A novel method for reducing motion sickness susceptibility through training visuospatial ability – A two-part study

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A Novel Method for Reducing Motion Sickness Susceptibility through Training Visuospatial Ability – A Two-Part Study

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   ABSTRACT Everyone can be susceptible to motion sickness (except those with complete loss of labyrinth function) and around one in three are known to be severely susceptible. Motion sickness can be experienced in many domains, including car travel, on a boat, using virtual reality headsets and simulator use amongst others. It is expected that due to potential designs and use cases, self-driving cars will increase motion sickness onset likelihood and severity for many car travellers. Besides medication, there are limited methods through which one can actively reduce their motion sickness susceptibility. This research develops a novel visuospatial training tool and explores the effect of visuospatial training on motion sickness. With a combined sample of 42 participants split between driving simulator trials (n=20), and on-road trials (n=22) baseline visuospatial skills and motion sickness were first measured. After a 14-day training period where participates completed 15-minutes of pen and paper tasks per day, it was found that visuospatial skills improved by 40%. This increase in visuospatial ability was shown to be directly responsible for a reduction in motion sickness by 51% in the simulator (with a 60% reduction in participant dropouts) and a 58% reduction in the on-road trial. This research has successfully identified a new method to reduce motion sickness susceptibility and the impact of these findings have wide reaching implications for motion sickness research, especially in the field of self-driving vehicles.

   INDEX TERMS Human Factors, Motion Sickness, Driving Simulator, Carsickness, Visuospatial, Mental Rotation

1. INTRODUCTION

Almost everyone is susceptible to motion sickness, and one in three are known to be severely susceptible [1]. In an automotive instance, it has been reported that 2/3 of people have suffered from motion sickness in cars [2], often referred to as carsickness. Symptoms of motion sickness are uncomfortable and include nausea, sweating and vomiting, amongst others [3]. Motion sickness is also known to negatively affect various areas of human performance [4] [5] [6]. Such findings bring concern about the feasibility of some automated vehicle concepts [5] – particularly in relation to proposed productivity gains that automated vehicles are expected to offer. Despite motion sickness being a known phenomenon for hundreds of years, little progress has been made in reducing motion sickness for the general population. There are a few areas of study in motion sickness 'management' where projects can be loosely categorised into design methods, medication, and habituation. Specifically related to the transport domain, there have been a small number of studies making design recommendations for example, work station user interfaces used in boats for navy staff [7], or automated vehicle cabin layout [8] [5]. However, the widespread benefit of specific designs recommendations are limited by the use cases themselves. For instance, for a display screen design to be effective one must be engaging with the display screen all the time. Medication (e.g. scopolamine), is another proven method to effectively reduce motion sickness where popular drugs have been broadly studied [9] [10]. However, all current effective anti-motion sickness medication bring unwanted side effects of drowsiness and fatigue – limiting suitability for widespread applications. Besides design and medication, habituation is considered to be a very effective method of reducing motion sickness susceptibility [11]. Although this too is somewhat limited where habituation requires repeat and frequent exposures to motion sickness-inducing environments to build a tolerance – an unpleasant experience for motion sickness sufferers and something that is actively avoided by many. It is also shown how anti-motion sickness medication reduces the impact of habituation itself [12].

There is a need to find new methods of reducing motion sickness considering the quantity of people who suffer from it and the broad impact it has on many people and industries. This need is further motivated due to the increased efforts to get automated vehicles on

the road by many manufactures. It is known that automated vehicles and many of their use cases will increase the likelihood of motion sickness onset and severity [8]. A new approach to reducing motion sickness susceptibility is required.

