and parts	
14	Rotated shapes	

Participants would be given the training pack as a hard copy, where instructions were given to complete one training task per day, and at the beginning of each day there was a short explanation on how to complete the task. Participants were told to spend at least 15-minutes on the training task each day, so everyone had the same training exposure. For example, if the days training only took 10 minutes to complete participants would spend the remaining 5-minutes re-reading and checking their answers – ensuring they were practicing visuospatial tasks for at least 15-minutes per day. If the task took longer than 15-minutes participants were asked to continue until the task allocated for that day was complete. For this trial, there was no benefit in randomising the task order between participants, as this study was not interested in how visuospatial skills can be trained or what tests are most appropriate, but instead more fundamentally, if they can be trained. There was no practical way to ensure adherence to the training regime, and participant training material was not marked.

6.3.2 COMMON METHODOLOGY

To assess the effectiveness of this training pack on visuospatial abilities (RQ1) and the subsequent effect this has on motion sickness (RQ2) two separate studies were used

(Phase 1 and Phase 2), although the methodologies followed the same basic format. Initially participants would be assessed to measure their baseline visuospatial performance. Alongside this, participants would also take part in a driving exposure to measure their baseline motion sickness susceptibility. In Phase 1, this would be a simulator study where participants will be driving the 3xD simulator as the motion sickness task. In Phase 2, this will be an on-road study where participants will be sitting as passengers in a vehicle (one at a time) which is being driven round Warwickshire roads as the motion sickness task. Once baseline visuospatial performance and associated motion sickness susceptibility is captured, participants will then enter the ‘training phase’ where, over the next 14-days, participants will train their visuospatial skills using the training pack developed. After the 14-day training period, participants will return and researchers will assess their visuospatial performance once again to see if training has had an effect. Immediately after this assessment, participants will take part in an identical driving task and their motion sickness state will be measured and compared to their baseline scores (before training). At no time were participants told that this training would reduce their motion sickness, the information sheets were kept vague so as to not influence any placebo affect. During both drives, participants wore the Empatica E4 wristband to collect physiological data for a later study. Figure 44 below provides a visual representation for the methodology of this project

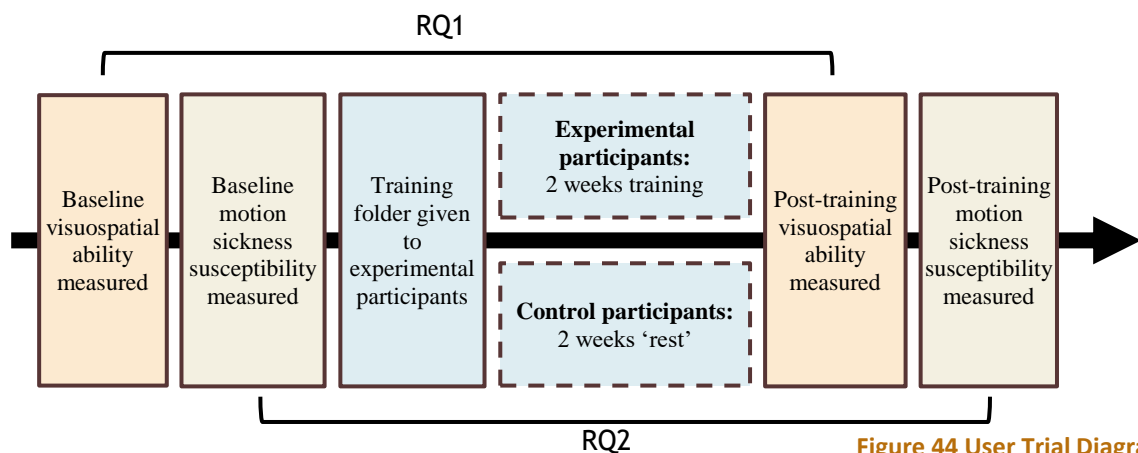


Figure 44 User Trial Diagram

6.3.3 PROCEDURE FOR PHASE 1- A SIMULATOR STUDY

To assess the effectiveness of visuospatial training on reducing motion sickness in a simulator (therefore simulation sickness) the participants who took part in the previous user trial assessing human performance were re-recruited (as per Project A and Submission 3). Those who reported the highest motion sickness scores were contacted to take part in this next user trial, where there was no benefit in reducing motion sickness for those who did not get motion sick. Participants were ranked in accordance to their SSQ score and 20 of those with the highest scores were contacted. Using the same participants was beneficial as baseline data on their motion sickness scores for the driving scenario had already been captured previously, so there was no

need for two exposures. It was also considered an ethical way of running this trial as participants will already be aware of the risks of taking part, so can make an informed choice if they want to take part in this follow up study. The second user trial would take place approximately 6-months after the human performance trial, therefore habituation to the simulator was not a factor.

Participants were recruited to this user trial via email and the participants received an information leaflet about the study proposal. If participants agreed to take part, they were met at the University of Warwick (UoW) and were asked to complete a mental rotation test (MRT) to capture their baseline visuospatial performance. The MRT was originally developed by (Vandenberg & Kuse, 1978) but the recreated version by (Peters M. , et al., 1995) was used in this study, which included CAD (Computer Aided Design) images and were much easier to read than the original. Two tests were assembled: one to be given before the visuospatial training pack and one to be given after to capture the effect of the training. Upon meeting at the agreed timeslot, participants were asked to complete one MRT test, where they were given three minutes to complete the test in silence. As before, a score of '1' was given only if they selected both answers correctly per question. Where two MRT tests are used, the order in which they are received (before or after training) was randomised. As baseline motion sickness (from the previous human performance trial) was already recorded for participants there was no need for a motion sickness exposure before training and data from the previous study was carried over.

The participants were then given the visuospatial training folder and an explanation as to how to complete the folder was given. Participants went away and completed the training pack for 14-days where they received a few follow up emails during the training period to remind participants what day they should be on. After this 14-day training period, participants returned to the 3xD simulator and completed another MRT, which was in the same style as their pre-training MRT, but a different set of questions to remove any memory or learning effect. Participants then completed the same driving task as described in Project A (and Submission 3), following identical instructions introducing them to the vehicle, an identical route and in identical conditions (climate, traffic, route speed, lighting etc.). Participants were recruited to return as close as possible to the same time of day as when they completed the first simulator study. As before, this driving task took up to 30-minutes to complete.

Motion sickness was measured by completing an SSQ (Kennedy, Norman, Berbaum, & Lilienthal, 1993) before and after the simulator exposure and through administering the once-per minute FMS (Keshavarz & Hecht , 2011) measure to track motion sickness throughout the exposure. As before, participants were made aware of all the risks of taking part and were reminded they can end the driving at any time if they feel too motion sick. The researcher again would monitor participant wellbeing throughout the

study and if someone was getting notably more motion sick, they were asked to consider if they felt fit to continue or not. All participants were reminded that if they feel unwell, to stay and recover for as long as necessary and not to drive a car for at least 1 hour after the simulator exposure, and until they feel well enough to do so.

From this experimental design, the data set collected included baseline motion sickness susceptibility (from the first study human performance study in Project A), baseline visuospatial ability (as assessed using the MRT), post-training visuospatial ability (as assessed using a second MRT) and post-training motion sickness (as measured in the second simulator exposure). To take part in this study, participants were given £40 in Amazon vouchers as a gesture of thanks for giving up their time to complete the 14-day training pack. Payment was given to participants mid-way through training so that there was no sense of payment being related to driving simulator performance. This study was given ethical approval by the Warwick BSREC with reference (REGO-2017-2090 AM01).

6.3.4 PROCEDURE FOR PHASE 2- A 'REAL-WORLD' STUDY

For Phase 2 of this study, the methodological approach was kept as similar as possible to that of the simulator-based study; however the main difference was the motion sickness exposure was an on-road scenario. For this study, participants would be driven around in a vehicle to measure the susceptibility to motion sickness in a car (car sickness) and it was further explored if increasing visuospatial skills (RQ1) could decrease motion sickness in the 'real-world' (RQ2).

To complete this study, a new set of participants were used, who had not taken part in any previous trials as part of this EngD. JLR, as the sponsoring company of this project and as a stakeholder for the IP (intellectual property) which is created from this study, insisted that the study must be kept confidential and therefore only JLR staff can be used, who all have agreed to a JLR non-disclosure agreement. Considering this, practicality of this user trial was of importance, where participants needed to be accessible from a common location during office hours. Participants from the JLR Whitley site (Coventry, UK) were recruited for this user trial where recruitment emails indicated that we were particularly interested in gaining participants who suffer from motion sickness. It was decided that all trials would be completed in the mornings, so that if motion sickness was a factor, symptoms should subside before participants have to drive home in the evening. JLR Whitley site was chosen as this site consists of mostly business-related staff, therefore reducing the chance that visuospatial skills would be skewed by job (e.g., JLR for design engineers who might use CAD frequently). Participants were recruited via email using an internal JLR email list where those who were most susceptible to motion sickness were of most interest. For this trial, there were 20 testing days available (five working days per week, and a four week study) and with three timeslots for testing (9am-10am, 10am-11am, 11am-12noon), a total of 30

slots for user trials. It was decided that this trial would aim for 20 experimental participants who would receive training, and 10 participants to act as control group – who would not receive the training pack. JLR were in charge of recruitment, where access to internal email databases was restricted. The method of assigning participants to the control and experimental group was limited whereby the first 20 participants to take part formed the experimental group, and the final 10, the control group. This was decided purely for a practical reason where the sponsor wanted to ensure firstly there were enough experimental participants to collect data on.

Participants will be assigned two 1-hour user trial timeslots spaced exactly 14 days apart, where the timeslot will be at the same time of day to ensure consistency for personal factors and road conditions (as much as possible). When participants were met for the first time they completed a demographics questionnaire and an MRT test. This MRT test is the same as used in Phase 1, where two tests were created and given to participants in a random order (one before training, one after). Once baseline visuospatial performance was measured participants were taken to the vehicle and taken on a ~30-minute drive around Coventry roads. Participants were to sit in the near-side rear seat of the 2018 Land Rover Range Rover Sport L494 fleet vehicle supplied by JLR. The same vehicle was used for all participants and temperature was maintained at a steady 21 degrees Celsius for all participants. The lead researcher sat in the front nearside seat and a trained JLR driver was driving the vehicle. No conversation unrelated to data collection was allowed between the researcher and participant. A mock-up photo of the user trial lay-out is shown below in

Figure 45:



Figure 45 On-Road Visuospatial User Trial

The route taken was designed to take approximately 30-minutes and included a mixture of road types and speeds. Including country roads, rural and town roads as well as a short section on a dual carriageway. Participants were reminded they can end

the drive at any time if they feel motion sick, where multiple safe pull-over spots were identified throughout the route. A map of the test route is shown below in Figure 46.

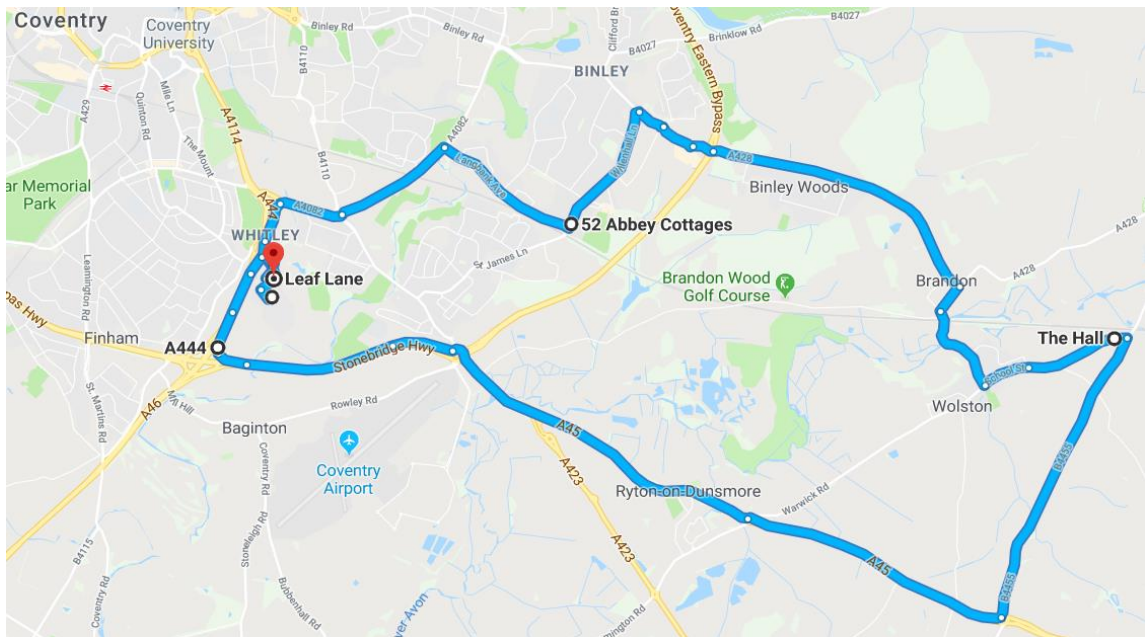


Figure 46 Route for On-Road Visuospatial Trial

The JLR driver was trained on the route, and practiced it multiple times before the trials, to ensure driving style was as consistent as possible between drives. It was considered that between the first and second drives (spaced 14 days apart) that participants may act differently. Specifically, if motion sickness was experienced in the first drive participants may spend more time in the second drive looking out of the window in front and doing other self-preservation activities. Therefore, it was important that participant activity was controlled as much as practical so that the two driving exposures were as comparable as possible (mostly considering sensory conflict). A reading task was designed whereby, throughout the drive, text would appear on the head-rest-mounted screen in front of the participants for 30-seconds at a time. Participants would read through the text and then it would disappear for 30-seconds before new text re-appeared and the cycle would continue throughout the drive. The reading tasks were taken from an adult learning website (British Council, 2019) and were written in basic English so comprehension for someone who has a full-time job at JLR was not considered to be an issue. The blocks of text were randomised so no specific story was followed which may have resulted in an emotional response. Two reading tasks were created, one for the first drive, and one for the second. The order in which they were received was randomised between participants. The use of this reading task was not likely to affect subjective or physiological responses as is validated in a recent text by (Horrey, Lesch, Garabet, Simmonds, & Maikala, 2017). An image showing the participants' view from inside the vehicle is shown below in Figure 47:



Figure 47 View of the Reading Task

Throughout the drive, the researcher measured motion sickness once per minute using the FMS method. Motion sickness was also assessed using the SSQ before and after the trial. This questionnaire was useful for making comparisons between the simulator-based trial and this on road trial. However, due to its simulator-focused design, the MSAQ was also used which is considered more appropriate for 'real-world' motion sickness. As there was a basic reading task being completed it was interesting also to collect some secondary data on the perceived workload of this task so the NASA TLX (Task Load Index) (NASA, 1986) was used after the drive to address the workload of reading whilst being driven around. The MSSQ (Golding J. F., 1988) was considered for participant recruitment, but there were limitations on what data could be collected before meeting the participant as recruitment was handled by JLR staff, so this was not used.

After the first drive, the experimental participants were given the training folder (the contents of which have been previously explained) and the training was explained fully to each participant. The control group did not receive a training folder. After 14-days and when the training had been completed, participants returned for the second (post-training) exposure at the same time of day as their first trial. Comparative visuospatial skills were measured again using another MRT (for both control and experimental participants). After this, participants were taken on another drive, following an identical route to the first drive and maintaining the same driving style from the trained JLR driver. Participants completed another reading task throughout the drive although the text was different. Motion sickness was assessed using the FMS

throughout the drive and the SSQ, MSAQ and TLX were given at the end of the drive. No payment was given to participants for this user trial and the user trial was approved by the JLR Ethics Committee (reference 12323185).

6.4 RESULTS

6.4.1 PHASE 1 – A SIMULATOR STUDY

All participants (n=20) completed the training tasks in their entirety and attended the simulator driving part of the trial. In total, there were 10 males and 10 females; ages were reported in discrete categories so no descriptives of age is possible. A total of seven participants ended the driving early on account of motion sickness (35%). All participants were able to complete the SSQ after the drive so data from all participants (n=20) was retained for analysis. People who dropped out of the driving task due to sickness are referred to as ‘dropouts’.

Addressing RQ1 it was explored to see if the visuospatial training pack was successful in increasing visuospatial ability (as measured with the MRT). Some descriptive statistics of the Mental Rotation Test (MRT) scores before the training period (pre-training MRT) and after the training period (post-training MRT) is presented below in Table 17:

Table 17 Exploratory Analysis of MRT Scores

	N	Minimum	Maximum	Mean	Std. Deviation
Pre-Training MRT score	20	1.00	9.00	5.1000	2.29186
Post-Training MRT score	20	1.00	12.00	7.0500	3.39466

The mean MRT score has increased (pre to post training) from 5.10 to 7.05, showing a mean average increase of 38.24%. A t-test revealed this increase in visuospatial ability before and after training to be statistically significant $t(19)=-4.278$, $p<0.0001$ thus answering RQ1.

Previous literature identified an interesting gender effect with regards to visuospatial ability. The data collected here showed males performed significantly higher than females for their MRT baseline with an average male MRT score of 6.2 (SD=1.39) compared to females with an average score of 4.0 (SD=2.53). A one-way ANOVA identified this difference as significant where $p<0.05$ ($F=5.76$, $p=0.027$). After training

males had an average score of 8.8 (SD=2.34) and females 5.3 (SD=3.47). This also proved to be statistically significant where $p < 0.05$ ($F=6.991$, $p=0.016$).

Looking then to motion sickness, first an exploratory analysis of SSQ data is presented below in Table 18, which includes the total SSQ score as well as the three SSQ subcategories where the change in mean score is presented as delta (Δ):

Table 18 Exploratory Analysis of SSQ Scores

SSQ Category	Pre-Training, Mean	Pre Training, SD	Post-Training, Mean	Post-Training SD	Δ Mean
Nausea	68.95	34.89	45.79	39.58	-23.16
Oculomotor	45.87	17.99	28.43	18.54	-17.44
Disorientation	77.96	25.30	45.24	31.57	-32.72
Total	66.29	20.11	32.16	20.96	-34.135

The data presented in Table 18, shows how total SSQ score for the group decreased from an average of 66.299 to 32.164, showing a 51.48% decrease across the group after the training period. A similar direction is seen for the subcategories where Nausea decreased by 40.36%, Oculomotor by 46.94% and Disorientation by 53.11%. These changes in motion sickness scores have been presented graphically below in Figure 48. For all results presented The notation * denotes a 95% confidence significant difference, and ** a 99% confidence and the error bars indicate the standard deviation.

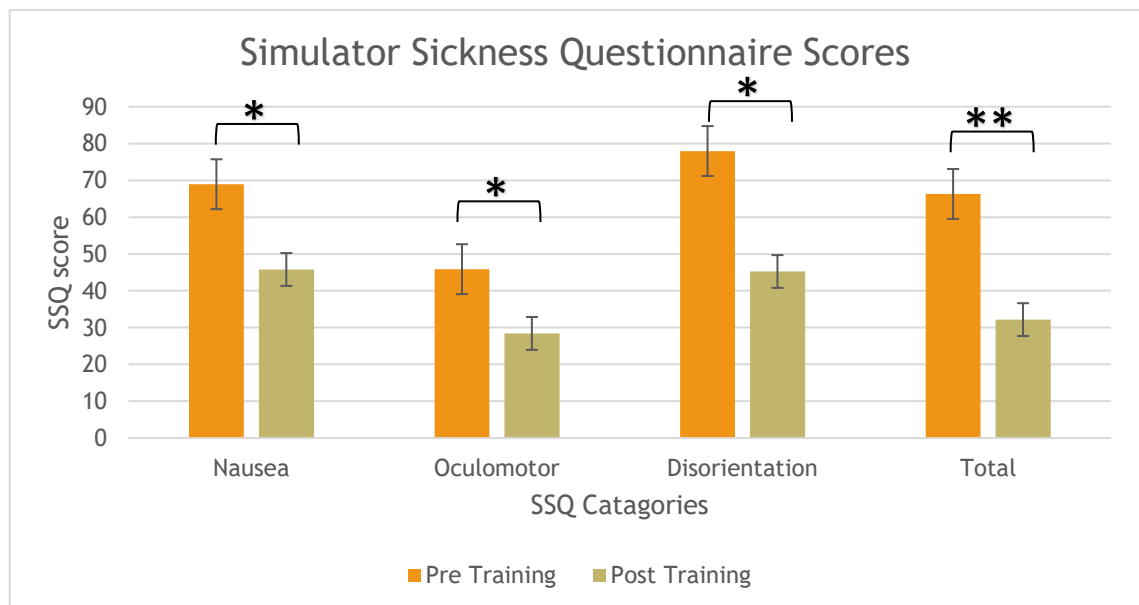


Figure 48 SSQ Scores, Before and After Visuospatial training

To analyse if these changes in SSQ scores before and after training were statistically significant, paired T-tests were first performed (where the data met all the assumptions of the test) and the results are presented in Table 19 below:

Table 19 Statistical Analysis of SSQ Scores

SSQ Category (pre training vs. post training)	df	t	Sig. (2-tailed)
Nausea	19	2.175	0.043
Oculomotor	19	2.597	0.018
Disorientation	19	3.236	0.004
Total	19	4.903	0.000

As shown above, all reductions in motion sickness measured across four SSQ outputs were shown to be statistically significant where $p < 0.05$ in all cases.

Looking at participants individually, it is seen that three participants did not improve their visuospatial ability through training, whereas the rest of the group ($n=17$) did. Removing these three participants from the group, it is then shown that motion sickness, for those who improved their visuospatial ability, was reduced on average by 58.02% in total SSQ score, 47.77% for Nausea, 46.16% for Oculomotor, and 46.94% for Disorientation. As before, all of these decreases were shown to be statistically significant when assessed using a paired T-Test where $p < 0.05$ in all instances. Despite the small sample size ($n=3$), it was further shown that for these three participants who did not improve their visuospatial abilities, also showed no significant change in their SSQ scores after training ($t(2)=-1.947$, $p=1.91$) where $p > 0.05$.

To understand if there was a gender effect in motion sickness reduction the change in motion sickness scores between genders was examined. The Shapiro-Wilk Test resulted in a p value greater than 0.05 for both groups, and a homogeneity in variance test (Levine) resulted in an output of ($F(1,18)=0.014$, $p=0.906$) - showing the data was both normally distributed had homogeneous variances. Therefore, an ANOVA was used to explore if there was a gender effect in the extent to which total motion sickness was reduced after training. The ANOVA provided a results of ($F=4.211$, $p=0.055$) indicating that there was no gender effect where $p > 0.05$. This showed both genders benefited to a comparable scale from the training.

Further to the subjective motion sickness questionnaires, it was also interesting to explore participant dropouts – looking at motion sickness in a binary manner. Rate of participant dropouts before and after training is presented below in Figure 49. The notation * denotes a 95% confidence significant difference and the error bars indicate the standard deviation.

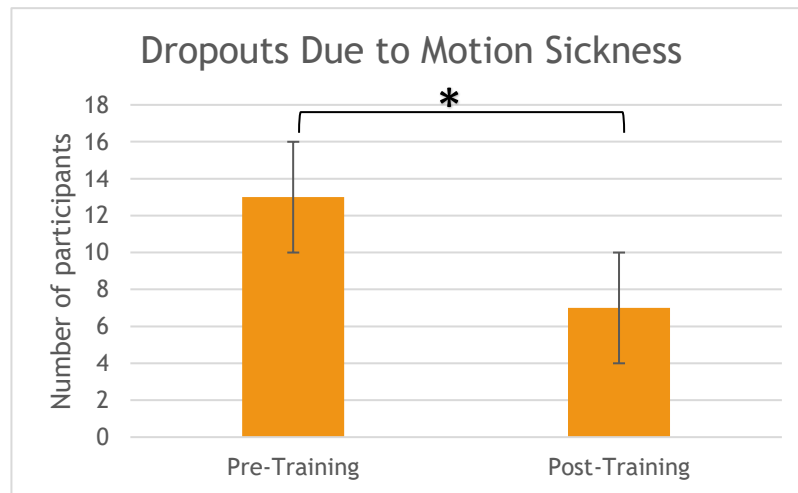


Figure 49 Dropouts Due to Motion Sickness

Total dropouts across the group decreased from 13 to 7 (a 46.2% decrease) after the training period. A paired T-test was used to examine the significance in observed reduction in propensity to drop out after training compared to before. This test showed this decrease to be significant where $t(19)=-2.854$, $p=0.010$. However, as this study (specifically RQ2) is interested in the effect of increased visuospatial skills on motion sickness, the three participants who did not increase their visuospatial scores can be removed from the group and it is then shown improving visuospatial ability was responsible for reducing dropouts by 60%, although given the small sample size statistical analysis is not reported on.

6.4.2 PHASE 2 – A ‘REAL-WORLD STUDY

Despite filling 29 (out of a possible 30) timeslots with 19 experimental participants and 10 control participants, there were seven people who withdrew from the study due to work commitments. The total experimental group therefore consisted of 15 participants, and a further 7 participants made up the control group. The experimental group consisted of 6 males (40%) and 9 females (60%) and the control group had 3 males (~40%) and 4 females (~60%). The mean age for the experimental group was 33.6 (SD=12.8) with the youngest participant being 20 and the oldest being 59. The mean age for the control group was 32.4 (SD=8.24) with the youngest participant being 24 and the oldest being 45. One participant (in the experimental group) asked to end the driving task during their baseline exposure due to motion sickness. No participants asked to end the driving in the post-training exposure. Data was reserved for this one ‘dropout’ for analysis.

Looking first to assess visuospatial performance, an exploratory analysis is shown below:

Table 20 Exploratory Analysis of MRT scores

	Group	Mean	Std. Deviation	N
Pre training MRT score	Experimental	5.27	2.789	15
	control	4.00	1.673	6
	Total	4.90	2.548	21
Post training MRT score	Experimental	7.6667	3.39467	15
	control	5.5000	1.51658	6
	Total	7.0476	3.10606	21

The mean MRT score for the experimental group increased (pre vs. post training) from 5.26 to 7.67, showing a mean average increase of 45.81% for the experimental group. For the control group (i.e., those who received no visuospatial training), average MRT score increased from 4.42 to 5.71, showing a mean average increase of 16.96%. To see if MRT score was significantly changed for the control and experimental groups a mixed ANOVA was performed. Box's test for equality of covariance matrices ('M test'), showed that with an M value of 4.163 and a p value of 0.321 we can reject the null hypothesis (with a 0.05 significance threshold) and assure reliability in a mixed ANOVA analysis where the data meets the assumption of a multivariate normal distribution. Using a mixed ANOVA with a Greenhouse-Geisser correction it was shown that there was a mean change in MRT scores before and after the intervention ($F(1,19) = 11.203$, $p=0.003$). Further, there was a significant difference between the groups (Experimental group vs control) after the intervention ($F(1,19) = 19.628$, $p<0.001$).

A paired T-test confirms the experimental group significantly improved their scores, $t(14)=-5.150$, $p<0.001$, whereas the control group did not $t(6)=-1.89$, $p=0.108$.

Considering any gender effect it was shown for the total sample (e.g, experimental and control participants) that males had a significantly higher MRT ability before training with a mean score of 6.38 (SD= 2.669) compared to females with a mean score of 4 (SD=2.082) ($F=5.210$, $p=0.034$) where $p<0.05$. Experimental participants (i.e., those who underwent the training period) were analysed again for a gender effect. Here, it was shown that with a mean male score of 10.50 (SD= 2.88) and mean female score of 5.77 (SD= 2.22) there was a statistically significant difference between the genders ($F=12.875$, $p=0.003$) where the p value was <0.05 showing males improved their scores to a greater degree than females.

As two MRT tests were used, one pre-training and one post-training (given randomly between participants) it was explored to see if the tests were of the same difficulty. A paired t-test revealed no significant difference between scores for the two tests (MRT1 vs MRT2) where $t(16)=0.566$, $p=0.579$

Looking at the motion sickness data for the experimental group, Table 21 below provides an exploratory analysis for both the SSQ and MSAQ data including all subcategories.

Table 21 Exploratory Analysis of Motion Sickness for the Experimental Group

Motion Sickness category	Pre-Training Mean	Pre-Training SD	Post-Training Mean	Post-Training SD	Δ Mean
MSAQ	49.07	28.28	22.22	7.57	
Gastrointestinal					-26.85
MSAQ Central	35.55	27.15	17.96	9.67	-17.59
MSAQ Peripheral	34.81	25.76	13.33	3.37	-21.48
MSAQ Sopite-Related	36.66	18.46	20.74	9.08	-15.93
MSAQ Total	36.85	21.10	17.73	6.08	-19.12
SSQ Nausea	59.78	29.39	19.08	14.86	-40.70
SSQ Oculomotor	40.93	23.41	23.75	16.91	-17.18
SSQ Disorientation	68.67	66.85	29.60	24.60	-38.98
SSQ Total	46.87	27.80	19.45	12.42	-27.42

Table 21 shows an average decrease in total MSAQ scores from 36.85 to 17.73, showing a 51.89% decrease. A similar direction is seen within the MSAQ subcategories with gastrointestinal decreasing by 54.71%, central decreasing by 49.47%, peripheral decreasing by 42.66% and sopite-related decreasing by 43.37%. For the SSQ, total scores were decreased from 46.87 to 19.45, showing a 58.50% decrease. For the subcategories of the SSQ, Nausea decreased by 68.08%, oculomotor decreased by 41.97% and disorientation decreased by 56.89%.

Presenting this graphically,

Figure 50 below shows the decrease in motion sickness scores for the experimental group. For all results presented error bars indicate the standard deviation.

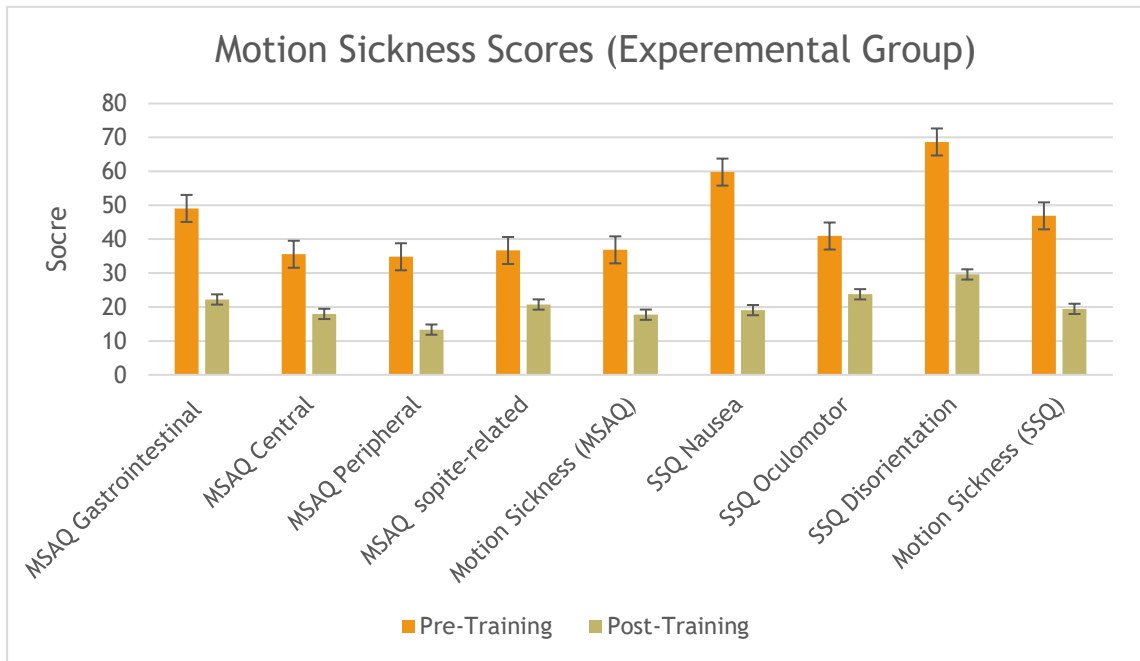


Figure 50 Motion Sickness Scores Before and After Training (Experimental Group)

A paired T-test was performed for both SSQ and MSAQ scores for the experimental group, including total scores and all subcategories, the results of which are presented below in Table 22:

Table 22 Statistical Results of Pre and Post Training for Experimental Group

Motion Sickness (experimental group)	df	t	Sig. (2-tailed)
MSAQ Gastrointestinal	14	4.370	0.001
MSAQ Central	14	2.841	0.013
MSAQ Peripheral	14	3.622	0.003
MSAQ Sopite-Related	14	4.181	0.001
MSAQ Total	14	4.342	0.001
SSQ Nausea	14	5.924	0.000
SSQ Oculomotor	14	3.956	0.001
SSQ Disorientation	14	2.866	0.012
SSQ Total	14	5.456	0.000

As seen in Table 22, all decreases in MSAQ and SSQ scores were statistically significant where $p < 0.05$ in all cases.

Again, to see if there was a gender effect in motion sickness reduction, the change in motion sickness scores between genders was examined for the experimental group. The Shapiro-Wilk Test resulted in a p value greater than 0.05 for both groups ($p=0.714$ for females and $p=0.238$ for males), and a homogeneity in variance test (Levine) resulted in an output of ($F(1,13)=0.066$, $p=0.802$) - showing the data was both normally distributed had homogeneous variances. Therefore, an ANOVA was used to explore if there was a gender effect in the extent to which total SSQ motion sickness was reduced after training. The ANOVA provided a results of ($F=12.875$, $p=0.003$) indicating that there was a gender effect where $p<0.05$. This showed females had a statically greater reduction in motion sickness compared to males where average reduction in scores for females was -21.57 ($SD=21.32$) and for males, -13.29 ($SD=21.97$).

Looking now to the control group ($n=7$) for any changes in motion sickness, an exploratory analysis of their data is presented below in Table 23:

Table 23 Exploratory Analysis of Motion Sickness for the Control Group

Motion Sickness category	Pre-Training Mean	Pre-Training SD	Post-Training Mean	Post-Training SD	Δ Mean
MSAQ Gastrointestinal	40.476	17.336	58.333	48.723	17.857
MSAQ Central	30.952	15.991	28.571	15.274	-2.381
MSAQ Peripheral	29.100	22.673	23.809	14.480	-5.291
MSAQ Sopite-Related	30.952	16.544	34.127	20.012	3.174
MSAQ Total	31.051	13.553	34.722	20.230	3.670
SSQ Nausea	61.328	29.070	57.240	25.240	-4.088
SSQ Oculomotor	48.728	37.354	50.894	30.544	2.165
SSQ Disorientation	47.725	33.961	61.645	46.763	13.920
SSQ Total	43.277	25.444	44.880	23.752	1.603

For the control group, mean total MSAQ score increased by 11.98% where gastrointestinal increased by 44.11%, central decreased by 7.69%, peripheral decreased by 18.18% and sopite-related increased by 10.25%. For the SSQ, total score also increased, this time by 3.70%, where the subcategories of nausea decreased by -6.66%, oculomotor increased by 4.44% and disorientation increased by 29.16%. Presenting this data graphically, Figure 51 shows the scores for all categories of the SSQ and MSAQ for the control group. For all results presented the error bars indicate the standard deviation.

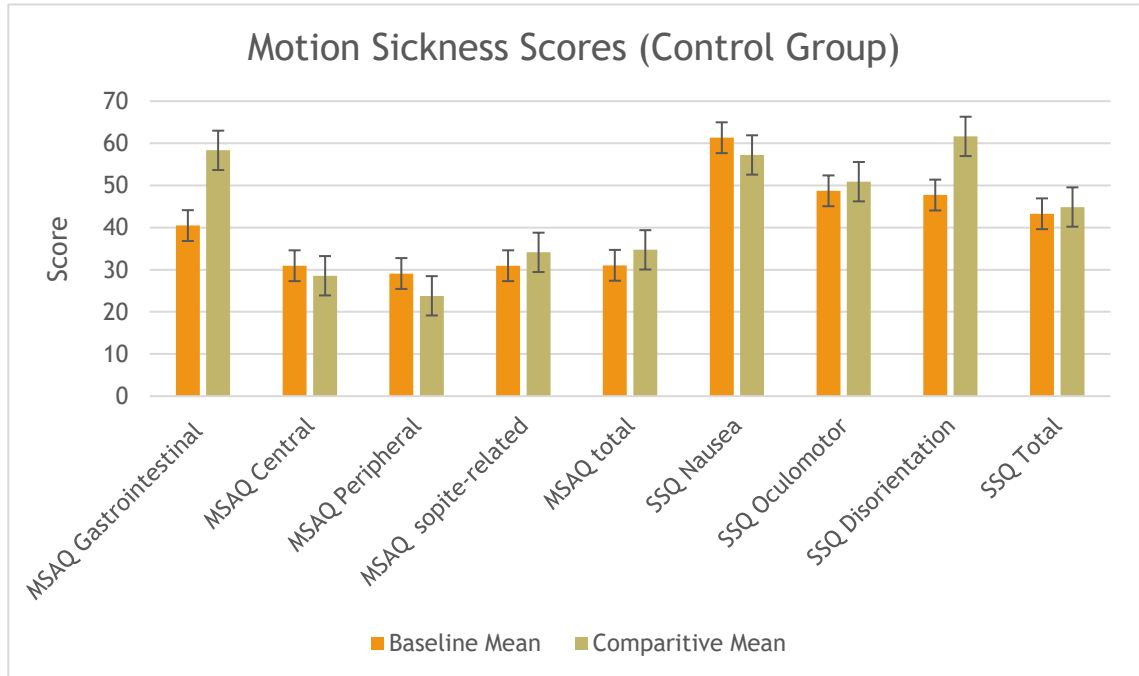


Figure 51 Motion Sickness Scores Before and After Training (Control Group)

Looking for any significance between the changes seen above in

Figure 51, paired T-tests were performed for each category, the results are presented below:

Table 24 Statistical Results of Motion Sickness Change for Experimental Group

Motion Sickness (Control group)	df	t	Sig. (2-tailed)
MSAQ Gastrointestinal	6	-1.158	0.291
MSAQ Central	6	0.679	0.522
MSAQ Peripheral	6	0.909	0.398
MSAQ Sopite-Related	6	-1.220	0.268
MSAQ Total	6	-0.997	0.357
SSQ Nausea	6	0.750	0.482
SSQ Oculomotor	6	-0.603	0.569
SSQ Disorientation	6	-1.871	0.111
SSQ Total	6	-0.549	0.603

Table 24 shows that there was no significant change for any motion sickness score for the control group – in either the SSQ or MSAQ where $p > 0.05$ in all cases.

Group data has been individually analysed (e.g., control and experimental groups are analysed separately). A mixed ANOVA has also been conducted with group (control/experimental) as the between groups variable and motion sickness (pre and post) as the within groups variables. The SSQ and MSAQ (totals) did violate the assumptions of this test where the null hypothesis of Box's test for equality of covariance matrices was accepted at a 95% confidence level where ($M=11.107$, $p=0.023$) for the SSQ and ($M=27.442$, $p<0.001$) for MSAQ. However, given the uneven groups it is understood that the M Test is not necessarily robust, so this is ignored. It was shown that SSQ total was significantly reduced between exposures ($F(1,20) = 11.23$, $p=0.003$) where $p<0.05$. Further, there was a significant difference between the control and experimental group for SSQ (pre vs post exposure) ($F(1,20) = 14.203$, $p=0.001$). There was a strong and significant interaction observed ($F(1,20) = 14.203$, $p=0.001$) Observing the estimated marginal means output presented in Figure 52 below, it is clear that the experimental group significantly reduced their scores where the control group did not.

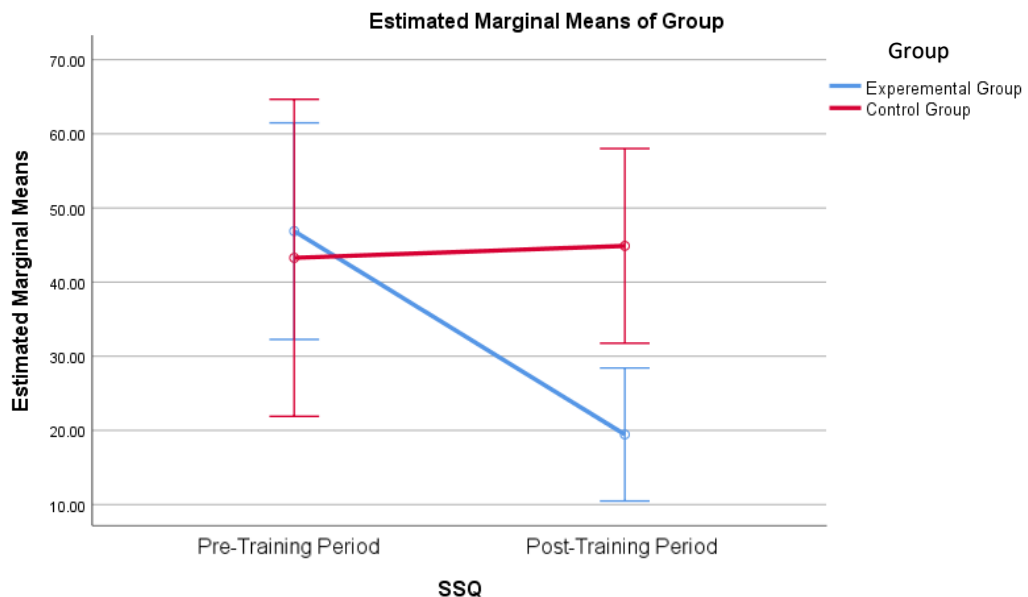


Figure 52 Estimated Marginal Means for Pre and Post SSQ Score Control Vs Experimental
Error Bars: 95% CI

Looking also at the MSAQ total, there was a significant change observed within the main effect of MSAQ scores between exposures ($F(1,20) = 4.908$, $p=0.039$) where $p<0.05$. Further, there was a significant difference between the control and experimental group for MSAQ (pre vs post exposure) ($F(1,20) = 10.679$, $p=0.004$). There was also a strong and significant interaction effect observed ($F(1,20) = 10.679$, $p=0.004$) Observing the estimated marginal means output presented in Figure 53 below, it is clear that the experimental group significantly reduced their scores where the control group did not.

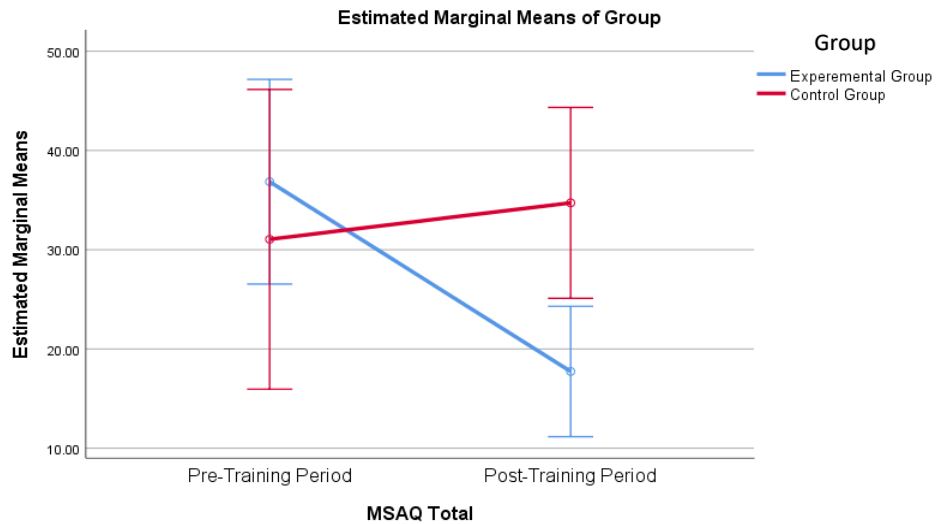


Figure 53 Estimated Marginal Means for Pre and Post MSAQ Score Control Vs Experimental Error Bars: 95% CI

Finally, it is also possible to explore the secondary data looking at workload of the reading task using the TLX (non-pairwise) – commonly referred to as Raw TLX or ‘RTLX’. For the experimental group RTLX score decreased from 33.80 to 24.40 showing a decrease of 27.8%. This decrease was proven to be statistically significant where $t(14)2.847, p<0.05$. For the control group, RTLX increased from 37.26 to 40.00, a difference of 7.35%. This increase was not significant however where $t(6)-0.961, p=0.374$. These scores are shown below in Figure 54 for both the control and experimental groups:

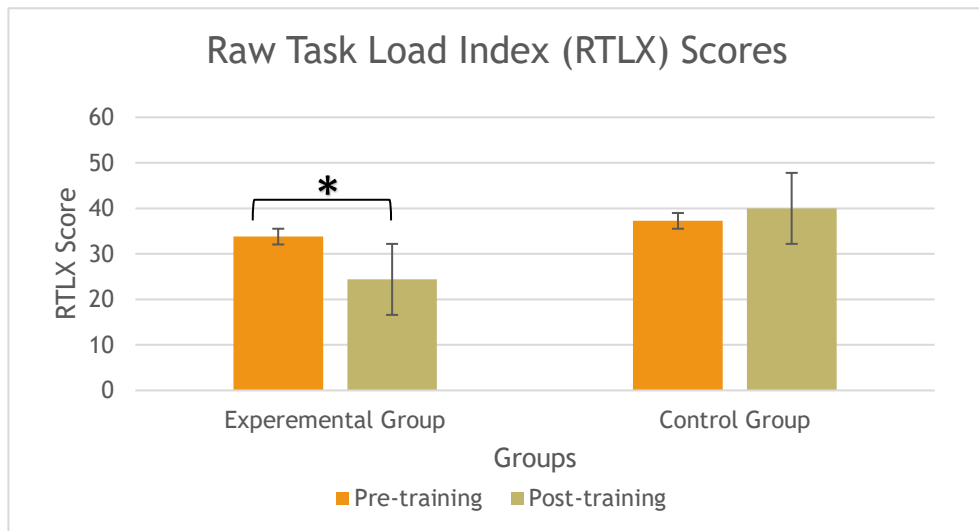


Figure 54 RTLX Scores for the Control and Experimental Groups

Rejecting the null hypothesis of Box’s test for equality of covariance matrices where $(M=5.034, p>0.05)$ it was possible to conduct a mixed ANOVA comparing change in RTLX (pre vs post) between the two groups. This test revealed at a group level there was no significant change in RTLX scores $(F(1,19) = 1.693, p=0.209)$. However,

contrasting the changes experienced within each group (control vs experimental) a difference was observed ($F(1,19) = 5.616, p=0.029$) where $p < 0.05$. There was also a significant interaction effect observed ($F(1,19) = 19.000, p=0.029$) The estimated marginal means graph below indicates how the aforementioned reduction in RTLX for the experimental group was significantly different to the control group:

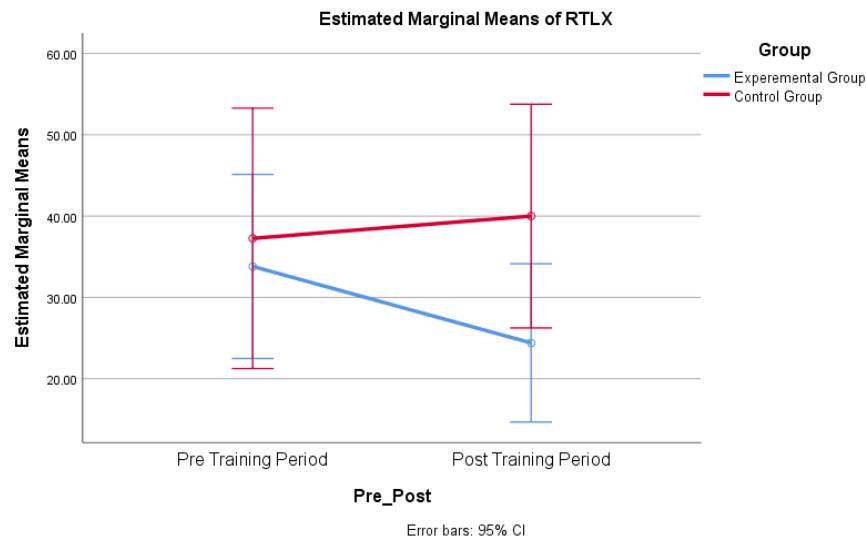


Figure 55 Estimated Marginal Means for Pre and Post RTLX Score Control Vs Experimental

As there were two reading tasks used, and given randomly between drive 1 and drive 2 between participants, a test to see if reading task influenced the RTLX score was carried out, to make sure there was no bias in the reading tasks. A paired T-Test showed there was no significant difference between RTLX scores for the two reading tasks $t(21)=1.123, p=0.283$.

6.5 DISCUSSION

This project looked to address two research questions:

RQ1 - Is it possible to improve visuospatial ability through non-invasive training tasks?

RQ2 - Does increasing visuospatial ability decrease motion sickness susceptibility?

To address these two research questions a two-part user trial was devised including both simulator-based, and on-road experimentation. The motion sickness being measured in the simulator is often referred to as 'simulation sickness' whereas for the on-road study it is commonly referred to as 'car sickness' for the on-road trial. However, as the term 'motion sickness' is an umbrella term capturing all forms of

motion sicknesses it can be summarised as such. Each research question can be discussed before conclusions bring the project together.

6.5.1 RQ1 - IS IT POSSIBLE TO IMPROVE VISUOSPATIAL ABILITY THROUGH NON-INVASIVE TRAINING TASKS?

Discussing first RQ1, which looked to validate a method for training visuospatial skills using a pen and paper training folder, it was shown in both user trials that this pack was successful across the groups. There was no literature or previously proven method for training visuospatial skills, therefore this pack was devised to facilitate practice with various visuospatial tests in hope that this would train participant skill. In Phase 1, it was shown how average visuospatial ability significantly increased by 38.24% across the group. In the on-road study it was shown that the training pack significantly increased visuospatial skill by 45.81%. As these two groups used the same training pack, it is possible to combine these two groups (giving a sample size of 35) to provide an overall average visuospatial score increase of 42.03% after training.

As a validation to this training pack being the only independent variable, a control group was used in the on-road study who did not complete the training pack over the 14 days. Strictly speaking, this control group was not a true control, where they did not complete any 'training task' and thus had a different experience to the experimental group. This group may be better considered as an 'untrained group'. However, the term 'control group' is used as an easily understood phrase. It was shown that for this control group, there was no significant change in their MRT scores, thus it is believed that this training pack is a successful way of training visuospatial ability. It is not known if this is the most effective method of training, and it is not known what specific tests contributed the most, and/or what training time, exposure frequency is optimal. This project did not set out to create the best training pack, but rather see if it was possible to train these skills so that later research can refine the training.