2. Background

Previous research using a driving simulator and 51 participants showed how motion sickness negatively affects various areas of human performance [4]. Within these core findings an unexpected, yet interesting relationship between driving simulator use, visuospatial performance and motion sickness was observed. Using a modified Mental Rotation Test (MRT) [13] to measure visuospatial skill ('mental rotation' as a subsection of visuospatial ability) it was observed that after using the driving simulator, average MRT scores increased and the average time taken to complete the task decreased. This was despite feelings of motion sickness and subsequent performance degradation in some key performance areas. Furthermore, it was observed that visuospatial skills for those with greater motion sickness improved more so than those with less severe motion sickness. These findings prompted further exploration to understand the extent to which motion sickness and visuospatial skills are related.

The direct relationship between the variables of motion sickness and visuospatial performance has rarely been looked at and as such, there is limited understanding of any affect between the two. One of the most commonly discussed links between these subject areas however is found within literature assessing gender and visuospatial skills, and gender and motion sickness. Across multiple studies, there is strong evidence that males outperform females across many different metrics of visuospatial tests. A meta-study summarised this sex effect across a variety of visuospatial tasks – finding particularly large sex differences in the mental rotation test [14]. The same direction of effect has been found in other mental rotation test research [15] as well as rod-and-frame tests [16] and water-level and cards rotation tests [17] amongst others. Sex makes a significant and direct impact to the prediction of visuospatial performance [17].

One key differentiating factor between males and females, which is commonly referenced as a reason for this difference in visuospatial abilities, is the difference in sex hormones. For example, it has been shown how the fluctuation in hormones during the female menstrual cycle can affect visuospatial performance [18], where visuospatial performance is most drastically reduced when menstruating. It was also shown that androgen deficient men (androgens being male sex hormones, including testosterone), were less skilful at visuospatial tasks [19] than men with normal or higher androgen levels. A further study looking at people undergoing hormone replacement therapy showed that higher testosterone levels resulted in females improving their visuospatial ability whereas lower levels of androgens and higher levels of oestrogens resulted in decreased visuospatial ability for males [20]. As well as concluding upon the link between sex and visuospatial performance, these findings importantly reveal that visuospatial skill is a dynamic skill, and something in which people can become better (and worse). Visuospatial ability is dynamic and trainable - further supported by the previous simulator study where simulator exposure seemed to have a training effect [4]).

Similar to the sex effect in visuospatial performance, there is also a strong sex effect for motion sickness susceptibility. The literature strongly supports that women are more susceptible than men to motion sickness [21] [22] and this is widely accepted in the field. Considering 'visuospatial skill and sex' alongside 'motion sickness and sex' a potential link between visuospatial ability and motion sickness susceptibility is identified. When ignoring sex, these relationships suggests that those with lower visuospatial performance are also those who are more susceptible to motion sickness, and vice-versa those with greater visuospatial performance are less susceptible to motion sickness. Research looking specifically at these two areas is sparse. One study has directly reported that within their sample, females performed significantly more poorly than men on spatial ability tasks (an area of visuospatial ability) and reported significantly more bouts of motion sickness [23]. They also showed how males with poorer spatial abilities were more prone to motion sickness [23]. These results were based on participants' self-reporting previous bouts of motion sickness through a motion sickness questionnaire, and despite the lack of direct motion sickness experimentation, these are important findings in supporting a potential relationship between visuospatial skill and motion sickness.

Considering previous simulator-based experimentation [4] and the literature presented it is possible that there is a link between visuospatial skills and motion sickness. Therefore, the concept of training visuospatial ability in an effort to reduce motion sickness was considered a reasonable pursuit. The previously mentioned simulator user trial indicated that visuospatial skill may be improved or 'trained' through exposure to a challenging visuospatial environment (a driving simulator in this instance). These findings, considered alongside the literature linking motion sickness to visuospatial skill [23] and the literature discussing manipulation of visuospatial skill (albeit through hormone manipulation) [20] allowed the formation of two research questions (RQ's) which this paper will address:

RQ 1 – Is it possible to improve visuospatial ability through visuospatial training?

RQ 2 – Does increasing visuospatial ability decrease motion sickness susceptibility?