In the simulator, three people did not improve their score and in the on-road trial, one person in the experimental group did not improve their visuospatial score. As there was no way to accurately control how people were training, there are three initially considered reasons why no change in visuospatial score was noticed. Firstly, it is possible that there was just no effect where these people did train as recommended, but this style of training was not successful for these people. Second, participants may not have trained as recommended and perhaps rushed the training without engaging with it properly. A third, perhaps more speculative reason, where all four participants who did not increase their scores were female it is possible that hormonal fluctuations had an effect on their ability, where it is known that natural hormonal changes throughout the menstrual cycle does have a significant effect on MRT score (Silverman & Phillips, 1993). Menstruation was not a variable that could be controlled, and this is highlighted as a possible drawback of this experiment.

6.5.2 RQ2 - DOES INCREASING VISUOSPATIAL ABILITY DECREASE MOTION SICKNESS SUSCEPTIBILITY?

With good evidence that the training pack increased visuospatial performance, RQ2 could then be addressed and the data was examined to see if this visuospatial performance was effective in reducing motion sickness susceptibility. For the simulator study, there are three methods of measuring the impact. It was shown that, for those who improved their visuospatial ability, participant dropouts due to motion sickness reduced by 60%, average, SSQ total reduced by 58.02% and drive time for those who did still drop out (n=4) increased by 104.87%. All of these changes were statistically significant. There was no control group for this study as simulator time was strictly limited and there was only time for 20 participants, it was decided to retain the entire sample as experimental where removing enough for a meaningful control may have impacted the validity of this first study due to limited sample sizes. However, three participants did not improve visuospatial skills. Despite this being a very low sample (n=3) it is interesting, on an anecdotal level to see that there was no significant change in their collective SSQ scores before and after the training period. Their drive time did not change significantly and there was also no change in their propensity to drop out (where all three dropped out both before and after the training period). No meaningful conclusions can be drawn from this due to its limited sample size, but does bode well for the validity of the relationship between increased visuospatial skills and reduced motion sickness where this is further evidenced.

Looking to the on-road study, it is positive to see a similar direction and scale of results for on-road motion sickness, or car sickness. It was shown that for the experimental group, average total SSQ decreased by 58.50% and average MSAQ decreased by 51.89%. Again, these reductions were proven to be statistically significant. Both of these scores are a very sizable reduction in motion sickness scores. Anecdotally, one participant dropped out of the first driving scenario (pre training) 13 minutes into the drive giving an FMS score of 17 out of 20. This same participant, after training, gave a score of 5 out of 20 at the same minute 13, and went on to complete the entire drive with a maximum FMS score of only 7 out of 20 for the entire post-training drive.

As this on-road study benefitted from having a control group it was positive to see that both MSAQ and SSQ did not significantly change between the two exposures for those with no visuospatial training. This, matched with the finding that their visuospatial skills remained the same helps validate that this visuospatial training was indeed the only factor which influenced the reduction in motion sickness for the experimental participants.

As well as motion sickness, this on road trial was able to collect data on the workload for completing the reading task. Using the RTLX it was shown that workload significantly decreased by 27.8% for the experimental group, but had no significant change for the control group. This was a very basic reading task – designed for adults

learning to read, and, as there was no goal for the readers it was not expected to see such a large decrease in perceived workload. However, this change was seen, and adds to the literature previously discussed where reducing motion sickness was shown to increase job performance (Stroud, Harm, & Klaus, 2005). There were no measures of how successful participants were at completing the reading task, as this was not the primary aim of the study, rather, workload was an easy secondary data set to capture with minimal interruption to the primary research questions. Support for the RTLX is given by (Byers, Bittner, & Hill, 1989), who show that the pairwise comparison (as is needed for the standard TLX calculation) is not needed and further validates the methodology of this analysis.

The results showing decreased motion sickness leads to decreased workload further builds on the findings within Project A, to show how motion sickness does have an impact on human performance. Linking this very basic finding back to automated vehicle productivity, where reading is a known desired use case for automated vehicles (State Farm, 2016), this work evidences the importance for motion sickness management, where motion sickness will likely impact productivity.

Considering the effect of gender again, it was shown in the simulator experiment that males and females benefited equally from statistically comparable reductions (considering scale) in motion sickness reduction. However, the on-road experiment identified that males reduced their sickness more so than their female counterparts, on average. This mixed result makes it difficult to conclude on the exact gender effect of this motion sickness management method and more data would be required to answer this question with controlling for the menstrual cycle advised for further study.

6.5.3 OVERALL DISCUSSION

Firstly, to discuss the validity of the findings, the first concern with this study was in ensuring that the habituation to the task from the first exposure would not impact the second exposure. The literature discussed indicated that anything over one week should be sufficient to reduce the chance of repeat exposures (Dunlap, 2000). Further a leading academic in the field of motion sickness was also consulted who agreed that 14-days was sufficient to ensure that repeat exposures should not have any effect (Diels C., 2018). In the simulator study, actual time between the first exposure (as discussed in Project A) and the second exposure to the driving task was 6 months, so this certainly would not be an issue. For the on-road study, the lack of change in the sickness scores for the control group confirmed that there was no habituation to the first exposure. Controlling the two exposures to ensure they were as similar as possible was straightforward in the simulator, where all factors (including, but not limited to, climate, traffic, route, vehicle etc.) were controllable and maintained the same between exposures. Driving style including speed could be a factor for motion sickness also, where self-regulation of driving could have been a factor. In the simulator study,

the six month gap between exposures is likely to be of benefit where participants were not freshly practiced in operating the simulator so they could not easily employ self-help measures which may have skewed results for the second exposure. Secondly, speed limit signs were placed very frequently and participants were under strict instruction to adhere to these speeds as close as possible throughout both exposures, so it is thought that driving style was as similar as reasonably possible to control between the two exposures. Also, the times of the two exposures were kept as close to the same time of day as possible.

For the on-road trial, the 14-day gap in between the two exposures was seen to be effective in removing any habituation where the control group showed no significant change in motion sickness scores. The driver was a JLR trained driver and was conscious to drive in a comparable manner throughout all drives, they were not aware of who was a control participant or an experimental participant. The lead researcher who was in the vehicle throughout all drives was also conscious of the driving style and despite (subjectively) monitoring for consistency did not need to advise the driver at any time as the driving style was considered to be very consistent throughout all drives. Traffic conditions were harder to control, however the route was checked with the Highways Department to ensure no road works were planned at any time during the study (which they were not). The time of day that participants completed the study was also kept the same between exposures, ensuring that routine traffic at specific times was going to be the same. These external variables are a limitation of any on-road study, but in this trial, there were no significant timing deviances between drives.

The only other significant factor which was uncontrolled was female menstruation. It is known that hormone fluctuations throughout the menstrual cycle affect both visuospatial skills (Silverman & Phillips, 1993) and motion sickness (Hausmann, Slabberkoorn, Van Goozen, Cohen-Kettenis, & Gunturkun, 2000). Unfortunately this was not possible to control or measure for this user trial. Succeeding in reducing motion sickness despite this, provides a more realistic use-case for the concept of visuospatial training.

Overall, the methodology of this two part study was thought to be very effective in isolating visuospatial training as the only variable which had changed between the two exposures. The scale of the impact of this study was not of great consequence as a first of its kind study to explore the relationship between visuospatial skills and motion sickness. However, it was of benefit to see this effect to be very strong, and this certainly adds to the justification for further experimentation. Specifically, this training method has a lot of scope for further development. Further research should look at the most effective training tasks, the optimal training time and frequency and, other methods (other than pen and paper) through which training can be possible. Further, the long-term effect of this reduced susceptibility is not known and should be further researched.

The exact psychophysiological mechanism through which motion sickness is affected through this visuospatial training is as yet unknown. This research represents the first time that this link has been identified and explored with data. Upon initial consideration, it is perceivable that the cognitive ability to understand/ comprehend/ process motion aids in the ability to sub-consciously process the moving environment – overcoming sensory conflict, the sense of ‘lack of control’. This concept of pre-conditioning is supported in the literature discussing the working memory model the ‘visuospatial sketchpad’. This model is concerned with the retention of object and spatial information (Buchsbbaum & D’Esposito, 2008), and it is considered that the training regime improved skills within this ‘visuospatial sketchpad’ as a collective of working memory skills. This improvement in working memory skills within this model linked strongly with orientation and movement may logically be of benefit when trying to comprehend and subconsciously resolve motions (actual and perceived).

Increased visual dependence is observed in individuals who have less ‘confidence’ in vestibular or somatosensory functions (i.e., a decreased dependence) and rely more on visual cues for information – see (Agarwal, et al., 2011). Research linking visual dependency to motion sickness is sparse. Looking at one paper however, researchers observed that participants who were more susceptible to motion sickness also were more affected by a visual motion stimuli (Yokota, Aoki, Mizuta, Ito, & Isu, 2005) – i.e., had an increased visual dependence. It is conceivable therefore to consider that through reducing visual dependence (though, say, training visuospatial skill to enhance somatosensory dependence) you may be able to reduce susceptibility to motion sickness. Linking this correlation of visual dependency and motion sickness to training previous literature has discussed how repeat visual motion stimuli can reduce visual dependence and manage (somewhat) postural sway (Pavlou, et al., 2011). Although there is recent agreement that postural sway is not a cause of motion sickness, the link between the two is certainly established and motion sickness is understood to commonly proceed postural sway effects (Stoffregen, Hettinger, Hass, Roe, & Smart, 2000).

It is possible this enhanced ability to resolve motions is linked to the habituation effect, whereby repeat exposures to a motion sickness-inducing, or spatiality-challenging task can reduce the susceptibility to motion sickness through ‘habituation’ - see (Wood C. D., et al., 1994). This supports the idea of the visuospatial sketchpad as a working memory function for the comprehension and therefore processing of motion. If this affect is linked to habituation and working memory, the length of effect time before reduced susceptibility to motion sickness is present may be linked to a similar period as habituation or working memory skill retention.

The impact of this method for reducing motion sickness by training visuospatial skills is considered to be very impactful for JLR, the automotive industry and the field of motion sickness as a whole. Considering the automotive industry, many current

recommendations for reducing motion sickness in future vehicles, as previously discussed, are limited by specific use cases. For example, many require the user to be looking at an HMI screen, some require the user to wear various wearables throughout a journey, and some require fundamental changes in a vehicles design (often referred to as body in white). All of the previous recommendations are useful and valid, however, the method presented in this project, is thought to be independent of all these limiting factors and is a method to reduce susceptibility to motion sickness across any use case, vehicle, or situation.

There are many benefits this new finding can have for the automotive industry. With the assumption that this effect can be translated into a refined training tool, it may be useful to help reduce simulator dropouts in future research as well as ensure transferability of simulator data is improved where the impact of motion sickness on human performance can be reduced. Considering real-world applications, many people want to use automated vehicles to complete entertainment and productivity based tasks (such as reading, watching films, working etc.) which have previously been identified as motion sickness-inducing tasks. With a method of reducing motion sickness susceptibility it is possible to improve automated vehicle users ability to complete these tasks comfortably. The exact scale to which this method can reduce motion sickness is as yet unknown, thus the full potential is not possible to comment on. As knowledge within the field progresses it is hoped that this training tool can be refined to be more effective than it has already proven to be.

There also is no reason to believe this effect would not be transferable to other motion sickness states where the utility of this technique has already been shown to work in a simulated environment (with no efferent motion) and an on-road environment (with limited afferent motion cues). The impact of increasing visuospatial skills could indeed be useful for reducing seasickness, VR sickness or airsickness. Although there is no data to support this claim, it is recommended that the transferability of this relationship should be further explored. This finding could have a great impact on other areas where motion sickness is an issue and this method has the potential to significantly benefit multiple fields. For example, studies have previously tried to improve job performance through reducing motion sickness susceptibility, for example, a military tank simulator training experiment showed how simulation sickness degraded training effectiveness (Lampton, Kraemer, Kolasinski, & Knerr, 1995). Various other projects, including Project A of this Innovation Report, have discussed the impact motion sickness has on human performance – for example (Bos, et al., 2008). It is possible that this knowledge about how to reduce motion sickness susceptibility can benefit many sectors where it is known that visuospatial training is useful for both simulator and real-world motion sickness. Such industries that could benefit include military simulator training, sea-sickness in navy staff, motion sickness for the tourist industry (e.g., seasickness on cruise ships, airsickness on aeroplanes etc.). The data presented

as part of this research supports the effectiveness of this training for both males and females. It is therefore conceivable that this method may help improve inclusivity in fields where motion sickness is a limiting factor for females – who, on average, are more susceptible to motion sickness than males.

As a final note on this project, and re-visiting the subject of transferability between simulator and real-world experimentation, this user trial evidences that the effect observed in the simulator was similar to that which was observed in the real-world. Direct comparison of the two motion sickness reductions is not possible, where the route design and task (i.e., simulator participants ‘drove’ the vehicle, and on-road participants sat as occupants) are not comparable. However, now it is known that this effect is useful for both simulators and real-world it is possible to recommend that future research to refine this method can be conducted in a simulator. The simulator allows for greater repeatability where many conditions can be kept the same and is both quicker and easier to run trials without being limited by uncontrollable external variables such as traffic.

Further discussions around gender differences and real-time motion sickness measured by the FMS for both the on-road and simulator study can be found in Submissions 6 and 7.

6.6 CONCLUSION

This project has validated a method, using a novel assemblage of pen and paper training tasks, to significantly improve visuospatial performance. It was shown that for the whole sample (n=35) visuospatial performance (as measured with the MRT) improved by 38.24%. A small control group (n=7) who received no training showed no significant change in their visuospatial skills, highlighting this training pack as a successful method of training visuospatial skills in a non-invasive manner. Further, through a two-phase user trial involving both simulator-based and on-road experimentation it has been proven that through increasing visuospatial performance it is possible to decrease motion sickness. Increasing visuospatial performance was shown to reduce motion sickness in a simulator by 58.02% with a further 60% reduction in simulator dropouts. This was also evidenced in an on-road trial where motion sickness was reduced by 57.19% after visuospatial training.

Although the exact mechanisms for this effect are as yet unknown, the concepts of visual dependency and the visuospatial sketchpad have been discussed. It is considered that this training method may be linked to reducing ones visual dependency through the training of spatiality and orientation working memory skills. This training may mitigate sensory conflict by resolving visual conflicts (by way of

reducing dependency) giving way to greater comprehension of motion through the somatosensory system.

The applications of this finding may be useful for reducing motion sickness for future simulator participants, reducing motion sickness in current vehicles, and reducing motion sickness in future automated vehicles. It is also shown, through some secondary data that this reduction in motion sickness was responsible for a significant reduction in workload (measured using the NASA RTLX) – adding to the strength of this method for enabling productivity in future automated vehicles. The applications of this method for reducing sickness go beyond just the automotive industry and may benefit various other industries and motion sickness applications, such as seasickness for navy staff and tourists or simulator sickness for military or professional training amongst others. The transferable nature of these findings evidenced through this two-part user trial show that simulator testing is a useful and valid way of continuing this further research where many more future questions have been highlighted.

6.6.1 LIMITATIONS

Within this research looking at visuospatial performance training, the majority of participants for the simulator trial were JLR staff or University staff/students and all of the participants for the second on-road study were JLR staff. Every effort was made to recruit from diverse occupations where both the university and JLR employ a wide range of job types. Although unmeasured, it is very likely that these groups were not representative of the general population where the group most likely had higher than average educational qualifications. This is worth considering when looking at the effectiveness of the training and working memory skills, where people with greater experience of further education may be more skilled at learning than others. It is conceivable that the effectiveness of the training pack may be greater for a group with more educational experience. This is not thought to affect the relationship observed between visuospatial performance and motion sickness, rather it could have skewed the results on the effectiveness of the training pack.

The training packs were not marked so understanding of individual training task performance was not possible. Further, there was no practical method to ensure adherence to the training regime. Although the data provided strong evidence that these skills can be trained, it provides limited evidence for the scale of training effectiveness where there was no control over training regime effort.

Finally, as mentioned within the body of the research, the ‘control’ group used was not a true control. A true control would have seen participants completing a training pack in the same routine of the experimental participants where this training pack would be for unrelated tasks -such as numeracy (for example). This would ensure that both

groups had a more similar experience, and ensure that there was no bias from participants and expectancy effect.

6.7 WORKSHOP

With the new knowledge created within this research project there were a few routes available for commercialisation, each would conclude on slightly different future research questions. There was, of course, a desire to make this research applicable to the sponsoring company, so it was decided that experts within JLR would be brought in to inform on the future of this research – giving a business case of direct benefit to the sponsor. A workshop was held to explore methods of exploitation of this knowledge, where through the creation of some project proposals, a research plan could be taken to higher management to fund a larger scale research project to develop this motion sickness management method. The workshop took place over one afternoon and a few ‘design thinking’ ideation exercises were used to gather information about areas of exploitation for this new finding in the context of JLR. Firstly, a presentation was given about this project (both simulator and on-road trials) to get everyone to a common state of knowledge about this relationship between visuospatial skills and motion sickness. After the presentation, three core areas of interest for further research were presented:

- 1 – Understanding underlying effect
- 2 – How can the effect be improved and developed
- 3 – How can this knowledge be applied and what ‘product(s) or service(s)’ can be created.

With these three categories as headings, groups were formed and research questions were identified which were deemed to be of importance to answer each area. Alongside this, workshop participants had to rank each research question (high, medium or low) for the impact to JLR, as well as for the complexity of the research question (using the same scale).

After research questions were established, everyone was asked to write down a company they perceive to be innovative and inspiring. The task then was to imagine that their chosen company has this new knowledge and to think, and write down how this company might turn it into a product. This was a useful way of enabling creativity in the ideas generation phase.

A product ideas matrix was then put up on the wall consisting of age categories on the X-axis (young, middle aged, retired) and use cases on the Y-axis (personal life, in car, other brand related ways). The task was then to think about what exploitation methods could be used for each category. When ideas started to slow, participants were stopped and they were told to imagine the IP now belonged to a theme park and now continue to place ideas on the board about how this theme park could exploit this knowledge – again to further enable creative thinking. A photo of some of the workshop participants filling in the ideas matrix is shown below in Figure 56 (where faces have been distorted to protect identities)



Figure 56 Workshop Participants Completing the Ideas Matrix

The final task was for the groups to identify what they thought to be the best product or exploitation ideas, taking them off of the ideas matrix and back to the research questions where each product idea was assigned research questions which participants decided needed to be answered to achieve this goal.

This workshop was very useful for quickly generating some concepts for further products to help the sponsoring company benefit from this new knowledge. The results from the workshop were given to the management staff for JLR as a business to decide how a new project could be developed based on the findings from this EngD research. A JLR team was formed to develop a mobile application for visuospatial training, the utility of which will be used by JLR to further answer some research questions highlighted and explore the idea of a possible future product. Some screenshots of this mobile app, which the information from this EngD project helped to develop is shown below:

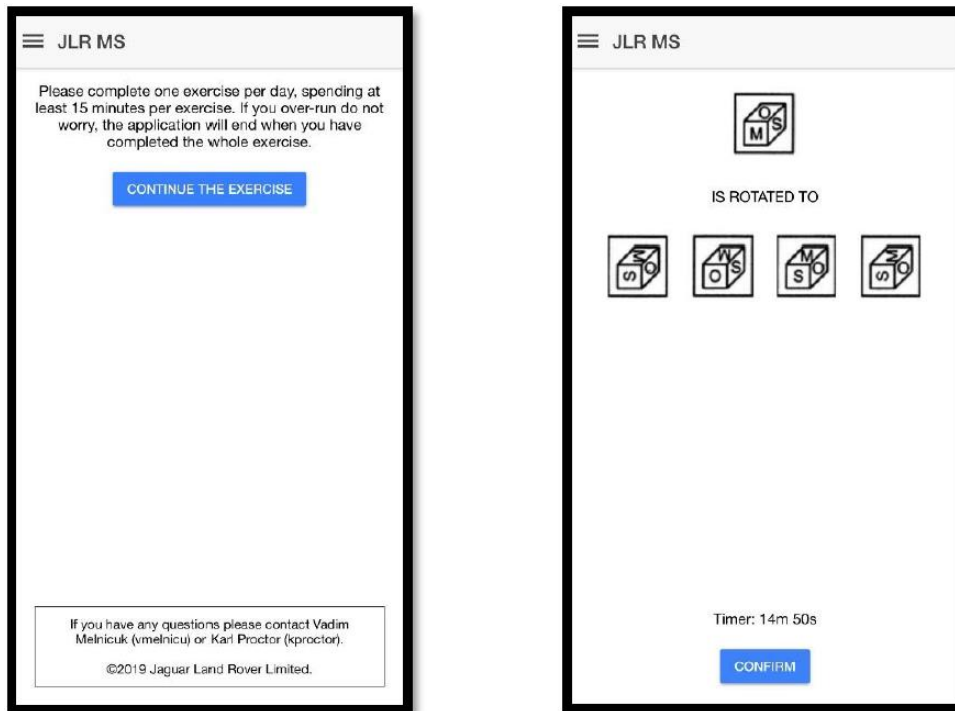


Figure 57 JLR Motion Sickness App

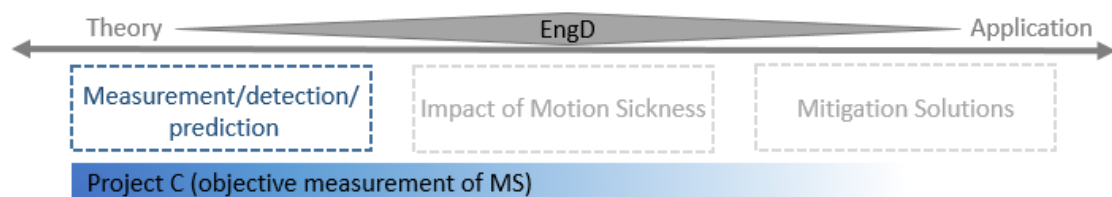
6.8 FUTURE RESEARCH

In summary of the findings from this project, and on reflection of the workshop which was run to further explore areas of exploitation of this knowledge, many areas for further research questions were highlighted. These areas of research were considered the most important questions for the automotive industry and the sponsor of the project (using a quantitative assessment of importance as measured in the workshop):

1. What are the psychophysiological underpinnings to this effect, through what mechanisms does visuospatial training reduce motion sickness susceptibility and how long does this effect last?
2. To what extent is visual dependency related to visuospatial performance and are those with a greater visual dependency more prone to motion sickness?
3. What are the most effective training tasks to use to reduce motion sickness, and what is the most effective medium to interact with the training ?
4. What is the optimal training regime, considering length of training sessions, quantity/frequency of training sessions and reinforcement?
5. How acceptable do people find it to train their visuospatial skills and are people willing to do these tasks to improve their motion sickness resilience?

7 UNDERSTANDING THE MEASUREMENT OF MOTION SICKNESS (PROJECT C)

This project looked to explore how motion sickness may be tracked, measured or even perhaps predicted for ‘real-time’ automotive applications – although the scope allowed this project to consider motion sickness in a cross-industry manner. The initial consideration for a physiological project came from the literature discussed in Submission 2, where there was much discussion about the utility of various physiological measures on which to track motion sickness. JLR, as the sponsoring company proposed the use of an physiological monitoring system using just two physiological measures (electro dermal activity and skin temperature) to measure and give feedback on motion sickness in real-time. This project therefore set out to explore the feasibility of such physiological measures to measure real-time motion sickness onset (presented in full in Submission 7). It used the machine learning model developed in Submission 1 to propose useful data sources which may be used to accurately measure, and perhaps predict motion sickness onset in the future. The human factors approach to machine learning model has been published (Smyth, et al., 2018) and the analysis of physiological data as an indicator for motion sickness has been submitted as a journal paper and is currently under review for publication.



7.1 BACKGROUND

Currently, the most accurate and useful methods for measuring real-time motion sickness onset is through the application of subjective questionnaires FMS (Keshavarz & Hecht, 2011) or MISC (Bos, MacKinnon, & Patterson, Motion Sickness Symptoms in a Ship Motion Simulator: Effects of Inside, Outside, and No View., 2005) – both of which require the subject to report their own subjective symptoms. These methods are useful for ‘lab-based’ research purposes where participants have the time and proclivity to respond to questioning. However, for commercial applications where it may, for example, be useful to measure motion sickness of a vehicle occupant, it would be advantageous to track motion sickness without requiring regular and in-depth questionnaires. Being able to track motion sickness state may be beneficial for many reasons. For example, there are a few known ways to help mitigate motion sickness and if a vehicle can notice an occupant is getting motion sick, these mitigation strategies can be implemented. Example mitigation strategies have been previously

discussed in this Innovation Report and might include, changing the route to a less sickness-inducing route, providing airflow to the occupant, and encouraging eyes-on-road to minimise sensory conflict amongst others. Having an objective measure of real-time motion sickness would also be useful for the purposes of future motion sickness research.

When this project began, JLR as the sponsor and case study of this EngD, were discussing the utility of physiological data for measuring motion sickness in user trials. Specifically they were keen to use the measures of skin temperature and electro dermal activity (EDA) to infer real-time motion sickness state for vehicle occupants and user trial participants. This was known as a challenging subject, with many discussions in the literature. This project therefore looked to see if these physiological measures alone were useful for measuring or even predicting real-time motion sickness state, and looked to advise on what data would be most useful for a future motion sickness monitoring system where the literature provided no definitive answers.

7.2 INTRODUCTION

The evolutionary theory of motion sickness (Treisman, 1977) argues that when a sensory conflict is taking place the body assumes a poison has been ingested and is responsible for the conflict in senses. This somewhat explains some of the common symptomology of motion sickness where people sweat (a response used to push toxins out through the skin) and core body temperature drops to preserve vital organs. It is therefore perhaps reasonable to presume that physiological measures may be a good indication of motion sickness onset.