3. Method

A two-part user trial was conducted in order to address the research questions. Part 1 was a simulator-based study using the 3xD simulator at the University of Warwick [24]. Part 2 (a different set of participants) was an on-road study where participants sat as passengers whilst being driven around UK roads, somewhat imitating a fully autonomous vehicle experience. Having this two-part study allows for further exploration of the finding previously found in the simulated environment – where the visually demanding nature of a simulator may be a dependent factor for the visuospatial effect previous observed. Subsequently, the on-road study provides the opportunity to explore the 'real-world' impact to address the utility of any effect for on-road motion sickness. For both Part 1 and Part 2, the overall methodology remains as similar as possible to ensure validity and enable comparability in results. Baseline visuospatial performance and baseline motion sickness susceptibility for participants were first measured. Participants were then given a visuospatial training pack to complete over 14 days. After training, comparative visuospatial skills and comparative motion sickness susceptibility were measured. This methodology allows the researchers to examine if the prescribed training pack improves visuospatial skill (RQ 1) and if so, how this visuospatial ability has affected their motion sickness susceptibility (RQ 2). To analyse the data collected, dependent sample t-tests (paired t-tests) were used where assumptions for the test were met. The data will be analysed through the comparison of group average scores pre-training period, to post-training period for both MRT score and motion sickness severity/susceptibility. Part 1 (the simulator study) consisted of 20 participants with 10 males (50%) and 10 females (50%). Part 2 (the on-road study) consisted of 22 participants including an experimental group of 15 participants, and a control group of 7 participants. The experimental group consisted of 6 males (40%) and 9 females (60%) and the control group had 3 males (~40%) and 4 females (~60%). For part 2, with a control group, mixed ANOVA's can been used to understand the relationships between visuospatial training and motion sickness.

Figure 1 below, represents graphically the process of this user trial for both simulator and on-road trials:
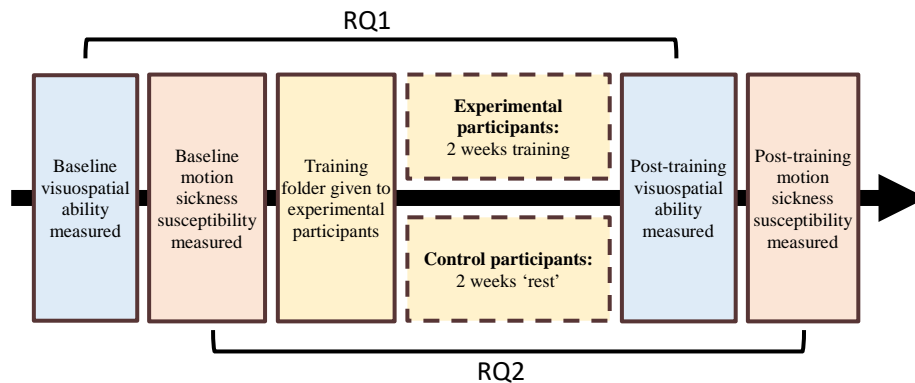

Figure 1 Design of User Trial

3.1 Visuospatial training

To train visuospatial skills for both Part 1 and Part 2 participants, a training regime was needed. Looking to the literature, the majority of research discussing visuospatial skill identifies repeat visuospatial task exposure as a mechanism of improving performance. For example, there has been strong evidence that regularly playing video-games improve visuospatial performance [25]. Similarly, repeat use of CAD programmes (Computer Aided Design) also seems to improve visuospatial ability [26], and as previous research shows, so does one-off driving simulator use [4]. Considering prescribed training methods, literature discussing methods to self-train visuospatial skills (ignoring hormone and drug related studies) is sparse. Methodologies behind the few studies that exist rely on repeat exposure to, and practice with, complex visuospatial tasks as a method to improve skill through reinforcement learning. The main application of such research projects tends to be relation to early-learning research – for example [27].