Looking at functions such as heart rate (and derivations) it has been concluded previously that there are no consistent agreement between heart rate measures and motion sickness state (Hu, Grant, Stern, & Koch, 1991). As an example, research has previously claimed to observe a correlation between heart rate and motion sickness (Cowings, Sutter, Toscano, Kamiya, & Naifeh, 1986), whereas others disagree, finding no correlation (Graybiel & Lackner, 1980). The lack of agreement has been documented well in a report by (Hu, Grant, Stern, & Koch, 1991). Although there is a great deal of contradictory literature, overall researchers tend to agree that heart rate (and derivations thereof) are not a useful indicator of motion sickness.

Other research looking to measure motion sickness using physiological measures looks to skin sweat response – also referred to as Galvanic Skin Response (GSR) or Electro Dermal Activity (EDA). This, given the known response to motion sickness explained by the evolutionary hypothesis (Treisman, 1977), makes logical sense as an area to explore. Research in this field has previously found a link between those with a

naturally high sweat rate (volar sweating) and increased propensity to become motion sick (Parker, 1971). This effect was further discussed in an aviation study which correlated increased skin sweat response to higher motion sickness questionnaire scores, after a motion sickness exposure (Warwick-Evans, et al., 1987). However, it was further explained how external variables are likely interfering with the data, where they found little support for the link between skin sweat response and single incidents of motion sickness. Another study claimed that phasic skin conductance was a useful indicator of motion sickness when all participants in the study had reached a similar level of subjective sickness (Golding J. , 1992). All these previous studies do show support for the relationship between motion sickness and skin sweat response.

The second measure of interest in the literature is that of skin temperature. This measure is a logical area for exploration where the thermoregulatory response to motion sickness is relatively well understood and documented (Nobel, Tribukait, Mekjavic, & Eiken, 2012). There are fewer research projects looking at skin temperature as a measure of motion sickness, although one key text does summarise this measure as worthwhile pursuit (Nalivaiko, Rudd, & So, 2014).

To date there has only been one published text looking at the 'real-time' measurement of subjective motion sickness analysis of associated skin response (Bertin, Collet, Espie, & Graf, 2005). The conclusion of this work agreed that motion sickness is related to skin conductance and skin temperature but concluded that the only 'useful' analysis of this data relies on post-hoc analysis (p287). This research required manipulation of the data based on the entire journey - involving minimum and maximum scores of the individuals as well as the group to normalise the data before processing. Further, there is discussion about the temporal nature of motion sickness onset where symptomology proceeds subjective discomfort, and the state of relaxation was concluded to be an effector, rather than motion sickness itself.

Given this background literature the research question was therefore set:

RQ1 - Is it possible to correlate motion sickness in real-time to electrodermal activity and skin temperature using non-invasive methods?

The scope of this research question was specific to 'non-invasive' where the goal was to assess these measures for utility in a consumer application. With this in mind, the scope was set to exclude lab-based medical grade physiological equipment as well as equipment which required head-mounted equipment or electrolyte gel – which would be inconvenient for a consumer. Further, the importance of 'real-time' is emphasised where the motivation for measuring physiological states was to help predict and measure motion sickness in real-time for both user trials and vehicle features. The methodology must therefore reflect practical real-time analysis techniques.

7.3 METHOD

To assess the relationship between real-time motion sickness and the physiological measures of EDA and skin temperature some original data was needed. The user trials discussed in this Innovation Report including the human performance simulator trial (Project A and Submission 3), the visuospatial training simulator study (Project B and Submission 5) and the visuospatial training on-road study (Project B, Submission 6) provided a good opportunity to collect physiological data. Throughout these studies, participants wore the Empatica E4 wristband (Empatica Inc. , 2016) which measured physiology in real-time. This wristband is a wireless wrist-mounted device, which requires no gel and can be worn comfortably without irritation. The E4 records EDA in the unit of micro-Siemens (μS) and skin temperature in the unit of degrees Celsius ($^{\circ}\text{C}$) both at 4hz which provides 240 data points per minute. Throughout the user trials, participants also reported subjective motion sickness at a rate of once per minute using the FMS (Keshavarz & Hecht , 2011). This subjective real-time information was used to compare to the objective physiological data collected. Due to the nature of the user trials, every participant had a minimum of two minutes rest time whilst wearing the E4 and before the trial began where baseline ‘rest’ data was collected. Environmental conditions were kept as similar as possible throughout the studies where both simulator trials and on road trials had an average temperature of 21 degrees Celsius maintained throughout and no windows were opened during the on road trials so airflow was not a factor.

7.3.1 DATA ANALYSIS

To analyse the data collected, three groups were established into which participants were categorised for analysis. These groups are described below in Table 23)

Table 25 Groups for Physiology Analysis

Group Number	Description	Group Size
1	Simulator study participants	N=14
2	On-road study participants, first exposure	N=26
3	On-road study participants, second exposure	N=21

Group 1 (as presented in Table 23) contained 14 participants made up of seven males and seven females with mean age of 30 (SD=10.69). Seven of these participants ended the simulator driving task early due to severe motion sickness (one male and six females) However, the physiological data of these participants was retained for analysis, but trimmed up until the point in which they ended the driving scenario. The average drive time for Group 1 was 22 minutes, with the longest drive being 33

minutes. Due to these dropouts, the shortest drive was 8 minutes. This group contains participants from both the human performance simulator trial and the simulator-based visuospatial training trial, although participants only appear once in this data set.

Group 2 contained 26 participants made up of 12 males and 14 females and the mean age of the group was 33.6 (SD=12.8). There were no dropouts in this group and the average drive time was 28 minutes with the longest drive being 31 minutes and the shortest being 27 minutes. Group 2 consisted of participants from the first on-road study as part of Project B's visuospatial training research.

Group 3 contained 21 participants made up of 10 males and 11 females with a mean age of 31.1 (SD=11.8). Again, there were no dropouts in this group and the average drive time was 28 minutes with the longest drive being 30 minutes and the shortest being 27 minutes. This group of participants contains the same participants as in Group 2 however; this is their second exposure to the on-road driving task explained in Project B. There are fewer participants in Group 3 as some in Group 2 withdrew from the study before their second exposure due to work commitments.

In total 1,603 minutes of motion sickness data was collected, which equated to 384,720 measures of EDA, 384,720 measures of skin temperature and 1,603 measures of subjective motion sickness. Given the amount of data collected, (with physiological scores being captured at a rate of 4hz), the data was first processed to calculate the mean score for both physiological measures (individually) for the one minute leading up to the associated FMS score. For example, if the FMS score was given at minute two, the associated physiological data was calculated from taking the average of the measures recorded between minute one and minute two. This process provided each participant with a once-per-minute score of EDA and skin temperature to correlate to that minute's subjective sickness score. Using each participants baseline scores, the delta (Δ) scores were then calculated using the same method as set out in this paper (Meehan, Insko, Mhitton, & Brooks, Jr, 2002) using the below formulas:

$$\Delta \text{ EDA}_{\text{minute } x} = \text{EDA}_{\text{minute } x} - \text{EDA}_{\text{baseline}}$$

$$\Delta \text{ Skin Temperature}_{\text{minute } x} = \text{TEMP}_{\text{minute } x} - \text{TEMP}_{\text{baseline}}$$

To analyse the data, the main motivation for this research must be considered so that any conclusions made are practical considering the overall goal – understanding the utility of physiological data for real-time measure of motion sickness. Firstly, the term 'real time' is often discussed within the literature with regards to physiological measurement. In many cases real-time is discussed as a matter of a few hundred milliseconds. However, considering subjective data is to be analysed at once every 60 seconds, this is our threshold for 'real-time' analysis. This means that methods involving post-processing of data are not suitable for the scope of this project. The data needs to be analysable within a rolling 60 second timeframe to be considered

practical. The motivation for method selection was driven solely on the goal to understand if these physiological outputs are useful as real-time predictors/measures of motion sickness. Therefore, methods involving significant post-hoc analyses (including normalisation of data) were disregarded. Pearson's correlations were to be the primary method for analysis of this collected data where this method is a practical method for determining real-time correlation without post-hoc data manipulation and can be done on a 'rolling' basis without requirements for a 'complete' data set.

7.4 RESULTS

Data was collected throughout all the user trials conducted in Projects A and B, however due to some technical issues with the device and the data collection method, some data was lost. Overall, data sets from 40 participants data was retained for analysis, where 21 of these participants completed repeat-measure trials so in total 61 sets of data were collected.

For Group 1, the average EDA during the rest period was $0.782\mu\text{S}$, $\text{SD}=1.063$, which increased during the driving scenario to an average of $1.015\mu\text{S}$, $\text{SD}=1.531$. The average skin temperature for the rest period was 32.644°C , $\text{SD}=0.935$, which decreased during the driving scenario to an average of 32.298°C , $\text{SD}=1.528$.

For Group 2, the average EDA during the rest period was $0.669\mu\text{S}$, $\text{SD}=0.635$, which increased during the driving scenario to an average of $1.092\mu\text{S}$, $\text{SD}=1.683$. The average skin temperature for the rest period was 32.086°C , $\text{SD}=0.559$, which decreased during the driving scenario to an average of 31.925°C , $\text{SD}=0.475$.

Finally, for Group 3 the average EDA during the rest period was $0.685\mu\text{S}$, $\text{SD}=0.262$, which increased during the driving scenario to an average of $1.225\mu\text{S}$, $\text{SD}=0.043$. The average skin temperature for the rest period was 32.368°C , $\text{SD}=1.448$, which decreased during the driving scenario to an average of 32.061°C , $\text{SD}=0.431$.

To begin to explore the relationship between these three measures (subjective score, skin temperature and EDA)

Figure 58 below presents the average EDA, skin temperature and FMS score for Group 1 – simulator participants.

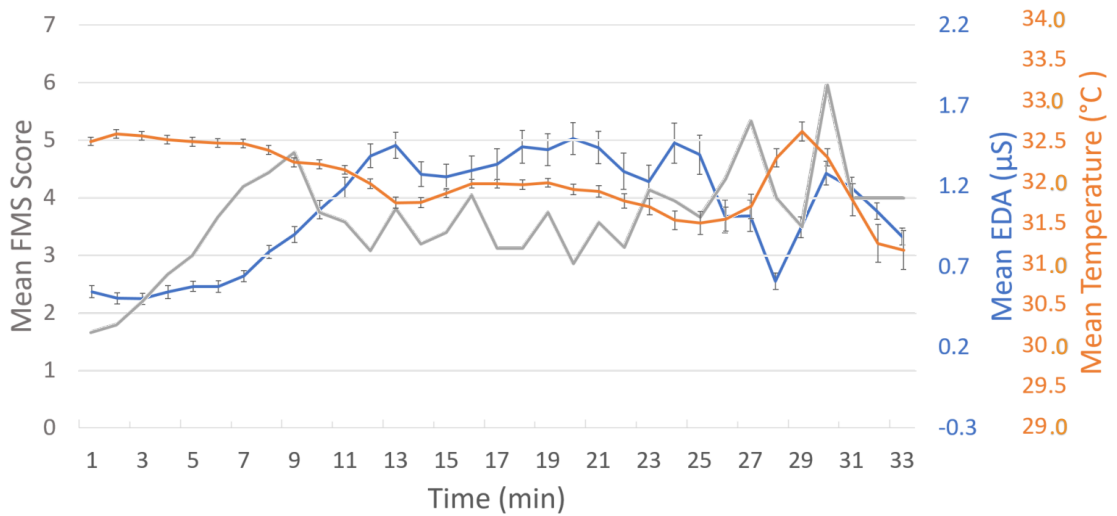


Figure 58 Electrodermal Activity (EDA), Skin Temperature and Subjective Motion Sickness (FMS) – Group 1 (simulator)

Figure 59, below, combines all the data from the on-road participants (where the environment is the same) to present the data from the average EDA, skin temperature and FMS score for Group 2 – on-road participants (first exposure):

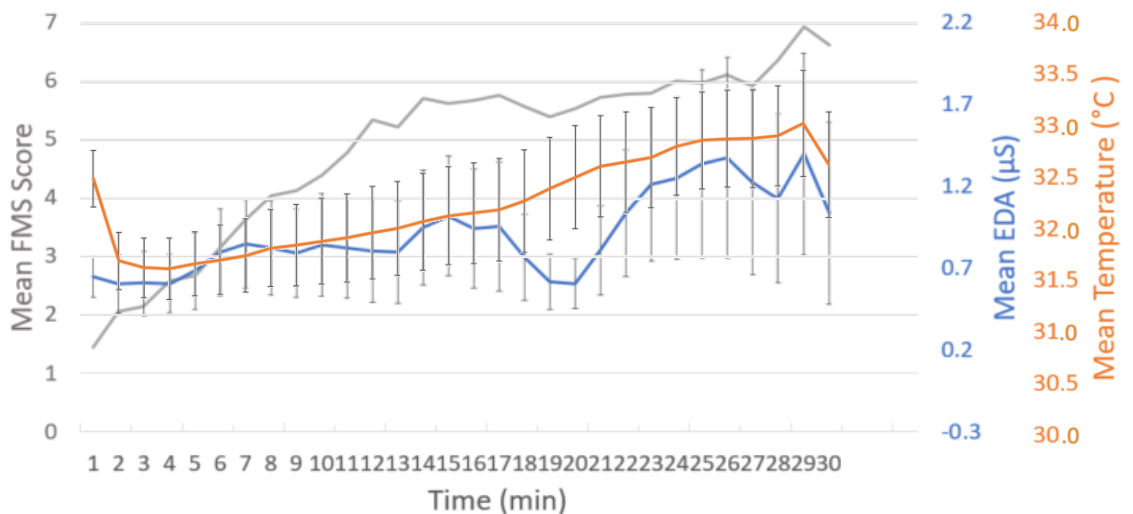


Figure 59 Electrodermal Activity (EDA), Skin Temperature and Subjective Motion Sickness (FMS) – Group 2 -on-road)

Looking at the graphs presented above in Figure 58 and Figure 59, there does appear to be some visual signs of a relationship between these variables at a group level, particularly when observing the timings of peaks and troughs. However, the error bars included (calculated from standard error) begin to highlight the degree of variance between each participant where there are substantial changes in the size of these error bars as the trials progress. The error bars appear much greater for the on-road trial presented in Figure 59 – perhaps due to the variance in environmental conditions that were tightly controlled in the simulator, but uncontrollable in the real world.

These graphs are looking at the groups as a whole, and do not consider any participants scoring or physiological response individually.

To better understand if there is an underlying practical relationship between real-time motion sickness severity and the physiological measures of EDA and skin temperature at an individual level, the correlations between these measures were considered on an individual basis. To begin analysis, the data within three groups was first checked for normality using the Shapiro Wilk test which showed the data was not normally distributed in any group (where $p < 0.05$ in all cases). Therefore the non-parametric Spearman's rank-order correlation was used to look for the statistical relationship between subjective motion sickness (as measured using the FMS) and the physiological measures of EDA and skin temperature. The results of this analysis are presented below in Table 26.

Table 26 Correlations of EDA and Skin Temperature (TEMP) Against Subjective Motion Sickness (FMS)

Group	Participant	r_s FMS vs. EDA	r_s FMS vs. TEMP	
Group 1	175	.815**	0.166	
	180	-.865**	-.814**	
	195	0.066	0.238	
	237	.847**	-.941**	
	388	0.145	0.084	
	489	0.232	.894**	
	549	-.647**	-.603**	
	607	0.181	-.651**	
	633	-0.365	-0.079	
	731	-0.334	-0.115	
	784	-0.228	-.825**	
	846	.627**	-.684**	
	950	.982**	-0.746	
	968	0.353	-0.263	
	Group 2	519	-0.516	-.491**
		699	0.316	0.316
524		-.723**	-0.267	
856		-0.145	-0.082	
394		.422*	.398*	
473		.563**	.821**	
57		-0.243	.460*	
781		.609**	.765**	
447		0.051	-.579**	
217		-.890**	.939**	
150		.529**	.737**	
766		0.003	-.514**	
110		-0.078	0.284	
956		.378*	.683**	
283		-.373*	0.115	
580		.779**	.841**	
20		.459*	.415*	
476		.484**	.436*	
146		0.092	-0.276	
480		0.216	.646**	
322	.433*	.427*		

	948	-.584**	.768**
	215	0.011	.667**
	9	.831**	.838**
	810	-0.126	-0.277
	177	.431*	-.527**
<hr/>			
Group 3	519	-.775**	-.796**
	524	-0.007	-.747**
	856	-0.144	0.176
	394	0.187	0.302
	473	-0.313	-0.205
	57	-0.097	-0.179
	781	0.857	0.000
	217	.750**	-.750**
	766	0.132	-.499**
	956	-0.064	0.187
	283	.567**	.645**
	580	0.250	-0.036
	20	0.257	.882**
	476	0.054	.381*
	146	.751**	.633**
	480	.810**	.943**
	322	0.133	0.285
	948	.439*	.428*
	215	.581**	-0.063
	9	-0.383	-.762**
177	0.228	.526**	

*=95%confidence rating

Table 26 presents all of the individual correlations (Spearman's r_s) between subjective motion sickness (FMS) and the physiological measures on a case-by-case basis. The notation of ** denotes significance at a 99% confidence rating and * denotes significance at a 95% confidence rating. The colour scheme of red, orange and green has been used to help identify the significant correlations, where green represents correlations that are significant with 99% confidence, orange with 95% confidence and red shows no significant correlation. Already there are many varying correlations here, with a mixture of significance values and lack of significance. To summarise the significant Spearman's r_s correlations Table 27 has been created which presents the quantity of significant correlations (using both levels of significance) and totals for each.

Table 27 Summary of Significant (99%), Significant (95%) and Non-Significant Correlations between Groups 1, 2 and 3

	Group 1		Group 2		Group 3		Total	
	n	%	n	%	n	%	n	%
p>0.05	15	54%	18	35%	23	55%	56	46%
p<0.05 (95%)	0	0%	11	21%	3	7%	14	11%
p<0.01 (99%)	13	46%	23	44%	16	38%	52	43%

As shown in Table 27, over the entire sample of 122 correlations, 54% were shown to be significant (at either 99% or 95% confidence) where 46% were shown to not be significant. Looking at just the significant results, correlations ranged from +0.982 to -0.865 for EDA and from +0.894 to -0.941 for skin temperature where positive one (+ve1) is a perfect positive correlation and negative one (-ve1) is a perfect negative correlation. There appears to be a great deal of variance between the scales and directions of these correlations so the histograms in Figure 60 and Figure 61 have been created below to give an indication of the variance of correlation values observed within the data set.

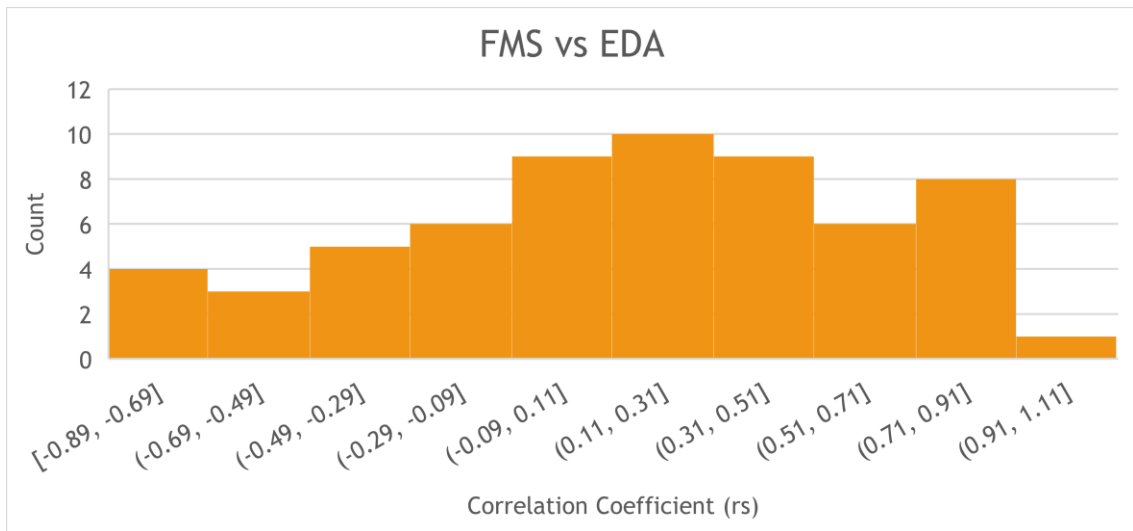


Figure 60 Correlation Values for EDA vs FMS

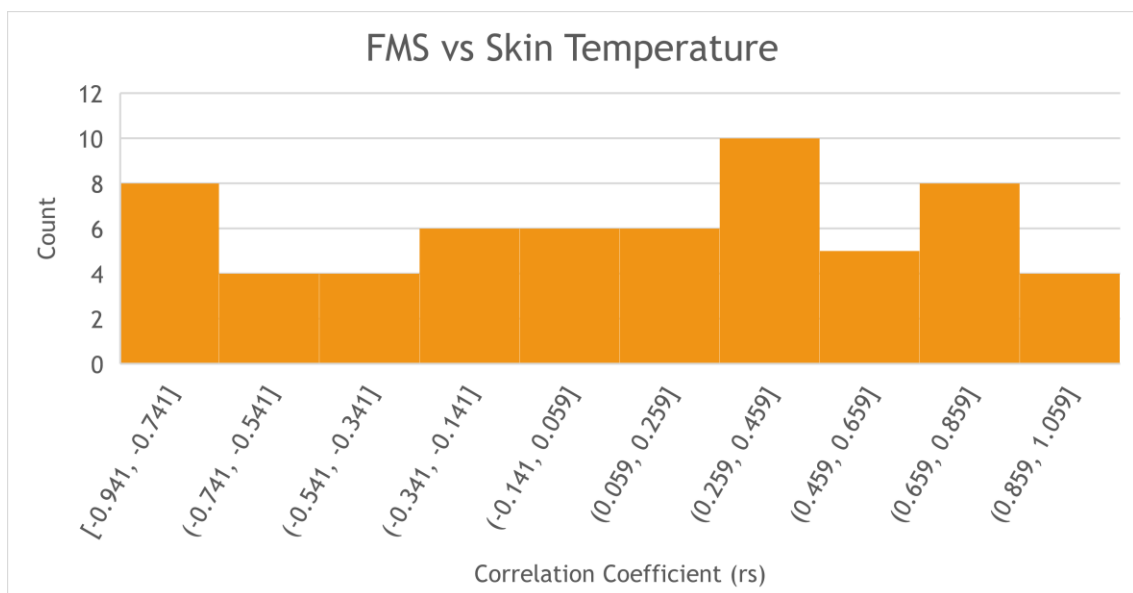


Figure 61 Correlation Values for Skin Temperature vs FMS

The figures presented above provide a good visualisation of the range of correlations observed within this data set. This gives an indication of a lack of utility of these measures at an individual level, where one might expect to see leptokurtic or platykurtic distributions trending towards either a negative or positive correlation

direction if these measures were directly related to motion sickness in 'real-time'. For the EDA vs FMS correlation, the distribution of the Pearson's correlations is normally distributed as shown with the Shapiro-wilk test where $p > 0.05$ at $p = 0.215$. Temperature vs FMS was non-normally distributed where $p < 0.05$.

This research (considering its application and motivation of the sponsoring company) is not concerned with correlation at a group level, but rather at an individual level. To help illustrate the range of correlations at a group level further, graphs from four example participants (two with no motion sickness and two with motion sickness) have been presented below. These participants were chosen as they (in pairs) showed similar styles of motion sickness onset, where the first two had a very flat FMS profile, and the second two had quite a varied and high motion sickness experience. These examples further identify the complexity in deriving commonalities between individual and group analyses where the physiological measures appear erratic.

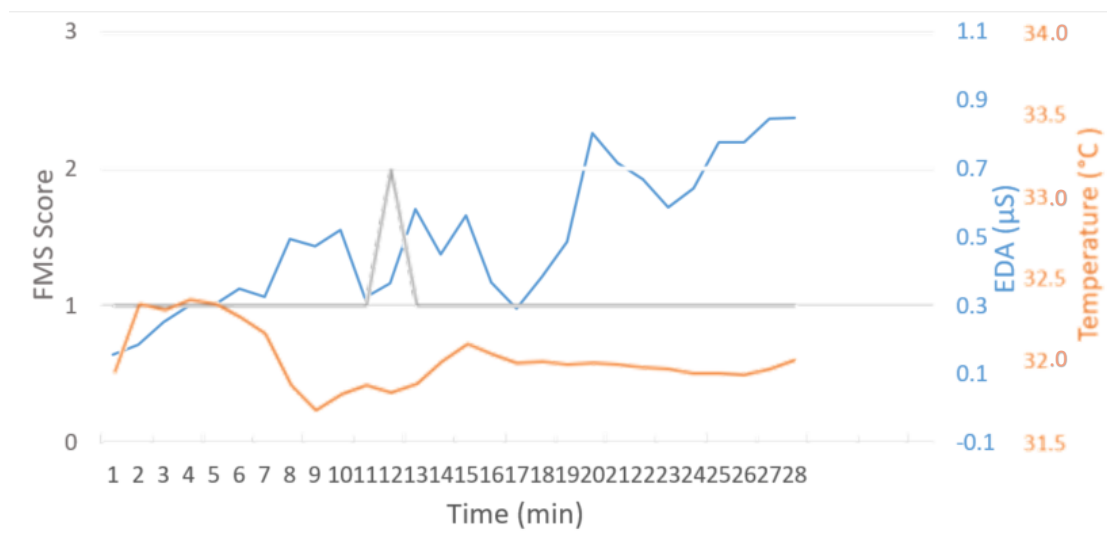


Figure 62 Participant 801 (no motion sickness)

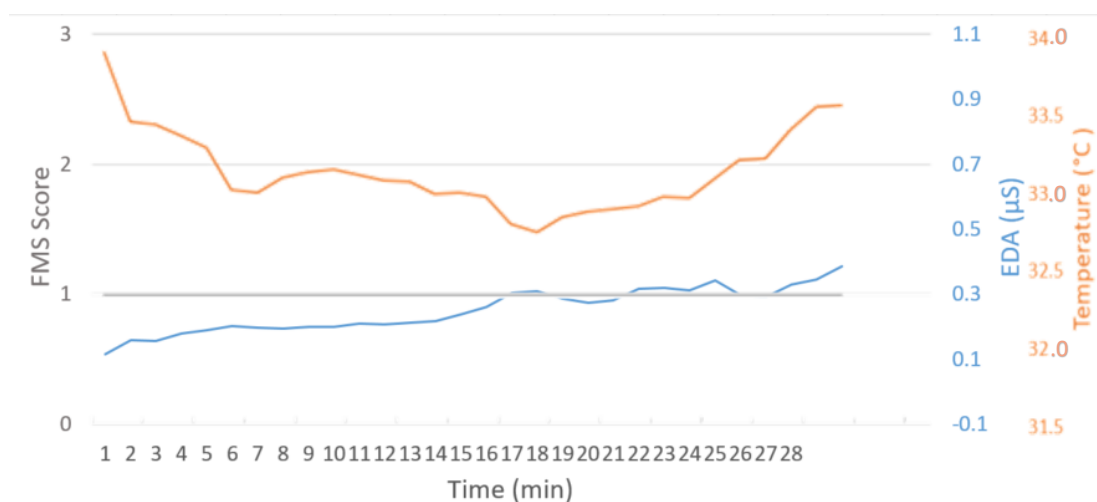


Figure 64 Participant 699 (no motion sickness)

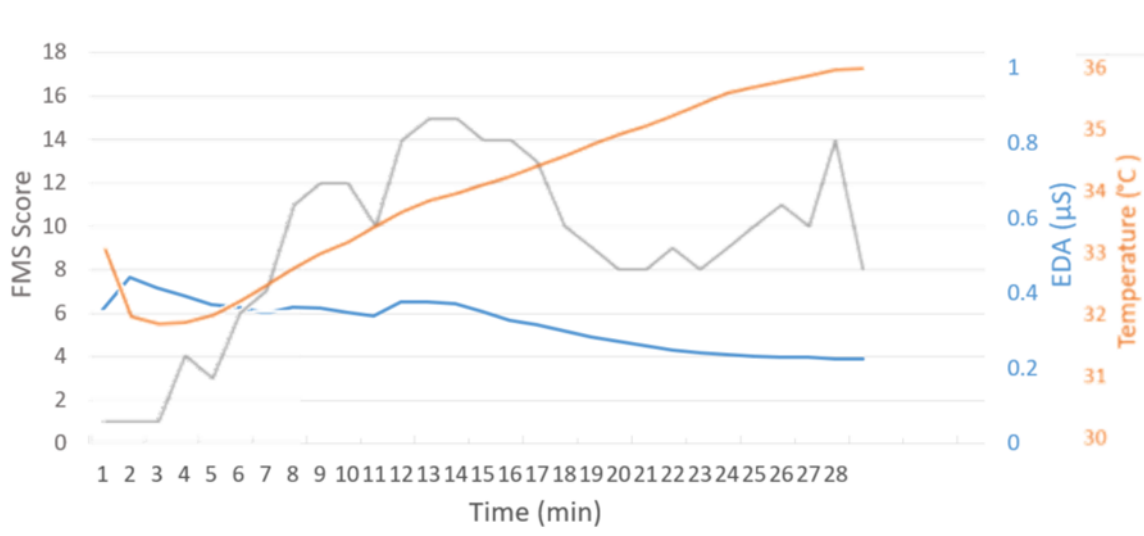


Figure 63 Participant 110 (varied motion sickness)

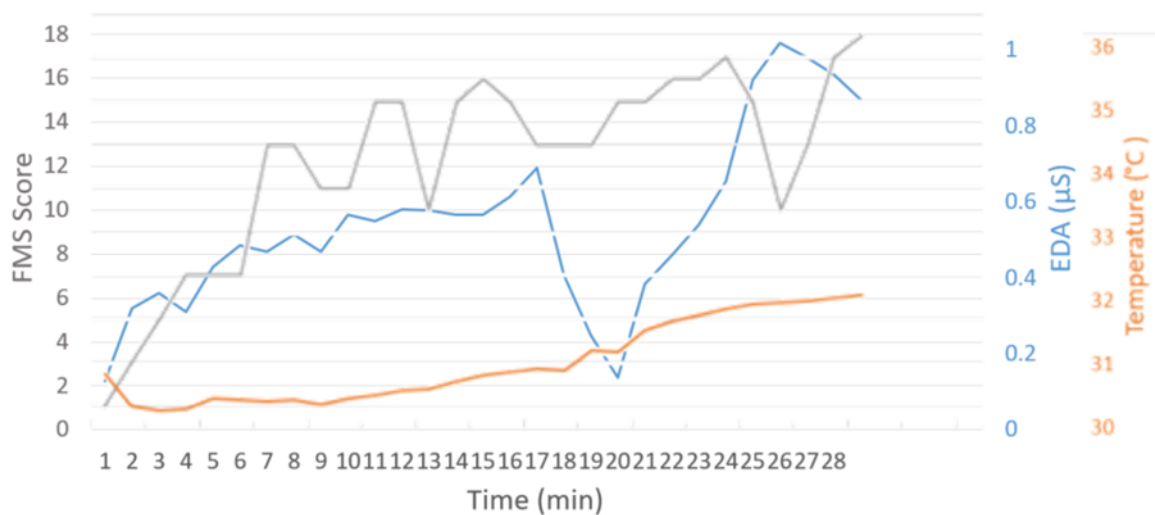


Figure 64 Participant 956 (varied motion sickness)

Moving back towards looking at these measures as a group, and away from individual scores an average correlation figure needed to be calculated. A common process for doing this involves transforming the data into a Fisher's z score, calculating the average, and then transforming the data back. Another method involves averaging observed sample r_s correlations (Alexander, Scozzaro, & Borodkin, 1989) which is thought to be a superior method (Alexander R. A., 1990). The process of this calculation is presented below:

$$\bar{r}^* = \frac{\sum(n_i - 1)}{\sum n_i - k} \left\{ r_i + \left[\frac{r_i(1 - r_i^2)}{2(n - 3)} \right] \right\}$$

Using knowledge presented by the original author on how this equation was derived author (Hotelling, 1953) it is possible to rearrange this equation slightly as in its current published form, it is easy to misinterpret. The revised formula used to calculate \bar{r}^* is presented below:

$$\bar{r}^* = \frac{\sum(n_i - 1) \left(r_i + \left[\frac{r_i(1 - r_i^2)}{2(n_i - 3)} \right] \right)}{\sum n_i - k}$$

Using this re-ordered equation (adapted from (Alexander R. A., 1990)) the average correlation figures for each physiological measure and each group have been calculated and is presented below in Table 28:

Table 28 Average Correlations for Groups 1, 2 and 3

	Average Correlation Coefficient (\bar{r}^*)	
	EDA vs. FMS	Temp vs. FMS
Group 1	-0.03	-0.30
Group 2	0.11	0.29
Group 3	0.20	0.07
Combined	0.12	0.15

The strongest correlation given in the above table is r_s -0.3 for Group 1 skin temperature vs FMS. This score of r_s -0.3 is considered to be a very weak correlation, and this is perhaps no surprise when observing the range of correlation values as shown in the graphs for Group 1 skin temperature vs FMS. Overall, none of these correlations are deemed to be of any use, where these average correlations are all considered to be very weak. The method used to calculate these averages is reported to be the most unbiased and useful method (Alexander R. A., 1990). However, the method using Fisher's Z score is more commonly used where more recent research often uses this method (for example (Ghassan , Flordelis, & Tufvesson, 2017)). Given this more recent support for this method, and considering the transferability of this project to future research, this Fisher's Z method was also used to re-run the calculations of averages for each physiological score. The method through which this calculation happens involves transforming each r_s into a z score, by using the following formula:

$$z_i = \tanh^{-1}(r_i)$$

After which these z values are averaged:

$$\bar{z} = \frac{\sum(n_i - 3)z_i}{\sum(n_i - 3k)}$$

And finally, \bar{z} is transformed to \bar{r} by:

$$\bar{r}' = \tanh(\bar{z})$$

Further information and detail on this method, including explanations of the notation is given in (Alexander R. A., 1990). Using this method, the results are presented below in Table 29:

Table 29 Average Correlations for Groups 1, 2 and 3

	Average Correlation Coefficient (\bar{r}')	
	EDA vs. FMS	Temp vs. FMS
Group 1	-0.04	-0.30
Group 2	0.06	0.21
Group 3	0.18	0.07
Combined	0.02	0.02

The results presented in Table 29 are very similar to that which is shown in Table 28 and the conclusion about the weak nature of these correlations remains the same despite using this different method.

7.5 DISCUSSION

Previously published research has identified the link between the physiological measures of EDA and skin temperature and motion sickness onset (Parker, 1971). These findings support our understanding about the body's response to motion sickness onset (Treisman, 1977) and the concept that motion sickness evokes both sweat and thermoregulatory responses is not disputed. Specifically, one might expect to see an increased sweat rate and decreasing temperature when suffering from motion sickness. The relationship between EDA and skin temperature as proven in previous literature is not disputed and at a group level, the relationship between motion sickness and EDA and skin temperature is established. Indeed, this effect was found within some participants, for example, participant 237 of Group 1 showed a correlation between EDA and FMS of $r_s+0.847$ and for skin temperature and FMS $r_s-0.941$ (where $p<0.01$ in both cases). When looking to the data as a whole (as presented in Table 26) many of the correlations observed are found to be significant with significance observed in 54% of all correlations found ($n=66$) which may indicate there is some utility in these measures.

The analysis of this data was conducted to understand if there was feasibility in using these physiological measures as 'real-time' indicators of motion sickness state. The intended purpose of these measures therefore dictated the analysis methods used and disregarded any methods requiring post-hoc analysis (e.g., normalization of data). The analysis of Pearson's correlation is rather basic considering the breath of the available

statistical tools available for physiological analysis. However, all methods, including phasic responses (measuring peaks and troughs) require significant post-hoc analysis. That is to say, they cannot be computed in real-time, and certainly not give an indication of prediction, where a peak is only identifiable after a decline. Similarly, cross correlation analysis was considered as a method for analysing the results, where it was shown in the plots (Figure 58 and Figure 59) physiological data falls somewhat behind subjective sickness. Such a calculation would account for difference in time-domains. However, this method was not of use considering the 'real-time' dependency for this analysis where any delay greater than one-minute (i.e., our minimum subjective threshold) would render these measures useless for a practical application. Other, traditional research looking to understand physiological measurements will first transform the group data to avoid skew, kurtosis, and heterogeneity of variance. However, the process of normalising data cannot be done in 'real-time' and thus those methods were avoided for this research. Similar motivations are seen commonly within the literature, for example (Khalaf, et al., 2020) who also are aware that individual differences (especially emotional reaction) can lead to group-level data being unrepresentative of data on an individual level.

Looking into the individual correlations across the group, a wide range of correlations are observed ranging from $r_s+0.982$ to $r_s-0.865$ for EDA, and $r_s+0.939$ $r_s-0.941$ for skin temperature. This range of correlations have been plotted in the histograms presented in Figure 60 for EDA and motion sickness and in Figure 61 for skin temperature and motion sickness. It is within these figures that it becomes quickly apparent that this range of correlations indicates a lack of utility for these measures for a 'basic' real-time assessment at an individual level. It is thought that this range of correlations is the most useful indicator for a lack of overall correlation between these variables using a real-time method. However, to quantify this further, average correlations were calculated using the method set out in (Alexander R. A., 1990). It was shown here that the overall correlations for the physiological measures to motion sickness (FMS) were shown to be $r_s0.12$ for EDA and $r_s0.15$ for skin temperature (see Table 28). This finding and ultimate conclusion at this time are in agreement with previously published literature (Harm, 1990) which summarises that there is a lack of utility for physiological measures at an individual level, and the experimentation and presentation of original data in this Innovation Report provides data to support this claim.

The data presented here is interesting for two other reasons, firstly in assessing the difference between simulator sickness and 'real-world' motion sickness. Secondly in providing data for 21 repeat measures participants, where all participants in Group 3 also appear in Group 2.

Looking firstly at the difference between the simulator and real-world motion sickness correlations where in the simulator trial there was afferent (visual) motion, but no

effluent (physical) motion, and in the on-road 'real-world' study there was efferent motion but limited afferent motion. It is not strictly possible to compare the scale or 'shape' of the motion sickness onset between these two scenarios, where the route design was entirely different. However, comparing results of significance between Group 1 and Groups 2 and 3 combined there is little evidence of differentiation. That is, nothing between the two categories of groups appears to highlight a difference between the data sets when looking at the individual scores in Table 26, or the summary of the group's correlation significance levels in Table 27. Therefore, despite not running user trials directly comparable to each other considering route design, at this time there is little evidence to say that the relationship between these physiological measures in the simulated and real-world differ from one-another. Although it is agreed that further research would be required considering transferability if a valid physiological method was found.

With more room for discussion (considering the availability of data collected) is the 'repeat-measures' aspect of Groups 2 and 3, where for all members of Group 3, they also appear in Group 2 as their first exposure. Any analysis and conclusions taken from this have to consider that participants were only measured during two exposures, it may be argued that two interactions is not enough for a true repeat-measures analysis. However, where it is well understood that individual characteristics such as aerobic fitness affect both motion sickness susceptibility (Cheung, Money, & Jacobs, 1990) and sweat response / thermoregulation (Green, Pritchett, Crews, McLester, & Tucker, 2004). It is therefore conceivable that individual/personal factors could influence the reliability of the real-time correlations. The (somewhat limited) data presented in this report however does not support this, where for example, participant 146 provided non-significant correlations of $r_s0.092$ for EDA and $r_s-0.276$ for skin temperature for their first exposure (in Group 2), but on their second exposure (in Group 3) their respective correlations were $r_s0.751$ and $r_s0.633$ both significant with a confidence level of 99%. In fact, with 21 repeat exposure participants, only one participant showed significance in both physiological measures during both exposures. Participant 217 showed correlations $r_s-0.890$ for EDA and $r_s0.939$ for their first exposure (both significant with a confidence of 99%). Where for their second exposure they showed correlations of $r_s0.750$ for EDA and $r_s-0.750$ for skin temperature – both again significant with a 99% confidence level. As seen, despite the strong significance level, both directions to the correlations were reversed from (+ve) to (-ve) for EDA and from (-ve) to (+ve) for skin temperature between the first and second exposures. The findings within this data set therefore provide no evidence to support the idea that physiological measures are reliable even within individuals.

Looking at reasons to explain this lack of agreeable correlation between these physiological measures and subjective motion sickness at an individual level, it is immediately apparent that the measures of EDA and skin temperature (amongst many

other physiological measures) are affected by a great deal of other 'real time' variables. For example, states of arousal (where the term 'arousal' is used to cover many emotional states) are known to evoke significant physiological responses (Warwick-Evans, et al., 1987). Where it is summarised in a further report how most researchers agree that the physiological responses of motion share many of the component characteristics of stress or alarm (Harm, 1990) (p.164). In fact, specific research addressing the relationship between stress and EDA confirms this correlation (Ionescu-Tirgoviște & Pruna, 1993). Using this knowledge, an anecdotal evidence that sensations of motion sickness can be both stressful, and alarming it is conceivable that the physiological responses being measured in a motion sick state could be significantly affected by emotional/arousal states – and not just the state of motion sickness. There are a great deal of motional states and arousal states that may alter physiological measures, such as excitement, anger, fatigue, stress, alarm, frustration, confusion, fear, discomfort etc. therefore it is likely these states of arousal that are responsible for a lack of correlation between physiology and motion sickness evidenced in this data. Previous literature also looking at simulator sickness and EDA concluded that sensations of relaxation were related to physiological measures (Bertin, Collet, Espie, & Graf, 2005) which supports this issue.

Further to these relationships between emotional state and physiological measures there are also other external factors that influence physiology and associated measurements. Specifically considering on-road experimentation, changes in environment may have a significant affect on physiology. Sunlight (directional temperature), ambient temperature, radiant temperature, humidity and airflow (amongst others) will likely affect both sweat response and skin temperature through conduction, convection and evaporation. Considering these factors (specifically evaporation of sweat) it also quickly becomes apparent how these physiological measures are themselves strongly linked to one another both as effectors and affecters. The thermoregulatory response to heat is to cool the body through sweating (measured as EDA) and associated evaporative heat loss. For such measures to be useful to compare at an individual level during a user trial or commercial application, the effect of environmental change and difference between exposures must be considered. Conclusively these physiological measures (and others) are not independent of emotion, environment, or even themselves.

As a final note on the applicability of these measures as a real-time measure and/or predictor of motion sickness, it has previously been concluded that physiology is a delayed response to subjective scoring (Min, Chung, Min, & Sakamoto, 2004) and this, also appears to be evident in this data set. When looking at the graph presented in Figure 58, there is a notable delay between the pick ups/decreases in subjective motion sickness (FMS) and the physiological measures. The challenge with addressing such a time delay within the scope of this work is that delays are only identified

retrospectively, if it was possible to predict future data based on existing data there would be no need to collect data at all. This is in agreement with the aforementioned literature (Min, Chung, Min, & Sakamoto, 2004) who also used a graphic simulator for their study, and further supports the idea that these physiological measures are less of a direct response to motion sickness, and perhaps a response to the emotional state / alarm / arousal of not feeling well and this may be responsible for such a 'delay'. Analysis of this delayed response were considered, but as the primary objective is to consider the applicability of these measures as a real-time measure (e.g., to replace a validated subjective scale), the conclusion of such an analysis would not address this objective.

It is known that the measures of EDA and Skin temperature are related to motion sickness. But the relationship has only ever been observed at a group level, with significant post-hoc analysis e.g., (Bertin, Collet, Espie, & Graf, 2005) – limiting the application of such measures for a consumer application. This previous research is the only identified paper discussing real time measures, and they also conclude that to find such relationships requires significant post-hoc analysis. Although, they did not provide data and analysis to explore the true real-time calculation, the results presented in this innovation report are in agreement with the previous conclusions from the literature.

7.6 CONCLUSION

This project, building on the previous literature which has identified a relationship between EDA, skin temperature and motion sickness has looked to see if there was a correlation between these various measures in the hope to find a method for objectively measuring motion sickness in real time using practical methods. Collecting data alongside three user trials, a total of 40 participants provided 61 sets of data (where some participants took part in a repeat-measures study) and a total of 1,603 minutes of motion sickness data was captured comprising of EDA, skin temperature and real-time subjective motion sickness.

Despite 54% of the correlations showing significance, the range of these correlations (ranging from +0.982 to -0.865 for EDA, and +0.939 -0.941 for skin temperature) indicated that at a cohort level, there is little evidence that these physiological measures alone are reliable or useful predictors or measures of subjective motion sickness on an individual real-time level. The reasons for this wide range of results, and lack of agreement between correlation direction are as yet unquantified. However, the literature provides ample evidence that many other factors and states of arousal also affect these physiological measures, where perhaps these other variables have a greater impact on these measures and thus render them useless as motion sickness

predictors. The average correlation throughout the entire sample was $r_s=0.12$ for EDA vs motion sickness and $r_s=0.15$ for EDA vs skin temperature – both are considered incredibly weak.

There are currently no other published works looking to assess real-time motion sickness as a correlate to these physiological measures (simulator or real-world based) so comparisons are not possible. The only text found which looks at similar measures utilises a technique involving significant post-hoc analysis and thus does not address this research question of real time assessment (Bertin, Collet, Espie, & Graf, 2005). Overall, it can be concluded that these physiological measures alone show little suitability as motion sickness measures for real-time assessment at an individual level and further research needs to be conducted to understand the effect of motion sickness on physiological measures and methods for measuring/analysing this in real time. It may be possible to combine much more information and/or filter physiology based on the understanding of external variables. The outcome of this research does not dispute the previously found correlations using more advanced analysis, and the conclusions from this research should be considered with an understanding for the motivations of the analysis methods used and their strict focus on ‘real-time’ practicalities.

7.7 FUTURE RESEARCH – A MODEL FOR COLLECTING MOTION SICKNESS-RELATED DATA

There are many factors that may influence the onset of motion sickness in a vehicle, from demographics, to specific driving scenarios. Some of these factors are already known and somewhat understood. Previous research discussed in specific relation to physiological measures of EDA and skin temperature have been proven to not be useful by themselves using real-time analysis methods. However, there may be the ability to predict or measure motion sickness using a collection of information and informative data.

Considering motion sickness onset likelihood it is known how gender (Jokerst, et al., 1999), ethnicity (Klosterhalfen, et al., 2005), driving experience (Turner M. , 1999) and perhaps age (Golding J. F., 2006) (Reason & Brand, 1975) (Turner & Griffin, 1999) are useful to identify motion sickness susceptibility for a group. Further, it is known how completing tasks which allow for sensory conflict (Reason & Brand, 1975) such as head-down reading, or interaction with HMI out of the line of sight of the window (Diels C. , Bos, Hottelart, & Reilhac, 2016) will all affect the likelihood of motion sickness. Considering an automated vehicle, route and driving style will have a further impact on motion discomfort (Mountain View , CA USA Patent No. US 10 , 107 , 635

B2, 2018), where exposure to specific periodic motion frequencies (vibration) is also known to be an affecter of motion sickness (Smart Jr & Stoffregen, 1998) (p.437).

Considering other factors, environmental changes can also have an impact on subjective discomfort, where cooler temperatures are often advised to limit motion sickness discomfort (although ambient temperature may not necessarily be linked to the motion sickness onset frequency (Turner & Griffin, 1999). Fresh airflow and unrestrictive clothing can also aid in the ability to manage the thermoregulatory responses to motion sickness and associated discomforts.

When looking into the propensity for motion sickness onset, with the overall goal of being able to predict motion sickness onset before it happens so that preventative measures can be initiated, it quickly becomes apparent that there is a plethora of information sources on which one can make a measurement or prediction. Submission 1 of this EngD looked at machine learning systems to automate in-vehicle features, based on user routine. The conclusion of this project presented a model for enhanced machine learning which can be used to identify different sources of data to collect. This data is thought to be useful for the machine learning algorithm to be both trained and used for various applications. More detail on the specifics of this model creation is found within Submission 1, as well as a full explanation of its expected utility within the realm of automotive in-vehicle features (such as climate). However, this model can also be used to help explore the various metrics which may be useful in measuring or predicting motion sickness. The human factors approach to enhanced machine learning model has been modified slightly to remove specific notations for the SLC project as well as to remove notations focused on 'user routine'. The revised model is presented below in Figure 65:

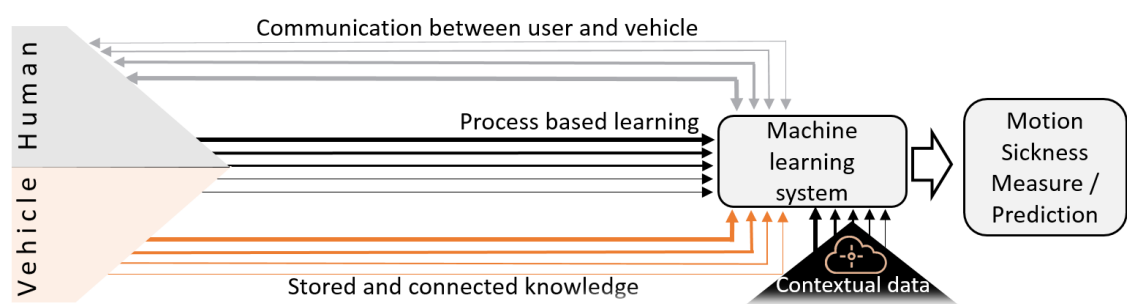


Figure 65 A Human Factors Approach To Machine Learning Model

As a brief explanation as to the utility for the model presented above in Figure 65, it is considered that through using this model to identify all the streams of information available to a machine learning system, the ability to understand/measure/predict motion sickness state may be enhanced. There are three primary sources of information highlighted here. The human (to the left of the model), from the vehicle (from the left of the model) and from contextual data (from the bottom of the model).

The machine learning algorithm, being an entire subject in itself is not of interest to this human factors model, where this is just designed to inform on types of data to collect, rather on what to do specifically with that data. Given the range of data types available between different sources, and within different sources, there is likely to be some data which is more important than others. For example, predisposition to motion sickness and history of motion sickness is perhaps more important than clothing for predicting the onset of motion sickness. Therefore, to highlight this, the arrows used are of varying thicknesses, symbolising varied weights of importance (which may differ, person to person). Each section of this model is now briefly explained with some example types of data that would be useful to collect.