Considering the relative support for repeat exposures as a method of training, it was decided that a training pack would be designed which requires participants to engage with different visuospatial tasks, utilizing this reinforcement learning technique. Pen and paper based activities were considered to ensure access to facilities/equipment was not a limiting factor for this initial experimentation. The training activities would be based on existing visuospatial assessments and tests. A 14-day training period was chosen for two reasons. Firstly, to minimize the factor of habituation between the baseline and comparative motion sickness exposures (where the training period is placed between the baseline and comparative exposures). Secondly and purely practically, 14-days was thought to be long enough to see some effect from training, but not too long to risk over burdening participants. It was decided that participants should complete one activity per day where it was aimed that each activity should take around 15-minutes to complete, again to combat the risk of participants withdrawing from the study if the training task was too long. In total, fourteen training tasks were compiled into a folder, one for each day.

To identify useful tests to include in the training pack, a paper specifically discussing visuospatial assessments was explored [28] (p.257). This was the primary source used for the initial search for suitable, free to access, pen and paper tasks. Three further sources included a website dedicated to testing and training visuospatial abilities (amongst other traits) [29], a book published about mechanical and spatial aptitude [30] and a US army flight aptitude test document [31].

Table 1 below gives the title, day number and source for each of the training tasks selected - there was no benefit in randomizing the testing order between participants as this initial study was not looking at the optimum training techniques, but rather if there is any affect between the training and motion sickness – regardless of what training task was most effective.

Table 1 - Visuospatial training tasks

Day	Test name	Source
1	Image analysis	[32]
2	Paper folding task 1	[33]
3	Perdue Spatial test	[34]
4	Block counting	[35]
5	Unfolded cube test	[36]
6	Paper folding task 2	[37]
7	Understanding patterns	[38]
8	Spatial analysis task	[39]
9	Embedded images 1	[40]
10	Rotated blocks	[41]
11	Mixture of tests	[42]
12	Embedded images 2	[43]
13	Matching pieces and parts	[44]
14	Rotated shapes	[45]

Participants were given a full explanation of the training folder, and instructions were included within the folder. Participants were asked to complete one test per day and to note down the time taken to complete the training. If participants finished before 15-minuites they were are asked to go through and check their answers until the minimum of 15-minutes had been used - ensuring all participants had at least 15-minutes of 'exposure' to training per day.

In order to measure visuospatial ability (for both baseline score and post-training comparative score) the mental rotation test (MRT) [13] was used. Two MRT tests were assembled using the CAD recreated images by [46]. These paper-based tests involve the presentation a 3D shape (the 'target' shape) followed by four similar 3D shapes. The task is to identify which two of the four shapes is the same as the 'target' shape, despite being rotated into a different orientation. Each test was comprised of 18 questions and participants had three minutes to complete as many questions as possible. The score was derived from the total number of correct answers, where a correct answer was given only if they identified both correct shapes. As the MRT was to be used twice in total (once as a baseline before visuospatial training, and once as a comparative measure after visuospatial training) two separate tests were compiled. Each test consisted of a random selection of questions from [46] and these tests are to be given to participants in a random order. An example question from the MRT is presented below in Figure 2 where the target shape is to the left.
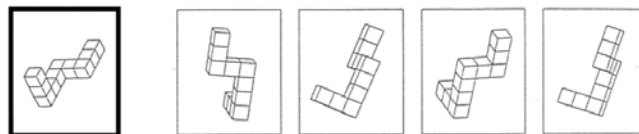