7.7.1 COMMUNICATION BETWEEN USER AND VEHICLE

This section explores the availability for the occupant to communicate with the vehicle and the vehicle to communicate with the occupant (represented with double headed arrows). The overall idea of a model such as this is to limit the requirement for the user to input information (such as filling out questionnaires), however there should still be an option to capture user input if they so desire, as their subjective motion sickness rating is the most important aspect. It is recommended the system includes the option for a user to input motion comfort feedback, where a dial, similar to a volume knob for a radio, may be an easy way for someone to set and adjust their subjective sickness to inform the car. Further to this, there must be a method through which the vehicle can communicate to the occupant. If, for example, motion sickness countermeasures are being initiated, (such as a change in route), informing the occupant of this will both inform them of the system status, and perhaps increase their self-efficacy in the knowledge that mitigation strategies are being employed. Another area of information about the human which is useful for the machine learning system is understanding the occupants' demographics, where it is known that factors such as fitness, age, ethnicity and certainly gender are all related to motion sickness severity. This information could be input by the user in a personal vehicle, or captured as part of a personal profile in a shared mobility instance. Further information, such as visuospatial performance may be accessible if the user is willing to communicate with the system. As a final point, despite the current lack of understanding about its utility, physiological measures could be transmitted from consumer wearables to the vehicle. At present, there is little support for the utility of this data, however, when combined with other information sources and/or filtered to remove other variables it could be of use.

7.7.2 PROCESS BASED LEARNING

The system should be able to register various interactions with the vehicle and, from these interactions (or processes) gain knowledge about motion sickness state. This could include monitoring preferred driving style, interaction with features known to be

linked to motion sickness management -such as opening the windows, or using the HVAC (Heating, Ventilation and Air Conditioning) system or other actions an occupant takes. Further, in an automated vehicle processes could include understanding what the activity of the occupant is at that time. For example, if on-board sensory equipment can monitor occupant activity to detect if they are reading, working with their head down, watching a film, sleeping or are monitoring the road, this information will help determine the chance of motion sickness onset.

7.7.3 STORED AND CONNECTED KNOWLEDGE

This category explored the ability for knowledge to be collected, stored and shared between vehicles. For example, route type and design could have an impact on motion sickness where straight roads and constant speed are preferred over winding roads with varied speed limits. This information (a 'heat map' of motion sickness routes for example) can be stored within the vehicle to both inform on motion sickness likelihood and use in case a mitigation is needed (changing route). Connected vehicles, will have the ability to share data between them, so based on many interactions with the same route, a database of knowledge can be stored about different road sections..

7.7.4 CONTEXTUAL DATA

Contextual data which may be of use to understanding motion sickness onset may include weather and climate, where increased heat and humidity (although may not be a cause of motion sickness) certainly will affect subjective discomfort through the inability to thermoregulate – a known factor for motion sickness onset. Other contextual information may include knowledge about the vehicle being used, including interior design layout (considering flexible seating, or size and location of DLO's) through which efferent motion cues can be gained. Further, vehicle dynamics and suspension could be monitored, adjusted and informed upon for understanding motion sickness onset and for counteracting motion sickness

7.7.5 SUMMARY

This model is designed to capture various data types, which can be used to inform a machine learning algorithm. The nature of a machine learning system is that it requires training data on which to learn about the correct interpretations. This data could be labelled (supervised learning), or unlabelled (unsupervised or reinforcement learning). The exact implementation of a machine learning system is well beyond the scope of this brief note on measuring motion sickness. However, as a brief hypothetical example, using information already discussed within the Innovation Report, it is possible to better understand the utility of this model. The benefit of this model is in its ability to combine data sources, such as (in this hypothetical example), an Asian female, who has history of motion sickness, is traveling on a route known to impact

motion sickness and approaching traffic moving at inconsistent speeds, she started head down reading and a change in her physiology has been noticed. Stringing a hypothetical set of information together starts to show how many streams of data, which on their own are perhaps not useful, can be used as a collective to understand motion sickness likelihood. Of course, this model is untested so the effectiveness of this cannot be discussed, rather the contribution is in highlighting how all these data sources may fit together for future research on the measurement of motion sickness state.

7.8 ADDITIONAL NOTES ON MOTION SICKNESS MEASUREMENT

Throughout this project, and EngD Innovation Report, three key methods of measuring subjective motion sickness severity were used: the Simulator Sickness Questionnaire (SSQ) (Kennedy, Norman, Berbaum, & Lilienthal, 1993), the Motion Sickness Assessment Questionnaire (MSAQ) (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001) and the Fast Motion Sickness Scale (FMS) (Keshavarz & Hecht, 2011). Given the amount of data collected and the reliance on subjective motion sickness assessment for many conclusions it is useful to explore the effectiveness of these measures. A correlation analysis has been done using the data collected in Project A and B and written up in Submission 6 as the on-road motion sickness trial where participants completed all three questionnaires simultaneously (SSQ, MSAQ and FMS). The results from the Spearman's Rank Order correlation is presented below:

Table 30 Correlation Between Subjective Motion Sickness Scales

		FMS Average	FMS Peak	FMS Final	SSQ	MSAQ
FMS Average	Correlation Coefficient	1	.975**	.933**	.718**	.803**
	Sig. (2-tailed)		0.000	0.000	0.000	0.000
	N	51	51	51	51	51
FMS Peak	Correlation Coefficient	.975**	1	.932**	.742**	.838**
	Sig. (2-tailed)	0.000		0.000	0.000	0.000
	N	51	51	51	51	51
FMS Final	Correlation Coefficient	.933**	.932**	1	.700**	.798**
	Sig. (2-tailed)	0.000	0.000		0.000	0.000
	N	51	51	51	51	51
SSQ	Correlation Coefficient	.718**	.742**	.700**	1	.888**
	Sig. (2-tailed)	0.000	0.000	0.000		0.000
	N	51	51	51	51	51
MSAQ	Correlation Coefficient	.803**	.838**	.798**	.888**	1
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	
	N	51	51	51	51	51

Table 30 shows every measure of subjective motion sickness was significantly correlated with 99% confidence ($p < 0.01$) as denoted by the double asterisk '**'. The correlations shown are strong, which bodes well for the validity of the results discussed within this EngD research. Despite the SSQ being designed specifically for simulators with a strong visual aspect, it is correlated to the MSAQ in this real-world study with a person's score of $r_s 0.888$. This is considered a very strong correlation and informs on the ability to compare simulator sickness to real-world sickness using these same measures in both environments. FMS peak score (i.e., the maximum FMS score given throughout an exposure) was recommended by the original author to be of most utility (Keshavarz & Hecht, 2011). The data presented confirms this, where the FMS peak score has the strongest correlation to both MSAQ ($r_s 0.838$) and SSQ ($r_s 0.742$). These strong scores validate the FMS scale for the real-time measurement of motion sickness as discussed in this project, and for the use of this method going forward in cases where full questionnaires are not possible.

Although not a core aim of this EngD project, transferability of data from simulator trials to real-world applications has been a significant consideration in many of the research projects that make up this Innovation Report. It is possible to conclude on some of the findings and discuss some of the implications that have been highlighted along the way.

Firstly, and upon reflection of Project A, it was shown how simulator sickness, as is a common phenomenon in simulator trials, can have a significant effect on human performance. It is with this understanding that future projects must consider user trial data collected in a simulator and the influence that motion sickness may have on this data. Thinking about common industry focused research methods, such as the '2/12 rule' as it is commonly referred to. This 'rule' is a guideline published by NHTSA (National Highway Traffic Safety Administration) in reference to eye-glance behaviour for in-vehicle HMI's, it advises that glances away from the road (to interact with a piece of HMI) should consist of glances no longer than 2 seconds, and for a total eyes-off-road time of less than 12 seconds to complete the task. It is deemed that anything longer (in glance duration, or total eyes-off-road time) constitutes a bad and possibly dangerous HMI design (Perez, Hulse, & Angell, 2013). Guidelines such as these, and others are commonly used in industry-based research, and some academic research also. It is therefore important, considering these small thresholds that performance is measured in a simulator. Specifically, if someone asks to end the driving task early, their user trial data should be omitted from the data set where it is likely their performance is degraded to the extent to which their interaction data is significantly different from their usual ability. Without a further grading criteria for motion sickness severity, it is not yet possible to say at what point, on a subjective scale, motion sickness affects results. Further to this issue of performance degradation, due to the known effects of Sospite Syndrome, and as the data supports in Project A it is not advisable to run reaction-time based user trials in a simulator due to reduced reaction times which may not be directly transferable to real-world abilities. If reaction time, or any other assessment-dependent specific performance ability is being studied, it is recommended that a baseline and post-simulator assessment is used (as was done in Project A). These additional assessments will be able to validate if the simulator has affected these fundamental skills, and thus conclude on the validity of the data collected during the trial.

From Project B, it seems that the effect of visuospatial training on motion sickness susceptibility is worthwhile testing in simulator and on-road environments equally. The data presented in Project B does not highlight that simulator sickness and car sickness differ from one-another in their relation to visuospatial ability and its relationship to

motion sickness. It can be recommended that simulator trials are beneficial here where transferability does not appear to be of concern. However, simulator trials seem to be more of an 'extreme' environment for people, with drop-out rates being higher than on-road trials. For example, 35% (n=7) people dropped out of the simulator visuospatial trial, whereas only one participant (4%) dropped out of the on-road trial due to motion sickness. This is a factor worthy of consideration when planning a study where motion sickness is a factor. Dropouts should be considered in the target sample size and in a simulator study the researcher should account for a greater number of dropouts when recruiting. Anecdotally, the estimated average number of dropouts per 3xD simulator trial is around 25%, observed through experiments at WMG. It is hard to compare dropout rates between simulators given how many factors, such as field of view (Bos, de Vries, van Emmerik, & Groen, 2010), impact motion sickness. A meta study on this subject, presented a mean drop-out percentage of 14% between 9 different simulator trials (Balk, Bertola, & Inman, 2013). This figure is thought to be realistic for a generic trial, but perhaps more pronounced when the test route is designed to be particularly challenging or in a 360degree field of view, such as the 3xD simulator.

No data presented in this research indicated that physiological response to motion sickness differs between simulated and real-world, despite the change in efferent/afferent motion cue significance. Simulators are far easier to control for this style of testing, where airflow, directional/ambient/radiating temperature can all be controlled or eliminated, as these are known effectors of many physiological signs. It is therefore predicted that there is greater utility in simulator testing for fundamental physiological research. However, of course the transferability of any effects found within a simulator may be limited in direct transferability to the real-world, where environmental factors an important variable.

It has been shown in the correlation matrix in Table 30 that the MSAQ and SSQ are strongly correlated. Therefore, ideally when running a repeat measures study including simulator and real-world experimentation (such as in Project B) both questionnaires should be used. This ensures that later simulator-only trials can be compared to the SSQ, and later on-road trials can be compared to other MSAQ's (where SSQ is advisable for simulator studies, and MSAQ for any real-world studies). However, if this is not possible, then either questionnaire may be suitable as a compromise. It is recommended that if only one questionnaire is to be used the MSAQ allows for a greater range of severity assessment, and four (rather than three) subcategories which improve precision and areas for exploration over the SSQ. As recommended by the author (Keshavarz & Hecht , 2011), the FMS peak score seems to be the most useful score for measuring motion sickness, and given its strength in correlations it may be sufficient to have as the only motion sickness measure if a trial does not allow for questionnaires.

Finally, considering the subcategories of motion sickness severity, in the simulated and real-world, previous literature has looked to classify the profile of the SSQ dependent on the environment (Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992). Using the categories of nausea (N), oculomotor (O) and disorientation (D), it was summarised that the motion sickness profiles in different motion sickness environments are as follows:

- Virtual environments as $D > N > O$.
- Space sickness as $O > D > N$,
- Simulation sickness as $O > N > D$
- Seasickness/airsickness as $N > D > O$

With the data collected over this EngD project, it is possible to compare simulation sickness findings and present a profile based on car sickness. Table 31 below summarises all simulator trial participants and all on-road trial participants over all experimentation (inclusive of repeat-measures) and presents the N, O and D average scores.

Table 31 Profiles of Motion Sickness (SSQ)

	Count	Nausea (N)	Oculomotor (O)	Disorientation (D)
Simulator Sickness	71	46.14	30.93	48.95
Car sickness	51	45.97	38.58	50.98

Given the results from the SSQ used throughout this study it is seen that with a sample size of 71, the profile of motion sickness in a simulator is: $D > N > O$ and for car sickness, it is also shown to be $D > N > O$.

The simulation sickness profile is entirely reversed to that which is presented previously by (Kennedy, Lane, Lilienthal, Berbaum, & Hettinger, 1992) where it is considered that simulator design may have a significant role to play. It is also interesting to note that despite the change in afferent/efferent motion cue significance, on-road motion sickness measured by the SSQ follows the same profile as the simulator.

This Innovation Report has detailed the background literature and the scope of the research completed within this project. It has then presented three research projects (A, B and C) which collectively address the aims and objectives as previously set out and focus on understanding the impact, reduction and measurement of motion sickness. Although each of these projects include their own discussion in specific relation to their individual findings, this section will bring together all research as an overall project. This discussion section will pull out the key findings from the three projects to show the impact of this project as a whole to both academia and industry. To complete this discussion, the limitations of the project as well as some opportunities for further research are highlighted. Firstly, the objectives as set out at the beginning of this Innovation Report are presented once again:

1. To critically review the body of literature covering motion sickness with an emphasis on impact to automotive applications
2. To explore the impact of motion sickness on human performance to inform transferability of simulator data to real-world
3. To advise on the most appropriate way to conduct user trials for future simulator-based experimentation (including that of motion sickness management) to inform 'best practice' of vehicle simulator trials.
4. To consider the impact motion sickness may have on the utility of future automated vehicles
5. To detail state of the art methods for managing motion sickness in vehicles
6. Design, test and validate a method of reducing personal susceptibility to motion sickness
7. Provide information on the ways through which a motion sickness management method could be implemented in production vehicles
8. Explore methods for the measurement and detection of motion sickness
9. Explore the feasibility of physiological data as objective measures of motion sickness and provide information about useful metrics through which motion sickness may be measured objectively.

Throughout this discussion, it will be possible to see how these objectives have all been met.

9.1 KEY FINDINGS – CONTRIBUTIONS TO ACADEMIA

The rapid and competitive development of automotive technologies sometimes means the technology is available before the human factors considerations have had time to be fully addressed. Human factors is often trying to catch up with technological developments, where it is often only after technology introduction that manufacturers consider, or have time to consider, human integration. As evidence to this, there is much ongoing research around existing (i.e., consumer available) technology such as touch screen HMI usage (Large, et al., 2019) and ADAS features (Caber, Langdon, & Clarkson, 2019) – many of which have been available on the consumer market for many years. With the next shift in the automotive industry heading towards automated vehicles, there are already concepts for such vehicles (for example see the concept vehicle in Figure 4), and a growing consumer expectation – as seen in Figure 10. There is therefore a pressing need to address the human factors considerations for such technology to enable future vehicles to be developed, designed and manufactured in a user-focused manner. There are already hopes for automated cars to be on the road in just a few years (Driverless Future, 2017), so there is a great urgency for human factors researchers to ensure the technology is usable, safe, enjoyable and effective. With that in mind, this EngD project looked to address the relationship between motion sickness and future automotive technology – covering both the development (using driving simulators) as well as considering the end goal of automated vehicles.

The first contributions of this EngD are found within the Literature Review presented in Submission 2 and as summarised in Section 3.3 in this Innovation Report. The relationship between motion sickness, driving simulators and automated vehicles was considered and contextualised. A clear argument as to why motion sickness is a factor for automated vehicles is presented evidencing innovation of existing knowledge. An update of the state of the art of motion sickness management for driving simulators and automated vehicles has been explored within Submission 2. Using this knowledge it was possible to conclude upon some areas for design recommendations within future vehicles (as summarised in Table 3) and form the basis for future research which this EngD then set out to address. Since then, the three core projects which tell the story of this EngD are able to break down further contributions:

9.1.1 MOTION SICKNESS AND HUMAN PERFORMANCE (PROJECT A)

Project A has, for the first time in an automotive context, shown how motion sickness significantly affects various areas of human performance (as seen in Table 10). This is of consequence for the transferability of simulated data to real-world applications where it has been recommended that simulator dropouts should be omitted from the

data analysis of performance related trials, where severe motion sickness resulting in someone ending the study early is known to significantly reduce their performance in many areas. This builds upon the previous literature which hints at motion sickness degradation in task-specific domains, such as in (Stroud, Harm, & Klaus, 2005), (Bos J. E., 2004) and (Lampton, Kraemer, Kolasinski, & Knerr, 1995). Through testing fundamental abilities rather than specific work or driving related tasks, the utility of the findings are not limited by or to the tests chosen unlike previous studies. Further, the utility of a simulator for reaction-time based experimentation has been questioned, where data suggests reaction times are significantly reduced when using a simulator, likely due to Sospite syndrome. These core findings have allowed for an update on the utility of driving simulators for user trials and allowed for the creation of a best practice guide for simulator use (see Appendix 2). With the on-road aspect to this trial, it was possible to explore the transferability of these simulator findings to the 'real-world', and the measurement of motion sickness was able to help validate the data found in the UK AutoDrive project (as summarised in Submission 4). Overall, this project helped to validate the transferability of simulator data where non-dropout performance was, for the most part, no different from baseline performance – adding reassurance to future user trials looking to develop technology in a simulator.

9.1.2 VISUOSPATIAL TRAINING AND MOTION SICKNESS (PROJECT B)

This EngD research has shown, for the first time how training visuospatial ability can significantly reduce motion sickness susceptibility for both simulator-based (Figure 48) and on-road motion sickness (

Figure 50). Previous research had indicated that visuospatial performance and motion sickness were related (Van Goozen S., 1995), but there has been no attempt, until now to try and train visuospatial skills to reduce motion sickness. This is of great significance for a few reasons. Firstly, for future simulator trials (where pre-training may reduce dropouts, and ensure transferability of performance related measures). Secondly, for the automotive industry in that this method may act as a mitigation strategy to reduce car sickness in both traditional and future automated vehicles. Finally, this key finding is of significance for the field of motion sickness in general, where this relationship has been identified and validated as a motion sickness management method. These findings, may be more effective than design-based methods for reducing motion sickness given their the to other environments. The ability to reduce personal susceptibility to a motion sickness-inducing task (proven for both simulator sickness and car sickness) may be a useful tool for the estimated 1/3 of the population who suffer from high motion sickness susceptibility (U.S. National Library of Medicine, 2019). Not only has this relationship been established, but this project has shown the effectiveness of pen and paper training tasks, assembled in a

novel form, using pre-existing tests in improving visuospatial ability – providing a method as well as the relationship.

Again, although not a core aim, this method has further shown how the motion sickness reduction (through the training of visuospatial tasks) can reduce workload for a simple reading task. It is possible that this method can be used to not only reduce subjective sickness, but improve productivity in automated vehicles, and possibly other job roles where motion sickness is a factor (such as navy crew, or for military simulator training tasks). This effect has not been quantified, but this project certainly has highlighted the scope for further research in this field.

9.1.3 UNDERSTANDING THE MEASUREMENT OF MOTION SICKNESS (PROJECT C)

Although this project has not concluded on a successful method of objectively measuring motion sickness, it is of equal importance to highlight how real-time motion sickness cannot be measured using just EDA or skin temperature alone - furthering the pursuit to an overall objective measure. This project, for the first time has looked at how real time motion sickness and the physiological response of EDA and skin temperature are (in their unfiltered and individual analysis) are not useful predictors of motion sickness state using 'real time practical methods'. Previous research has identified a link between EDA and motion sickness (Parker, 1971) (Warwick-Evans, et al., 1987) (Golding J. , 1992), and this may have been misconceived by some to think EDA is a direct measure of motion sickness. However, through disbanding this as an objective measure for real-time severity or onset (although not disputing that the two are related) this project has made progress in the continuation of this pursuit to find an objective measure. Through the exploration of physiology and motion sickness this research (exemplified in Figure 60 and Figure 61) has shown the importance of sample size in such research where given the diversity in correlation strength and diversity, with a small sample size the relationship could be easily misinterpreted. As a conclusion of this project, a new model is presented through which other data (known to affect motion sickness) can be collected to help identify a holistic method of measuring motion sickness in real-time through the use of machine learning (presented in Figure 65). The utility of each data stream suggested has been of proven utility in other research projects highlighted in Submission 2 and throughout the EngD. It is expected that the sum of these parts may provide the ability to infer motion sickness state and this contribution will stand as justification for future research.

9.2 KEY FINDINGS - IMPACT ON THE SPONSORING COMPANY

Throughout this research, consistent consideration has been given to the applicability

of key findings to JLR as the sponsoring company – ensuring this EngD remains not only innovative but also relevant. Although the project has shifted quite far from its initial conceptualisation – within the SLC team some valuable contributions were made during this first small project (Submission 1). The SLC team were struggling at the time to understand why there was such disparity between users’ actual routine, and their prediction of their routine. Through the creation of a new model on which human-focused data could be collected, this research was able to identify some errors in their current model, and propose considerations for the next iteration of product development. The impact of this project was proven through the invitation to present at the internal JLR technical specialist conference where the model created was disseminated among the research team and taken on board when the project was handed over to mainstream engineering.

The identification of motion sickness as a consideration for future JLR vehicles and research was a significant contribution, where few people within the business were aware of the subject of motion sickness and there was limited knowledge across the human factors teams about the subject. This research was of great utility to JLR, through the contextualisation and clear argument for the subject of motion sickness both in initial reports, and through company meetings. The first experiment identified how simulator dropouts had significantly decreased performance in many areas including physical-visual, physical, cognitive-physical and cognitive performance. Identifying this as an issue helped JLR understand the nature of simulator transferability, where future trials could be assured for transferability (considering fundamental human performance) so long as motion sickness was not an issue. Further information was provided around the limitations of simulators for reaction-time related studies. Although Submission 3 included all the in-depth information (which was available to JLR) a two-page summary of best practice for simulator trials was also created as a result of this experimentation and further reading (Appendix 2). No data has been collected on the utility of this best practice guide, but it is expected to help reduce simulator dropouts (saving time and money when running trials), inform on the ethics of running simulator trials where motion sickness is a risk and help in validating the data collected considering transferability.

Another outcome of the first project was in the validation of the UK AutoDrive user trial data, where motion sickness was tracked and shown to not be a significant issue. This report was written up in Submission 5, but a one-page ‘industry friendly’ summary was also created. This is of use for the JLR owned project where they can be assured that human performance in their trials was not affected by motion sickness, adding to the validity of their study.

One of the most exciting contributions and areas of impact made to the sponsoring company (considering its novelty) was in the creation of a method to reduce motion

sickness through visuospatial training. This method provided a solution to the issue of motion sickness within future vehicles, and if created into a consumer focused product could help in *“Creating experiences people love for life”* (Jaguar Land Rover, 2019) by helping reduce motion sickness discomfort for passengers in both traditional and future automated vehicles. Not only was this new knowledge created, but a workshop to explore exploitation methods was held and the results of this were handed over to JLR to inform them on possible areas of exploitation, and associated research questions that would help in product development. One of the outcomes of this research was in the creation of a JLR mobile app which this EngD research helped inform. This app was co-created to enable future testing and refinement of this method within JLR’s research division and, ultimately, would be considered for its applicability of being used as a consumer product. The development of this app, and JLR embargo of publications of this work to retain the IP is good evidence of the impact this research had on JLR.

The concept for measuring motion sickness objectively through only the measures of skin temperature and EDA was being discussed within JLR and in response to the overall lack of conclusive information in the literature the third project of this EngD helped JLR to understand the utility of these physiological measures. This paper was taken by the head of JLR research and used to update the state of knowledge within the company about objective motion sickness measures. The impact this project had was one of prevention rather than addition, where this research prevented JLR spending time and money following these physiological measures as individual measures, although the impact to the wider field was greater in presenting real-time motion sickness physiology vs subjective measures for the first time. The conclusion of this research showed how there are many useful points of data that can be collected for future motion sickness measurement projects and this EngD provided an adapted model for data collection on which to inform a machine learning system to track/measure and perhaps predict motion sickness in the future.

Considering other impacts created through this EngD, the detailed review of the literature and a strong understanding of the subject allowed for the creation of design recommendations for future automotive vehicles which will be useful for JLR to consider in the design of their future cars. Further to this, over the course of two workshops the information collected in this EngD was presented to the JLR automated vehicle interior design team where JLR staff were trained in the area of motion sickness countermeasures which was of great impact to the team. A letter from the manager of the user interface for automated driving team, written to the internal JLR EngD funder is shown in Appendix 5 as testament to the impact and contribution made. Further to this design project, the information and knowledge collected thought-out this EngD was used to inform JLR on future research strategies for motion sickness. Through multiple sessions JLR were advised on what areas of research should

be pursued, where the gaps in the knowledge are, the benefits of specific research projects and the impact to JLR for each research item. As testament to the utility of this information another letter has been included in Appendix 6, written by the lead engineer of interior sensing and sent to the JLR internal funder of this EngD.

Overall the research conducted and the knowledge gained through this EngD has had many direct impacts on JLR as the project sponsor, and to the automotive industry as a whole. The impacts made to JLR speak well to the strengths of the EngD scope where creation of new knowledge, along with the innovation of this has shown to be of great benefit and success. There is still much more work to be done in this field, but JLR now have the understanding, tools and direction to tackle further motion sickness related issues, working towards their goal of creating experiences people love for life.

9.3 LIMITATIONS OF THE RESEARCH

Despite the many strengths of this research there are a few limitations that should be highlighted. Project specific limitations have been presented within the individual projects There are a few overarching limitations of the project overall.

Given the geographical location of the experiments conducted, the vast number of participants were white, British participants. Given that motion sickness is known to vary between ethnicities this lack of diversity is considered a limitation for widespread representation.

Throughout all user trials, and specifically relating to Projects A and C where the effect of motion sickness was being measured, a potential limitation of these studies was that the entire range of motion sickness was not experienced. As discussed, participants were free to end the study when they felt as if they were too uncomfortable to continue. This, although ethically advisable, limited the data set where little data was collected for severe motion sickness.

Age is an often discussed characteristic of motion sickness. Motion sickness susceptibility variation is particularly observed in children (under 18s). The variance in susceptibility throughout the development of a child may be linked to developments of the brain, balance organs, familiarisation (habituation) and hormones. This research project has purposefully omitted the consideration of children within both experimental groups and discussions.

Vehicle dynamics and vibration management is a popular area of research within motion sickness. This field was not discussed within this project, nor was data collected. The sponsoring company were already working in the field of dynamics so it was important for them that this project did not overlap. This does not limit the findings or results presented as part of this research, rather it limits the transferability

of data to other research. Particularly considering performance metrics in vibration environments (project A), and effectiveness of visuospatial training compared to vibration management (project B)

9.4 OPPORTUNITIES FOR FURTHER RESEARCH

Throughout the research projects presented, some ideas of further research have been highlighted. As a summary of these questions raised along the way, and considering wider aspects of the field, a few areas for further research have been highlighted:

Project A:

- How does motion sickness, and subsequent human performance degradation affect specific driving tasks in a simulator (simulation sickness) or in real world driving (considering automated vehicle control handover)?
- How does motion sickness affect the various areas of visual performance (visual acuity, depth perception, target identification etc.)?
- Is it possible to categorise motion sickness severity states using the SSQ or MSAQ?
- What is the best method to measure at what level of sickness does performance (across individual categories) become significantly affected?
- Does motion sickness affect the ability to regain control of a Level 3 or 4 automated vehicle? (safety)

Project B:

- What is the most efficient way of training visuospatial ability (considering training duration and frequency)?
- What tasks are most useful for training visuospatial skills?
- What is the underlying mechanism through which motion sickness is related to visuospatial ability?
- When training visuospatial ability, how long does the reduced motion sickness susceptibility affect last for?
- How might the relationship between visuospatial training and car sickness/simulation sickness be applied to other fields where motion sickness is a concern?
- What is the most acceptable method through which to train visuospatial skills and would automated vehicle users be willing to train? (also considerate of children as a stakeholder)

Project C:

- What key components affect the physiological measures of EDA and skin temperature and is it possible to filter the data to reduce the impact of variables other than motion sickness?
- Can physiological data be analysed within specific time sections to give a better understanding of motion sickness state per specified timeframe?

- What data is most effective for a machine learning system to identify real-time motion sickness state?

General:

- Considering the propensity for automated vehicles (and non-driving related tasks which they enable) what is the actual expected productivity gain of these vehicles?
- How can automated vehicles be designed to enable productivity through managing motion comfort?
- Considering how motion sickness severity varies between demographics, how can future vehicles be designed in an inclusive manner to ensure no demographic is designed out of utility due to motion sickness?
- How acceptable are the many proposed solutions to minimise motion sickness (including vehicle designs, wearables, visuospatial training, habituation, route changes etc.)

10 FINAL THOUGHT

This EngD project has contextualised the issue of motion sickness within driving simulators and future automated vehicles. It has highlighted how motion sickness affects human performance, and discusses the impact this has on simulator trials and the utility of automated vehicles. A novel method of reducing motion sickness susceptibility has been developed, validated and discussed and further information around objective motion sickness measurement has been presented. Through the creation of new knowledge and the multiple innovations that this EngD generated, this research is of significance for academia, the sponsoring company (JLR) and the future of the automotive industry as a whole.

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Appendix 1 Design recommendations for autonomous vehicles publication

Are you Sitting Comfortably? How Current Self-Driving Car Concepts Overlook Motion Sickness, and the Impact it has on Comfort and Productivity.

Joseph Smyth¹, Paul Jennings¹, and Stewart Birrell¹

¹ WMG at the University of Warwick, Coventry, United Kingdom

¹{j.smyth.2, paul.jennings, s.birrell}@warwick.ac.uk

Abstract. A proposed benefit of self-driving cars is that of increased comfort and productivity of the occupants. Self-driving vehicle concepts and published research show the desire for engagement in non-driving related tasks while traveling in such vehicles. Based on survey results and financial productivity estimations, it is likely that completing work activities within such vehicles will be desirable, even expected. These predictions, along with current concepts for self-driving vehicles, fail to consider motion sickness. This paper explores why motion sickness is likely to be a factor in these vehicles, and explicit implications with a range of in-car non-driving related activities is discussed. Through a critique of current concepts, a contrast between that which is advertised, and what may be possible is highlighted and discussed. The importance for inactivity in future self-driving vehicles considering demographic differences in motion sickness susceptibility is highlighted, and design recommendations for future self-driving vehicles are made.

Keywords: Human Factors · Motion Sickness · Comfort · Self-Driving · Autonomous Vehicles · Productivity

1 Introduction

The introduction of self-driving cars can bring many benefits to society, including increased safety, enabling greater mobility for the disabled, and a reduction in congestion amongst other things. There are many areas of this technology that still need to be addressed before a successful rollout of such vehicles is possible. However, predictions, concepts, and ideas of how they will be used are already fairly well developed. Self-driving and autonomous vehicles have the potential to increase comfort and productivity for occupants where the focus on the packaging of occupants can shift from enabling driving to increasing comfort and facilitating engagement in non-driving related tasks. Indeed, in a level 5 vehicle ('full automation' as set out by [1]) there is no option for an occupant to physically drive the vehicle, where even in lower levels of automation (including conditional/3 and high/4 automation) there is certainly more freedom to consider non-driving related tasks.

KPMG estimate that "all vehicles produced in the UK by 2027 will have at least L3 technologies" [2], where many vehicle manufacturers are hoping to release vehicles with

varying levels of autonomy within as little as one year. Regardless of the specifics of timelines and rollout strategies considering automation levels, the end goal for most mainstream vehicle manufacturers is to provide enhanced support for the driver, or even removing them from the driving task altogether. This technology will drastically change road transportation as we currently know it in 2019, and if handled appropriately it could bring immense benefits to many areas. A considerable benefit from a consumer view, and as many manufacturers are promoting, is in relation to increased comfort and productivity. The opportunity for increased comfort is relatively easily understood through considering the lack of need for driving controls and subsequent opportunity for changes to the occupant packaging design that this enables. The concept of increased productivity relates to the ability to complete non-driving related tasks whilst traveling in a car. This could include reading books, watching films, or even working – all very realistic tasks for a level 4/5 vehicle. Considering productivity, the research group at Morgan Stanley have estimated a US\$507billion annual increase to the US economy based purely on the increased productivity due to the ability to work within a self-driving car during a commute [3]. They go on to explain how Americans "spend some 75 billion hours a year driving" which, they forecast could be put to better use if traveling in an autonomous vehicle. In this instance, they see the opportunity to transform this wasted commuting driving time into working hours (see [3] p.50 for the full calculation). An idea which is not difficult to imagine considering evidence already showing 40% of train commuters spend their journey attending to work related emails [4], it is even common practice for some commuters to count travel time as paid office hours. Based on this prospect of work-related productivity in a future self-driving car, another report estimates a US\$220 billion gain to the economy as drivers become passengers and are able to complete work based activities whilst commuting [5]. All looks very promising for the future of driverless cars, especially with significant financial predictions such as these. However, there is one common oversight in these predictions and current expectations – the propensity for people to become motion sick.

2 An Introduction to Motion Sickness

As suggested by its name motion sickness is a sickness feeling commonly associated with traveling in cars, boats or trains – all scenarios with an element of motion. Sensory conflict theory [6] dictates that when a mismatch between visual, vestibular and/or somatosensory senses occurs, motion sickness can prevail. Where the visual system can detect movement through eye sight, the vestibular system can detect movement through the movement of fluid within the semi-circular canals of the inner ear, and the somatosensory system can detect movement through motion felt through limbs and pressure on parts of the body. This theory is thought to be the most useful at explaining why people become motion sick. The evolutionary hypothesis [7] goes on to explain how sensory conflict 'tricks' the body into assuming a toxin has been ingested, and is to blame for the conflict. This hypothesis provides understanding for the common symptomatology of motion sickness of sweating, bumping and vomiting as the body attempts to eject the believed toxin. Another theory of motion sickness is the hypothesis of postural instability, which explains that motion sickness is caused by loss of postural control [8]. As such, an underlying contributor to this theory is postural sway – where the

human body is understood to be in constant movement through small, multi-axial swaying motions – which are observed in all states, including sitting. This sway helps the brain predict motion through comparing expected variations to swaying against any immediate effects. This theory is somewhat less discussed more recently, where the opinion is now that postural instability is more of a precursor to motion sickness and recent findings show postural instability may not necessarily cause motion sickness, but does precede subjective motion sickness symptoms [9] [10]. However, this theory is still particularly interesting considering seating design and occupant packaging, where seat support is a factor of postural sway and therefore linked to motion sickness.

Cause(s) aside, the symptoms of motion sickness are well understood in a subjective sense, where many people have had personal experiences with motion sickness. Sweating, burping and vomiting (as previously mentioned) are known symptoms of motion sickness, but other symptoms can include cold sweats, fatigue, stomach awareness, temperature change, nausea, disorientation, and oculomotor issues/strain amongst others. Such symptoms have been explained and discussed (in terms of grading the severity) within reports from [11]. It is important to understand motion sickness is not a binary state, where even with mild motion sickness, symptoms can begin to show – making even mild motion sickness an undesirable experience. More recent research looks beyond just subjective comfort, and highlighted the effect of motion sickness on human performance [12]. This research has shown how motion sickness can significantly negatively affect various areas of fundamental performance, including cognitive and physical ability. Other research, looking specifically at occupational skills found that motion sickness affected the ability to complete work-related cognitive tasks [13]. Where further work highlighted similar performance degradation during a seasickness trial [14].

The literature evidences how motion sickness has undesirable effects for people considering both their comfort and their performance. Further, it is known how motion sickness susceptibility and severity is not uniform across the population where there are many differences between a variety of demographics including ethnicity [15] age, [16], and perhaps most interestingly (considering the size of the demographic proportions) gender. It is reported in almost all studies looking at motion sickness that females are more susceptible than males to motion sickness (for example [17]). This gender difference was shown to be true in previous simulator sickness studies [18] as well as other dedicated gender focused studies [19]. Such demographic differences mean that motion sickness and its effects are not uniformly problematic across the population, where for some people onset frequency and severity is much worse than for others.

3 Why Self-Driving and Autonomous Vehicles will Increase Incidences of Motion Sickness

Considering motion sickness, it is understood that ‘around 60% of the population has experienced some nausea from car travel, whereas about a third has vomited in cars before the age of 12’ [20]. These figures are however considering traditional vehicles. When considering future autonomous vehicles – such as those with conditional, high or full automation – the consideration of motion sickness is of much greater importance. It is expected that self-driving vehicles are likely to significantly increase motion sick-

ness onset frequency and severity. One paper [21] has summarized the reasons for increased motion sickness in autonomous driving into three areas: ‘First, automation alters the driver’s function from an active to a passive, monitoring one. Secondly, occupants are assumed to engage in non-driving tasks taking the eyes off the road ahead. Finally, flexible seating arrangements may involve rearward facing seats’ [21] (p. 303). Addressing the first point, it is almost unheard of that a driver of a traditional vehicle will become motion sick, as they are physically inputting directional controls including lateral and longitudinal accelerations. However, when the role changes to merely observing movement within a vehicle (as a passenger might currently, and a self-driving vehicle occupant will) there can be a lack of anticipation of motion which can contribute to motion sickness. This phenomenon has previously been explored and summarized [22] where the effect is described as a ‘profound helplessness reaction’ (also commonly referred to as ‘loss of control theory’).



Fig. 1 Example of sensory conflict in an Autonomous Vehicle (AV)

Figure 1 illustrates how when driving traditionally the majority of the field of vision is on the road, and thus with the anticipated vehicle movement and flow of traffic. However, if reading a book, or engaging in other non-driving related activities as levels 4 and 5 automated vehicles may allow, the majority of the field of vision is static while movement is still detected by the inner ear and somatosensory system. Thus in this second instance, sensory conflict can occur and motion sickness is likely. The final point made by [21] discusses flexible seating arrangements. It is understood that rearward-facing seats will compound the lack of motion cues and anticipation of future motions – increasing the opportunity for sensory conflict and postural instability, therefore increasing the likelihood of motion sickness onset.

Considering consumer expectations, a survey conducted by insurance company StateFarm in 2016 [23] looked to understand what people want to do within a self-driving car, given the premise that self-driving technology would free up their time to engage in other activities. They reported 45% of people would be more willing to read texts, 36% would be more willing to access the internet, 21% would be more willing to watch movies and 19% would be more willing to read a book. These figures would be expected to increase as trust and familiarity with the technology increase, with research showing that the development of trust is a dynamic process and needs to be calibrated to the correct levels [24]. Further, considering the productivity benefits that have been predicted [3] [5], it is becoming likely that employers may expect their staff to work in these vehicles. Considering these activities discussed, it has been theorized that “all envisaged use cases can be predicted to increase the risk of motion sickness” [25] and

with an understanding of the physiological causes of motion sickness it is clearer to see why self-driving vehicles have this increased potential to exacerbate motion sickness onset. To this end, one paper looking at motion sickness likelihood of adults riding as passengers in self-driving cars found that, of the people surveyed, 37% of Americans, 40% of Chinese, 53% of Indian people would “experience an increase in the frequency and severity of motion sickness” [26] (p.5). However, they also added that the “actual frequency and severity of motion sickness in self-driving vehicles might be greater than calculated” (p.9), mainly due to this great variation in activities passengers could engage in, and the potential design changes in self-driving vehicles. In [26], the state of motion sickness is presumed to be severe motion sickness, where they did not report on more mild motion sickness. This is significant as it was found that even mild motion sickness (although less subjectively uncomfortable) can be just as detrimental for human performance as severe motion sickness [18]. Further, these figures look at just an ‘increase’ of motion sickness, where they do not capture the current motion sickness statistics for traditional vehicles, which we know already affects a significant proportion of the population. Considering these points, the aforementioned statistics are considered relatively conservative, where it is likely motion sickness would be a factor for a larger percentage of the population under many circumstances. For the most part, estimating the percentage of the population likely to experience motion sickness in a self-driving car will be dependent on five defined areas as presented in Table 1 below:

Table 1 – Categorizing Areas of Motion Sickness Management

Category	Explanation/Examples
1 – Occupant characteristics	i.e., a person’s natural susceptibility to motion sickness - including demographic differentiation, habituation, clothing, etc.
2 – Interior design	i.e., the design of the cabin including seating, displays, interfaces, windows, climate control and features, etc.
3 – Vehicle design	i.e., size, height, vehicle dynamics, suspension etc.
4 – Activity	i.e., the activity of the person inside the vehicle such as working, reading, looking out the window etc.
5 – Driving	i.e., the driving style, speed, route motion path of the vehicle etc.

Occupant characteristics (point 1) are fairly well documented in the literature considering demographic trends, and with an understanding of the thermoregulation aspect of motion sickness, the importance for cool, light and non-sweat restrictive clothing is also understood. Habituation is a key area and is relatively under researched however. Points 2, 3, 4 and 5 are difficult to report on empirically as there are no full automation vehicles on the road currently on which to collect data, nor are there any finalized designs for such vehicles. However, it is possible to assess self-driving vehicle concepts to understand how these factors are likely going to affect motion sickness.

4 Current Self-Driving and Autonomous Concepts

This paper has previously discussed the many productivity gains forecast on the premise of the introduction of self-driving vehicles. However, it is argued that unless motion sickness is taken into consideration in the design of such vehicles, and expectations of

what is possible for some people is addressed, these forecasts may not be realized. As an example of some of these challenging concepts for self-driving vehicles, three concepts from three separate sources are presented. For the purpose of this review, points 1, 2 and 4 will be the primary focus as they relate to factors understandable through imagery.

The purpose of this analysis is not to discourage or criticize the efforts made in these designs, but rather highlight the factor of motion sickness and therefore challenge the feasibility of such concepts – especially considering the productivity forecasts. At the end of the exploration presented in this paper, design recommendations are given.



Fig. 2. Mercedes-Benz Autonomous Vehicle Prototype. [27]

Figure 2 shows a concept made by Mercedes-Benz, where occupants are engaging together in work based tasks. In this example much of the view of the outside world is not visible, where the windows are limited and all visual fixation points are below the window line – with interfaces on the door or center table. This design would not allow for appropriate visual motion cues in either a direct line of sight or peripheral sight. The probability of sensory conflict for all occupants is high, and the ability to understand current motion and/or predict upcoming motion is further limited. The seat designs appear unsupportive, hence the ability to manage postural sway would also be problematic. With a lack of support from the seats, it is likely the effectiveness of the somatosensory (perceived movement) system will be limited due to the lack of contact with the static seats. With rearward facing seating the motion experienced would be unfamiliar for someone used to traveling forwards, again leading to a disconnect between motion cues. Statistically speaking, the female occupant is more likely to become motion sick than the males, where comfort and performance degradation may be more severe for the female compared to her male colleagues - illustrating a lack of inclusivity. Overall, this concept, although visually appealing, has given little consideration to motion sickness and the expectation of productivity is an unlikely scenario for many who would travel in such a vehicle.



Fig. 3. Rinspeed Xchange Autonomous Vehicle Prototype [28]

Figure 3 exhibits a similar cause for concern for motion sickness sufferers. In this scene the rearward facing seats are limiting the ability to predict future motion, the windows are again limited in size – reducing visual indication(s) of motion, and the fixation point for occupants is a large display screen. In this example not only is the inability to predict oncoming motion and the lack of visual motion cues likely to induce motion sickness, but sensory conflict may be compounded where the visual system may be exposed to conflicting motion cues if the display screen is showing moving images.



Fig. 4. Volvo Autonomous Vehicle Prototype [29]

The scene presented in Figure 4 also raises concerns for motion sickness onset. The main work surface and interface is a table, which requires occupants to be looking with their heads down – a known issue for sensory conflict and perhaps the worst head position for motion sickness management. Further, the window is being utilized as a display screen, which limits views of outside motion and therefore impacts the ability to understand current and predict future motion – limiting the ability to receive coherent sensory cues. The panoramic roof and wide windshield would be beneficial however, and this is a good example of how to decrease sensory conflict. The bench style seat is undesirable, where without the ability to anticipate future motion it is likely that the occupant will not be well supported. The literature surrounding demographic changes in motion sickness variation is fairly comprehensive, where not only is there a gender difference, but also ethnicity bias – where this example highlights the possibility for lack of inclusivity for such designs.

In summary, looking at the designs presented, it is clear that the possibility for increased motion sickness is likely in all scenarios. The issues raised in this paper surpass the physical designs showcased in these concepts, and questions the very use cases they

propose. Such use cases are clearly desirable for many people and organizations, based on the opportunity for increased productivity and the statistics previously presented support these ideas. However, these scenarios as they are currently envisaged and conceived highlight a disconnect between what is desired, and what is possible for many people. Along with design and use case(s), personal susceptibility (including demographic factors) will play a critical role in the further development of such vehicles. If commuters in the future are expected to use time spent traveling as working hours, and it is known how certain people are more likely to be motion sick than others, the ability – or expectation – to work is not uniformly accessible, hence a new area for inclusive design is highlighted. Current productivity estimates do not differentiate between demographics or consider individual accessibility. With the concepts presented, there is a significant productivity benefit bias towards those who are less susceptible to motion sickness. Therefore, due to lack of consideration for motion sickness, many demographics are being designed out of much of the benefits these vehicles aim to bring and it is therefore possible that the productivity estimates are vastly over optimistic, and importantly not inclusive for all populations.

4 Recommendations for the Management of Motion Sickness in Future Autonomous and Self-Driving Vehicles.

There is growing amounts of information in the literature highlighting the causes of motion sickness and, more recently, how such motion sickness may affect productivity and comfort. There is however, a comparative lack of proven methods to reduce or eliminate motion sickness. Considering the five areas highlighted in Table 1, and in reflection of the above concepts, some design recommendations can be summarized, and areas for further research can be highlighted. In all recommendations, the execution is likely as important as the theory itself; testing and development will be needed to understand the most effective way of reducing motion sickness and implementing these solutions.

1. Occupant characteristics

- Habituation is known to be the best way to manage motion sickness, where repeat exposure to motion-challenging environments can reduce susceptibility over time (see [30]). People should be aware of their own susceptibility and they can aim to reduce it through repeat exposures, whereas avoiding motion sickness inducing scenarios will slow habituation. Further, motion sickness medication can reduce habituation, so for long term benefit, medication should be avoided [31] (p.628). Other methods for aiding/expediting habituation should be explored, such as simulation, exposure time/frequencies etc.
- Scarfs, heavy jackets and restrictive clothing should be avoided to aid in thermoregulation and allow participants to cool, as it is known that improving the ability to lose heat through evaporative heat loss and vasodilation are beneficial for reducing motion sickness discomfort and severity [32] [33].

- An awareness of personal susceptibility will aid in understanding what tasks should be avoided, and where counter measures can be self-initiated, such as taking breaks from non-driving related activities.
- ## 2. Interior design
- Some very useful recommendations in this area have already been made where layout of vehicle cabin features have been considered as well as some user interface aspects [25] and building upon these points:
 - Window areas should be maximized [25] to ensure visual motion cues for current and upcoming motion.
 - Seats should be positioned to allow for views of the outside [25] (including height adjustable for shorter occupants), and in the direction of travel (i.e., avoid rearward facing seats).
 - HVAC systems should be adaptable if flexible seating is required, to enable ventilation and cooling at any seat angle to aid in thermoregulation.
 - Seats should be supportive for cornering and changes in accelerations – providing adequate bolsters to help the management of postural sway.
 - Methods for communicating future motion through cockpit or HMI design should be considered – including cues for braking, accelerating and cornering. Methods could include audible motion cues such as navigation directions, indicator sound for corners, sounds for acceleration/braking etc. Tactile motion cues such as using the HVAC system to simulator motion through air movement. Dynamic cues such as a preemptive small turn before the main corner. Visual motion cues such as using lighting inside the vehicle to simulate motion, or artificial horizons within HMI's to allow motion to be inferred.
 - Alternative thermo-comfort management systems should be considered such as cooling seats to allow for management of body temperature and sweat.
 - Location of working stations or displays should be in the line of sight of the outside world so that motion can be inferred through peripheral vision [25].
 - Tables and workstations that require head-down posture should be avoided.
 - Objects obstructing the view of the outside world should be reduced (e.g. large displays should be avoided, seats not in use could be folded, and sun visors should be up when not in use).
- ## 3. Vehicle design
- Suspension should be optimized to manage unnecessary motions through accelerations (including corners and braking).
 - Suspension to reduce low frequency vibration should be used where frequencies of 0.08 to 0.4 Hz are particularly sickness inducing [34].
 - Vehicle ride height should be considered where greater distance from the road will increase pitch/roll in accelerations, but may increase outside visibility.
- ## 4. Activity
- Any task requiring looking down should be avoided, where looking straight forward, out of a window is the ideal position.

- “avoid dynamic or static display content in constraint or varying velocity driving scenarios, respectively” [25]
 - Tasks should be interruptible at any time (e.g. limit use of scrolling text or timeouts due to inactivity for any task).
 - Tasks should be designed with breaks and rest points – avoiding fixation for extended periods and encouraging brakes to look out the window.
 - Devices requiring physical interaction should be in an area which can aid in supporting the upper body e.g. in armrests or other fixed supports so that limbs are not self-supported and thus postural instability/sway can be managed.
 - Visual tasks should be in line of sight of the outside world, where displays could be presented on transparent displays (such as heads up display) to enable processing of visual motion cues.
- ## 5. Driving
- Route type could be chosen based on motion sickness susceptibility of occupants, where for example slower speed cities are more preferable than highways for most people [35]. Route could also be chosen based on occupant activity expectancy e.g. avoid bending roads and roundabouts if the occupant will be working.
 - Constant speeds are preferable rather than braking and acceleration – avoiding areas with high stop/start traffic light density and similar will be beneficial.
 - Driving style should be consistent where braking / acceleration rates could be predicted and uniform across instances - allowing for better understanding of motion paths and habituation to driving due to increased predictability of motion(s).
 - Minimize steering corrections and adjustments by planning optimal cornering paths for the road.
 - Changes in velocity whilst cornering should be avoided where possible, to reduce compound motion cues.

5 Conclusion

Self-driving and autonomous vehicles are likely to induce motion sickness for a considerable percentage of the population, with motion sickness being further exacerbated through the engagement in non-driving related activities. Current predictions of the benefits of such vehicles have overlooked the factor of motion sickness, and productivity predictions are unlikely to be achieved without further consideration of how to reduce, or manage motion sickness. Motion sickness causes significant subjective discomfort – leading to a likely reduction in willingness to engage in many tasks, and even if those tasks are completed, actual performance has been shown to be significantly affected. Further to this, through understanding demographic differences in motion sickness susceptibility it is clear to see a lack of inclusivity in these current designs, where without methods of managing motion sickness some users will be much more affected than others. This paper has highlighted some key concerns for such future vehicles, and through the exploration of the literature and in reflection of some current self-driving vehicle concepts, a series of design recommendations have been made across five areas of self-driving vehicle design. Many of these recommendations are

theory-based where there is a current lack of proven methods to manage motion sickness through physical vehicle design, and given the variation in many vehicle designs, the implementation of recommendations will be dependent of the characteristics of individual vehicles. It is hoped that vehicle manufacturers will consider these motion sickness design solutions presented for future self-driving and autonomous vehicles so that everyone can benefit from the many comfort and productivity gains that have been predicted.