<div align="right">

Figure 2 – Mental Rotation Test (MRT) Example

</div>

3.2 Motion Sickness Measurement

To measure motion sickness two subjective scales were used in both simulator and on-road trials. The Simulation Sickness Questionnaire (SSQ) [47] is a validated and commonly used assessment method for the measurement of motion sickness. The SSQ is a 16-item questionnaire, using a 4-point Likert-type scale to report on the presence and severity of various symptoms after a motion sickness exposure. The SSQ provides an overall motion sickness score as well as subscales of Nausea, Oculomotor and Disorientation scores - all of which are calculated using weightings. Despite originally being designed for simulator use, The SSQ's utility also extends to non-simulator motion sickness assessments and has been used for on-road studies previously, for example: [48]. To capture 'real-time' motion sickness, the Fast Motion Sickness Scale (FMS) [49] was used. The FMS involves asking

participants to rate (once every minute, during the exposure) their overall motion sickness on a scale of 0-20 whilst considering a combination of nausea, general discomfort, and stomach problems.

3.3 Part 1 – A Simulator Study.

Participants who took part in a previous user trial by the same authors [4] - which used the 3xD Driving Simulator at the University of Warwick [50] were recruited for Part 1 of this user trial, where baseline motion sickness susceptibility on a pre-designed test route had already been measured. In total, twenty participants were recruited for Part 1 of this user trial including 10 females and 10 males. They were selected as they were known to be susceptible to motion sickness (as identified from data from the previous user trial). Upon recruitment, participants completed a MRT test to measure baseline visuospatial ability. Baseline motion sickness susceptibility had already been measured during the first user trial, five months previously [4] where SSQ and FMS data were collected. Participants were all given the visuospatial training folder and begun a 14-day training period.

After 14-days of visuospatial training, participants attended their booked time slot in the 3xD simulator at the University of Warwick. Before the driving scenario, visuospatial ability was assessed again using another 3-minute MRT activity. Participants were then introduced to the 3xD simulator using the same method and explanations as used in the previous user trial [4], with a full explanation of the simulator, driving route and instructions. The driving scenario was identical to that of the previous user trial, again with no other traffic on the road, audible navigation instructions and frequent speed limit signs to ensure participants were progressing through the route at the same pace. As before, the route took approximately 30-minutes to complete, with the first 5-8 minutes acting as a familiarization run, whereby the road was straight with a 30mph speed limit. Gentle bends were gradually introduced after the familiarization run along with increased speeds. The final 10-minutes of the route were particularly challenging and involved increasingly complex bends and junctions. The route was designed in such a way that participants never drive on the same part of the road in the same direction more than once (i.e., is a continuous track, rather than a loop) so it was highly unlikely that familiarization to the route between the two exposures (five months apart) would be a factor. During the drive, participants were asked to rate their subjective motion sickness again using the FMS - as they were in the previous user trial [4]. The cabin temperature was again maintained at 21 Degrees Celsius throughout the drive using the simulators in-build climate control and was also measured using an external electronic thermometer to ensure accuracy. Upon completion of the driving scenario (even if participants asked to end it early due to severe motion sickness), participants came back to the control room and completed the SSQ.

To ensure this second exposure to the simulator (post visuospatial training) was as similar as possible to the first (pre-training) exposure [4] participants were recruited to attend the simulator at a similar time of day for both exposures. This ensured factors such as fatigue and food intake routine (which could affect motion sickness) were as controlled as much as practically possible. The 'baseline' user trial took place between 2nd-13th October 2017. The second user trial (which constituted 'Part 1' of this paper) took place between 7th-9th March 2018, giving participants a 5-month period between simulator exposures. Participants were screened upon recruitment and were only eligible to take part if they had not used a simulator, or any other virtual reality (VR) experience within 14-days of their planned simulator drive. No participants had used a simulator or VR since the first user trial. It was imperative that there was a reasonable time delay between repeat simulator exposures, so that habituation to motion sickness was not a factor. It is known habituation to a motion sickness inducing source can reduce subjective symptom severity [12]. The literature suggests that when looking to habituate someone to a motion sickness task, repeat exposure should take place within one week [51], which is supported by [52]. It was concluded that with habituation controlled (i.e., exposures took part more than one-week apart) and besides the uncontrollable factor of female menstruation (as per [18]), the only variable that would be changing in-between the two exposures was the visuospatial skill as influenced by the training. It was concluded this method was a valid way of assessing the influence of visuospatial training on motion sickness.