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Best Practice Guide for Simulator-Based User Trials



This best practice guide has been created to enable the most effective simulator-based user trials considering efficiency of user trials, participant wellbeing and reliability of user-collected data. All the recommendations made within this report are based on peer-reviewed findings from previous literature and original research collected in WMG's 3xD simulator. It is recommended that all researchers using a simulator to collect data read understand and adhere to this guide. The guide has been split into six sections including scenario design, recruitment, pre-trial, during-trial, post-trial and data analysis.

The most prevalent and accepted theory of why people become motion sick is 'sensory conflict theory', which states that "mismatches between (or within) the visual, vestibular, and somatosensory inputs" cause motion sickness [1]. That is to say a person can detect motion with their eyes (through sight), with their vestibular system (the inner ear) and through the somatosensory system (the brain area responsible for sensation of movement of limbs). If one or more of these senses conflicts with the other motion sickness can prevail. In a simulator, for example, the eyes will detect movement, but the vestibular system will detect none, so there is conflict and motion sickness is possible.

Scenario design

- Total user trial time should ideally be 15 minutes or less to minimise the chance of motion sickness. Multiple shorter runs separated by breaks are better than one long single run.
- Routes should be mainly straight roads and minimal tight bends. Avoid multiple changes of speed and ensure any speed change happens on a straight road and not a bend.
- Avoid roundabouts if possible, where making participants take the 3rd exit on a roundabout is perhaps the most disorientating action possible in a simulator. If roundabouts are needed the 1st or 2nd exits are preferable.
- Give all participants a 5 minute (at least) familiarisation run where they can drive at a steady slow speed on a straight road and are gradually introduced to speed and bends (if required).
- Ensure the simulator is set up with no trip hazards if the participant has to exit quickly due to motion sickness. Provide a recovery space with plenty of water for unwell participants.
- Reaction-time based user trials should be avoided, where Sopor Syndrome (a side effect of simulator use) is likely to induce fatigue and has been shown to significantly decrease reaction time. If reaction time is being measured it is recommended that Sopor Syndrome is also measured and pre and post simulator exposure reaction time is measured, where significant changes after simulator exposure indicate the user trial may be compromised.

Recruitment

- An exclusion criterion can be used if researchers need to minimize the amount of people dropping out due to motion sickness. This should be used with caution considering excluding participants will not give a true representation of the general population.
- Participants should be made aware of the risks of motion sickness upon recruitment, where the exclusion criteria can be provided (even if not being enforced) and participants made aware that if they meet any points they have an increased risk of motion sickness.
- If participants are being paid to take part they should be made aware that they will receive the payment before simulator exposure and will receive payment even if they dropout.
- Participants should be made aware at recruitment that motion sickness can affect human performance and they are advised not to operate heavy machinery (e.g. driving a car) for at least 2 hours after the simulator study – even if feeling subjectively well.
- Participants should be advised not to consume caffeine directly before the user trial where this can increase the chance of motion sickness.
- When recruiting be aware that around 25% of participants may dropout due to motion sickness (although some user trial have no dropouts) so recruit more participants than is required to

compensate. Females are more likely to drop out compared to males, so recruitment of more females may help ensure an equal demographic in the final data set.

Pre-trial

- Before taking part in the trial, make participants fully aware of the risks including subjective discomfort due to motion sickness. Ensure participants have signed a consent form.
- Increasing self efficacy decreases motion sickness, so explain the simulator positively, where if the participant believes they will not get motion sickness, they are less likely to.
- Acclimatise the participant for at least 5 minutes to the lighting conditions. If possible introduce the participant to the user trial inside the simulator so they have time to adapt.
- The SSQ (Simulator Sickness Questionnaire) by [2] should be administered before the exposure to the simulator to capture any baseline feelings. Research has shown a pre SSQ. has no effect on likelihood of becoming motion sick and does not prime participants.
- Participants should be reminded they are free to withdraw and end the study at any time.

During-trial

- The simulator should vent cold air to the participant, where increased airflow and lower temperatures are known to reduce motion sickness.
- Remind participants to look ahead as much as possible – avoiding looking out the side or rear windows as much as possible.
- The FMS (fast motion sickness questionnaire) can be administered by the researchers to capture subjective motion sickness in ‘real time’ [3].
- Ensure the intercom system is turned on and advise the participant they can contact the researcher at any time to end the study if they become motion sick.
- Participants should be observed throughout the trial via the in-cabin cameras. Researchers should look out for signs of severe motion sickness so they can end the study. Anecdotal evidence of motion sickness onset highlights these actions: change in face pallor where participants can turn pale, increased sweating on the face, participants raising their hand to their mouth or brow, burping. A general ‘path’ to sickness is sweating – burping – vomiting.

Post-trial

- If participants dropout of the trial due to motion sickness their trial data should not be used. It has been shown that people who dropout due to motion sickness have impaired performance so their data is invalidated and non representative of their actual ability. Post-trial questionnaires relating to the user trial will also be invalidated so should not be used.
- Participants should complete the SSQ post-simulator exposure to measure new symptoms.
- Participants should be welcomed to sit, drink water and recover fully before leaving.
- Participants should be asked to not mention to any colleagues the nature of the user trial until the trial period is over. Discussing the trial with others may impact future results.

Data analysis

- SSQ scores should be evaluated looking at the difference between pre and post scores to eliminate prior conditions (such as a headache or fatigue) from affecting the SSQ scores.
- If participants withdrew due to motion sickness, no performance data should be used and further questionnaires should not be given at risk of collecting unreliable data.
- For those who don’t dropout due to motion sickness, human performance should be considered unaffected, however, transferability of simulator-collected data to ‘real-world’ applications is very much dependent on the trial specifics (e.g. risk perception of an AV)

[1] J. T. Reason and J. J. Brand, “Motion Sickness,” Academic Press, 1975.

[2] R. S. Kennedy, N. E. Lane, N. E. Berbaum and M. G. Liienthal, “Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness,” International Journal of, pp. 203-220, 1993.

[3] B. Keshavarz and H. Hecht , “Validating an Efficient Method to Quantify Motion Sickness,” Human Factors: The Journal of the Human Factors and Ergonomics Society , vol. 53 , pp. 415-426, 11 April 2011.

Appendix 3 UK AutoDrive One Page Summary

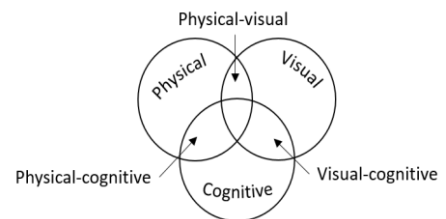
Motion Sickness and Human Performance – A Follow-up Study with the UK Auto Drive Project (Project Summary)

Background:

Previous research in this EngD has shown how motion sickness can affect various areas of human performance. Specifically - cognitive performance, physical performance, physical-visual performance and physical-cognitive performance were all shown to be negatively affected by motion sickness. This impact may invalidate some user-collected data in future user trials where motion sickness is prevalent. Where it is thought that motion sickness is likely to affect the validity of user data if they are motion sick. It was important to see if effects observed in the 3xD simulator were similar to effects in the UK AutoDrive pods

Method:

Human performance can be broken down into a Venn diagram (right) considering performance skills needed to drive. Because time was a factor only two areas of performance were addressed - Cognitive performance, where driving cognitive performance is required for route planning, appraising danger, contextual awareness etc. In addition, Cognitive-Physical performance which is the intersection of cognitive skills (as mentioned) and physical skills which are required for dexterous interaction with HMI and physical manipulation of controls etc. The test used to assess cognitive performance was an N-back test - which relied on the participants cognitive ability to remember and add numbers in their head. The test used for assessing physical-cognitive skill was a reaction speed test where participants clicked a button when a light illuminated, thus depending on cognitive processing speed and subsequent physical response. Both tests are pre-validated representative of the specific areas without being impacted by other abilities. Motion sickness was measured using the Simulation Sickness Questionnaire (SSQ) so results were transferable to the previous simulator study. Participants completed the SSQ (to capture any pre-existing conditions) and completed both performance tests (in a random order) when they arrived at the facility. They were then exposed to the pods for a standardised time. After exposure participants completed the two tests again (randomised) and another SSQ. Results were analysed looking the change in motion sickness and comparing this to the change in task performance ability.



Results:

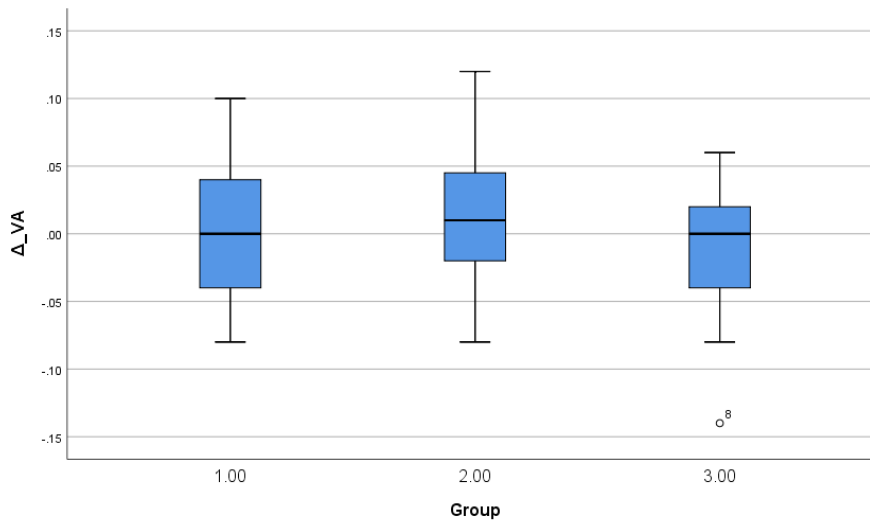
There was no statistically significant change between pre and post SSQ scores for the Nausea (N) subscale, Disorientation (D) subscale, Oculomotor (O) subscale and total SSQ scores where in all cases $P > 0.05$. Looking at the difference between the pre and post cognitive scores there was no difference found ($Z = -1.270$, $p = 0.204$). However, looking at the pre and post physical-cognitive test scores a significant difference was observed - $t(16) = -0.251$, $p = 0.039$. Indicating that there was a significant increase in reaction time scores where the mean score pre exposure was 0.299 seconds and the mean post score was 0.317 seconds. There was no statistical significance observed between delta SSQ total (i.e., the change in total SSQ score) and delta reaction score as determined by the one-way ANOVA ($F = 0.967$, $p > 0.05$). Likewise, there was no significance shown between delta total SSQ and delta N-Back ($F = 1.1998$, $p = 0.05$).

Conclusion:

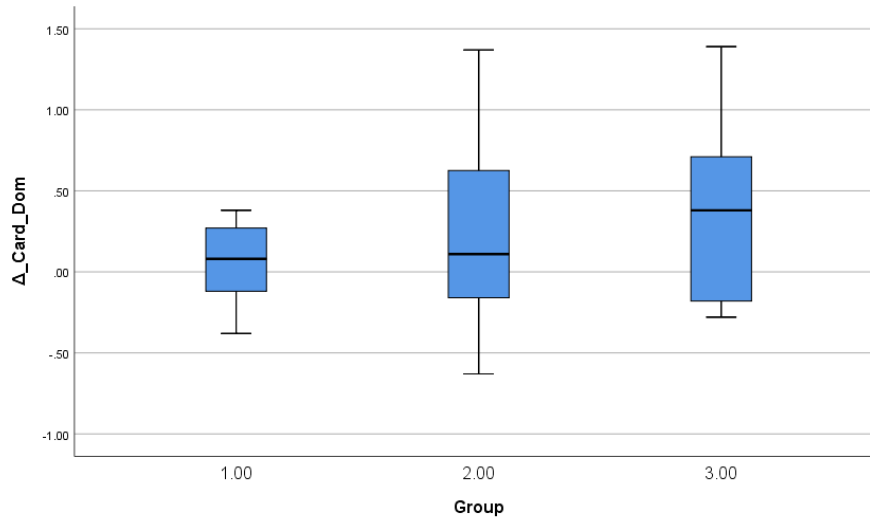
Overall, motion sickness does not appear to be an issue for these UK Autodrive trials, where the design of the pod, test track and scenario are all designed in such a way that motion sickness onset likelihood is low. It is recommended that motion sickness is continued to be tracked whereby the Motion Sickness Assessment Questionnaire (MSAQ) by Gianaros et al. (Gianaros, et al. 2001) can be used in future studies. For real-time subjective scoring the Fast Motion Sickness Questionnaire (FMS) (Keshavarz and Hecht 2011) can be used. Previous EngD research has validated the effectiveness of the FMS (Pearson's correlation = 0.620, $p < 0.001$). If motion sickness does become more common in future trials then researchers are advised to consider if such motion sickness may affect the validity of results, where it is known motion sickness can affect performance. As for the performance scores, reaction time was significantly increased for participants. There is no evidence this was related to motion sickness, instead it is likely that cold test conditions impacted dexterity and motor control or Sospite Syndrome induced through the vehicle motion was a cause. If physical interaction is a measured variable in future trials, the impact of such factors should be considered.

Appendix 4 Box Plots for Motion Sickness Severity Groups' Performance Change

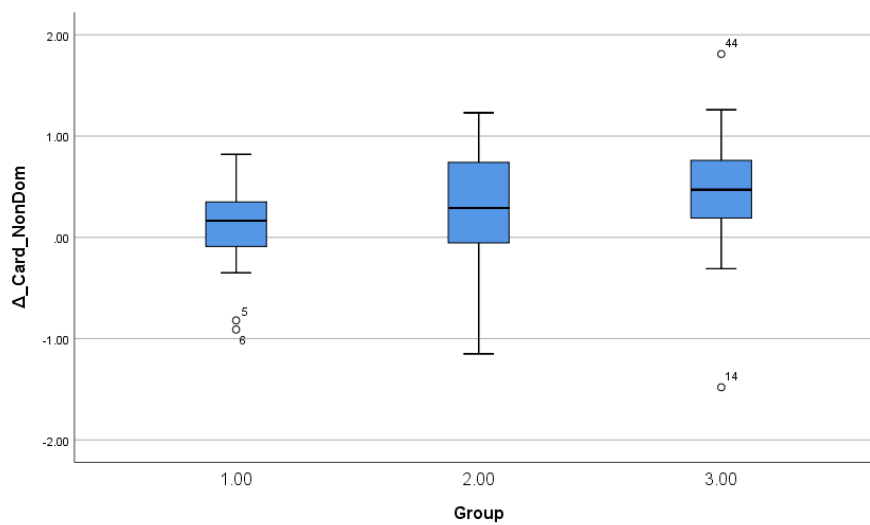
Visual Performance



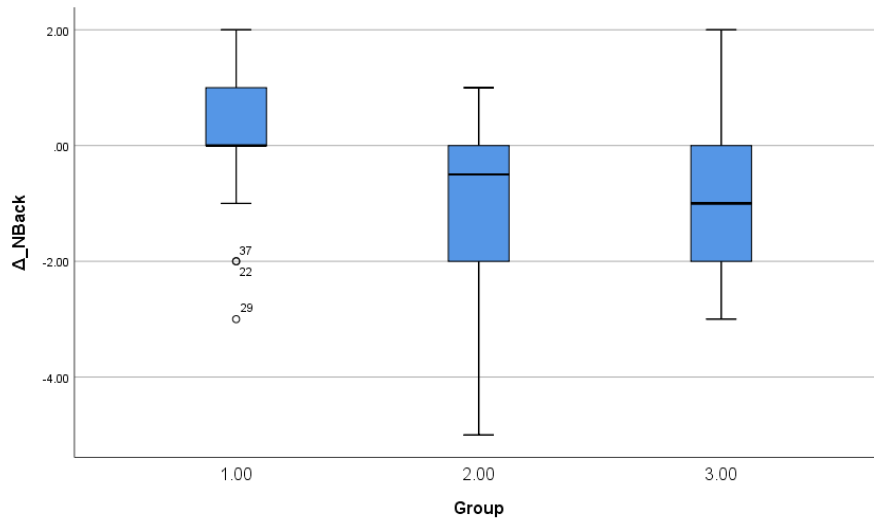
Physical Performance (dominant)



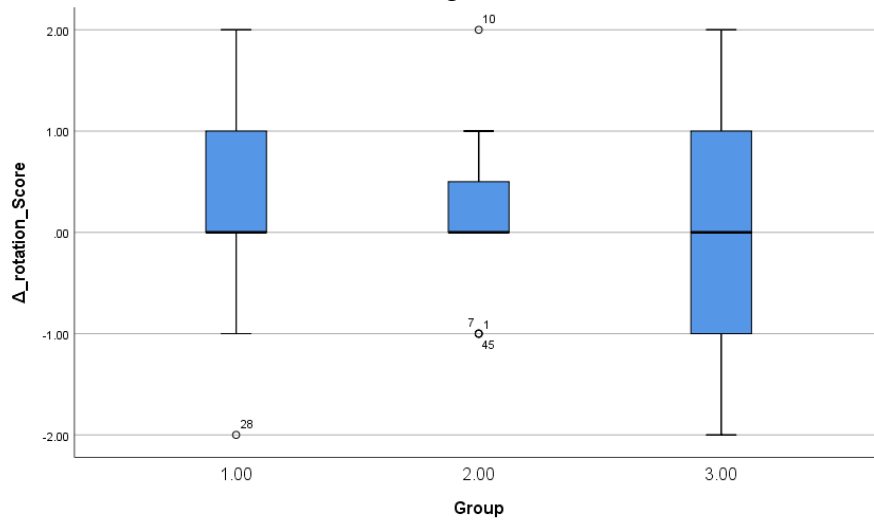
Physical Performance (non-dominant)



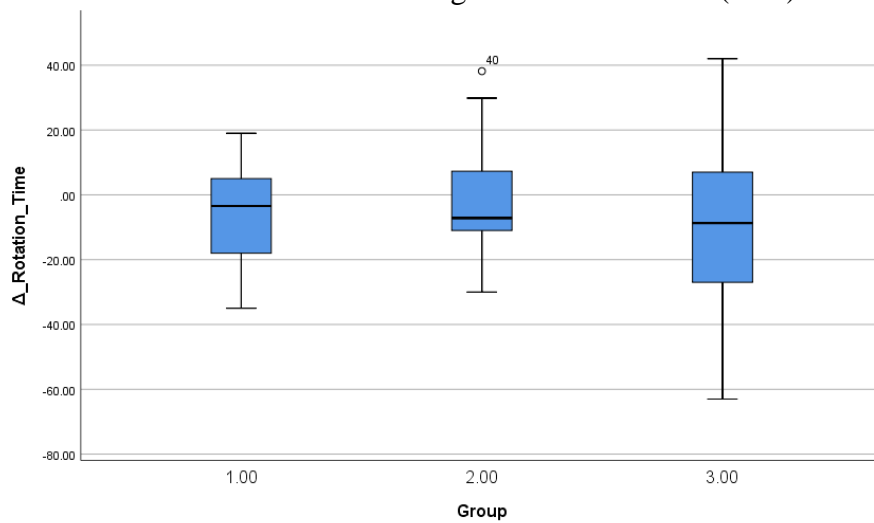
Cognitive Performance



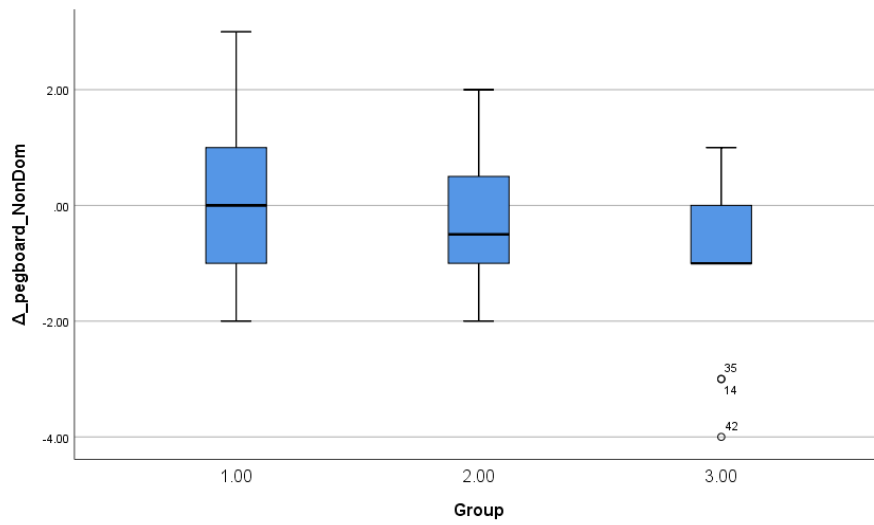
Visual Cognitive Performance (score)



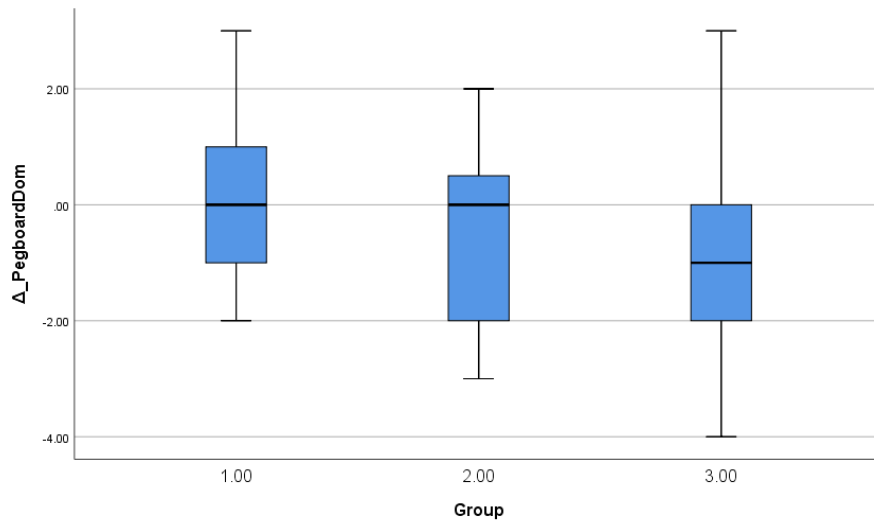
Visual Cognitive Performance (time)



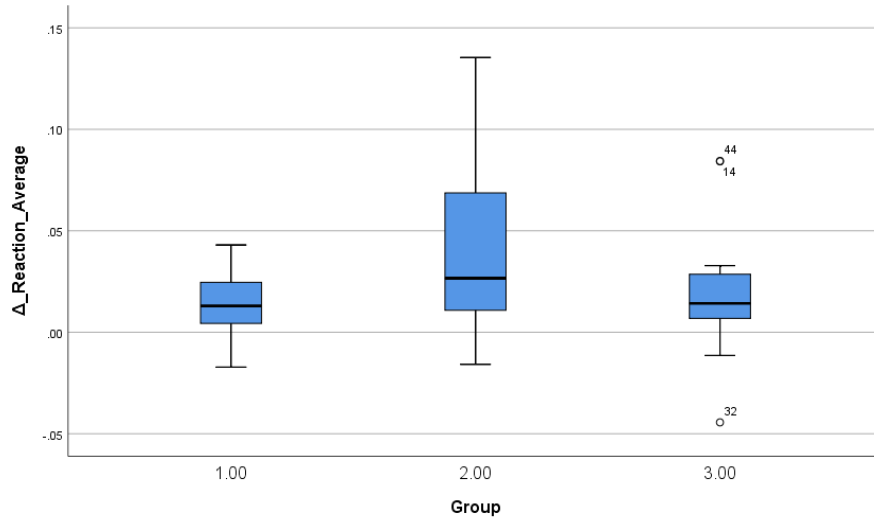
Physical Visual Performance (non-dominant)



Physical Visual Performance (dominant)



Cognitive Physical



Appendix 5 Letter of Contribution From the Automated User Interface Manager

RE: Joseph Smyth's input to Automated Driving Comfort & Wellbeing concept

3rd December 2018

Dear Alex,

I would like to call your attention to the contribution that Joseph Smyth made to the work that my team is leading, which is the development of the User Interface concept for Automated Driving.

As you may know, part of this concept may involve the utilisation of UI elements to provide the vehicle occupants with anticipatory cues of the vehicle motion, to contribute to their comfort and maintain their wellbeing.

Joseph's expertise was highly valuable for us last week to understand the theories underpinning comfort and wellbeing in motion. His opinion was also of great value when he carried out an expert assessment on the UI concepts developed at the end of the week.

I will definitely seek to bring his expertise into JLR's future expert sessions in the near future, if his PhD commitments allow it.

Yours sincerely,

A black rectangular redaction box covering the signature of Diana Franganillo.

Diana Franganillo

UK Assisted and Automated Driving UI Manager

Appendix 6 Letter of Contribution From the Interior Sensing Systems Lead Engineer

5th April 2019

Documenting contribution of Joseph Smyth (EngD student).

Throughout the month of March 2019, Joseph and I met on multiple occasions where his expertise was used to assist in the creation of the 'Motion Sickness Prevention Mechanisms' document. This document is designed to detail the scope of motion sickness research currently available, as well as to identify what research is needed for future JLR projects.

Through Joseph's contributions, it was clear he has a strong breadth of knowledge in the subject of motion sickness and his input was very valuable for this project, and therefore JLR as the sponsoring company. It was beneficial that Joseph had written a paper just recently for the AFE 2019 conference specifically looking at motion sickness preventions for autonomous vehicles, which he shared with me. We were able to use this papers' categorisation method to help structure the document – as well as fill in some of the research questions with what had already been highlighted in this paper.

Overall, it was very useful to have Joseph lend his expertise to this project and the project has benefited greatly from his involvement.



Signed Matt Symonds, Lead Engineer, Interior Sensing Systems, Jaguar Land Rover

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