As a gesture of goodwill for participants giving up their time to take part in this trial, participants were given £40GBP in shopping vouchers. Before taking part in this study all participants were given a comprehensive participant information sheet and signed an informed consent form. Part 1 of this user trial was approved by The University of Warwick BSREC (REGO-2017-2090 AM01).

3.4 Part 2 - An On-Road Study.

Part 2 of this project involved the recruitment of a further 22 participants (9 males and 13 females) and this cohort was independent to Part 1 of this project, where participants could not take part in both Part 1 and Part 2 to reduce any learning effect for the training tasks. Of this group, seven participants (3 males, 4 females) were used as a control group where the remaining 15 participants would form the experimental group. The control group was sampled randomly and aimed to have a comparable male/female ratio to the experimental group.

The methodology was kept as similar as possible to Part 1 described in this paper. The primary difference was the motion sickness exposure task, i.e. using an on-road vehicle. For this trial, participants attended a booked timeslot at either 9am, 10am or 11am. On their booked timeslot participants were met at a common location in Coventry, UK where they completed both a baseline mental rotation test (as in Part 1), and a demographics questionnaire. Participants were then driven on a pre-planned route around Coventry which took approximately 30 minutes to complete. The route comprised on a mixture of motorway, city and rural roads. A trained driver was used, who had practiced driving the planned route and drove following a strict routine to ensure all drives were as similar as possible. The driver was not aware whether a participant was allocated to the control or experimental group. The participants (one at a time) sat in the rear, near side seat of the 2018, right-hand drive Range Rover Sport L494 fleet vehicle supplied by Jaguar Land Rover UK. The driver sat in the front, off-side driving seat and the lead researcher sat in the front near-side passenger seat. The cabin temperature was maintained at 21 degrees Celsius for all participants and an in-cabin thermometer along with the vehicles' sophisticated cabin climate system ensured temperature was consistent.

All 22 participants completed drive 1, and 15 participants were then given the visuospatial training pack as used in Part 1. The control group (n=7) received no training pack. 14 days after their first exposure, participants returned for their second drive and were driven around the same route, at the same time of day, at the same pace. To ensure repeatability and ensure participants were acting in a similar way for both drives, they were asked to complete a reading task throughout both journeys. The reading task used the headrest-mounted display in the Range Rover, which displayed static text for 30 seconds at a time, with a 30 second rest period in-between blocks of text to minimize fatigue. The screen was 8'' inches from corner to corner. The text was taken from an adult learning website [53] designed as practice material for people learning to read so the complexity of the writing was uniform and achievable for all participants. Blocks of text were displayed randomly between participants so the participant received different text for both drive 1 and 2. Two photos in Figure 3 below illustrate the user trial set-up:

Figure 3 On-Road User Trial

No form of payment was given to participants for Part 2 of this study. Before taking part in this study all participants were given a comprehensive participant information sheet and signed an informed consent form. The study was approved by the Jaguar Land Rover research ethics committee (Reference :12323185).

4. Results

4.1 – Visuospatial Ability (RQ1)

Looking first at how visuospatial training affected visuospatial ability (addressing RQ1) participants from both simulator and on-road studies were analysed separately and together. For the simulator trial, mean MRT score increased (pre to post training) from 5.10 to 7.05, showing a mean average increase of 38.24% which was statistically significant according to the paired t-test $t(19)=-4.278$, $p<0.0001$. For the on-road study 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% which was statistically significant $t(14)=-5.150$, $p<0.001$. For the control group (i.e., those who received no visuospatial training), average MRT also appeared to increased slightly from 4.42 to 5.71, however this was insignificant $t(6)=-1.89$, $p=0.108$.

Combining all experimental participant from both simulator and on-road trials it was shown that MRT scores improved by 40.38%, which was proven to be statistically significant $t(34)=-6.578$, $p<0.001$. Visuospatial skill was therefore successfully improved through 14 of training exercises, completed for 15 minutes per day. As two MRT tests were used for each participant, one as a baseline and the other after the training period the order in which they received the tests was randomised. It was also shown that there was no significant difference between baseline scores for the two MRT tests where $t(16)=0.566$, $p=0.579$ showing they were of equal difficulty and the measurement was valid. As the two experiments controlled (as far as practically possible) all other factors which may affect motion sickness, RQ2 investigating the impact visuospatial training has on subjective motion sickness ratings were then studied.

4.1 Visuospatial ability and motion sickness susceptibility

i) Part 1- a Simulator Study

An exploratory analysis of SSQ data is presented below in Table 2, 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 2 Exploratory Analysis of SSQ Scores (Simulator Trial)

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

Looking at subjective sickness scores collected using the Simulator Sickness Questionnaire (SSQ) for the whole group in Part 1, average total SSQ score decreased by 51.48% from 66.299 to 32.164 after visuospatial training. Using a Paired T-test this reduction in motion sickness was shown to be significant $t(19)=4.903$, $p<0.001$. The SSQ Subscale scores were also significantly reduced with Nausea decreasing by 40.36% $t(19)=2.175$, $p=0.043$, Oculomotor by 46.94% $t(19)=2.597$, $p=0.018$ and Disorientation by 53.11% $t(19)=3.236$, $p=0.004$. This data has been plotted graphically below in Figure 4 where error bars represent standard deviation:
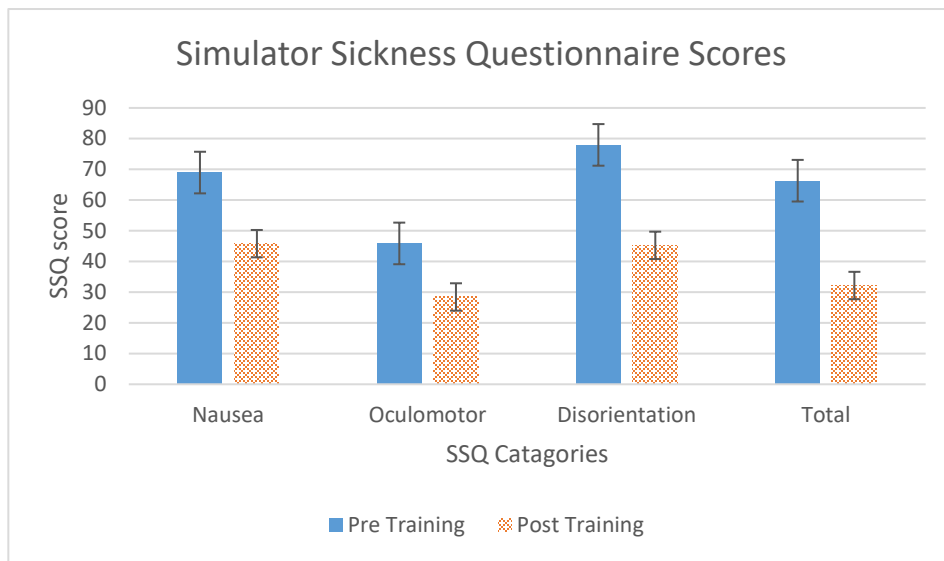

Figure 4 SSQ Scores Simulator Study
Error Bars: Standard Deviation

The author of the Fast Motion Sickness scale (FMS) recommends that the FMS Peak score is the most appropriate metric on which to analyse one's subjective motion sickness [49]. FMS peak is the maximum score achieved throughout an exposure. It was shown in this user trial that after visuospatial training, FMS peak reduced from an average of 10.8 to 8.4. This 22% decrease in FMS peak was shown to be statistically significant $t(19)=3.066$, $p=0.006$. Plotting only participants who completed the entire scenario both pre-training and post-training Figure 5 below plots the average FMS score at each minute of the driving. A visible reduction in motion sickness was observed between minutes 10 – 12 which is likely to align with the motorway section of the route which was a particularly straight section and driven at a constant speed.
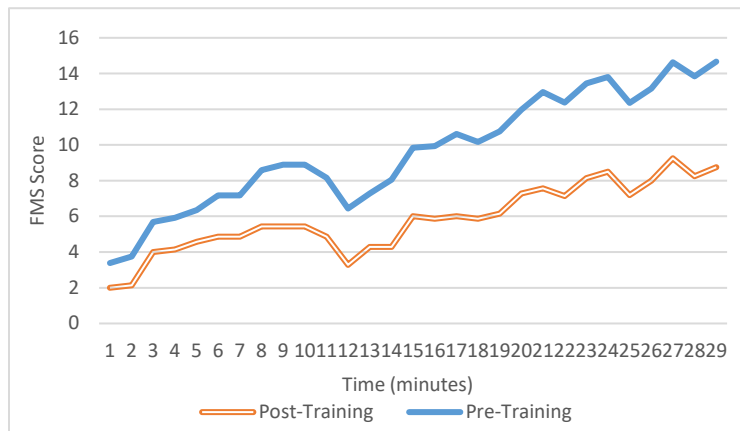
Figure 5 FMS Scores Throughout the Simulator Driving Scenario

Further to the subjective motion sickness assessment, it is also possible 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 6. The error bars indicate the standard deviation.
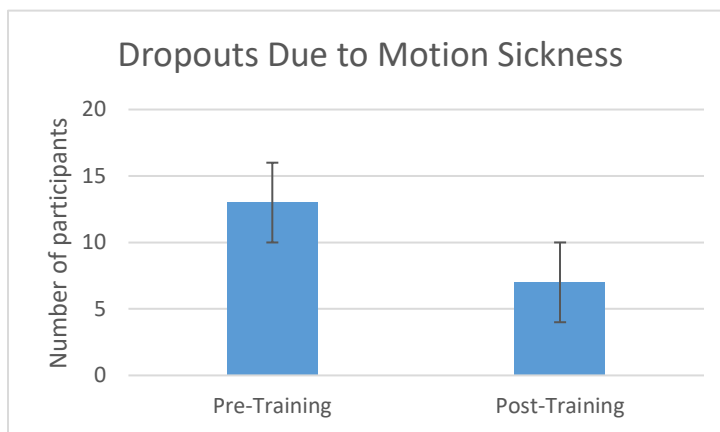

Figure 6 Dropouts Due to Motion Sickness
Error Bars: Standard Deviation

In the first (baseline) exposure, 13 (65% of) participants ended the simulator driving early on account of severe motion sickness. During the second exposure, after training, only seven (35%) of participants ended the driving early on account of severe motion sickness. Between the two studies there was a 46% reduction in participant dropouts which was a significant difference $t(19)=-2.854, p=0.010$. Looking at the participants who dropped out in both studies (n=7) as a group, it was interesting to see that these participants had not improved their visuospatial skills through training $t(6)=-1.327, p=0.233$. Looking at the raw data however, four of the dropouts did show an improvement in their visuospatial ability and for these four it was shown that even though they dropped out of both studies, average time spent in the simulator before dropping out increased by 104.87% from 10.25 minutes pre-training training, to 21 minutes post-training. The reliability of statistical analysis on a sample size of n=4 is tenuous, but the increase in drive time was significant $(t(3)=-3.507, p=0.039)$ where $p<0.05$. There was no change in drive time for the remaining three dropouts, in fact, for this group drive time decreased slightly and motion sickness score was also unchanged

Ss 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.

ii) Part 2 – an On-Road Study

For the baseline drive, one participant ended the study early due to motion sickness, however after training no participants asked to end the study early. An exploratory analysis of the data for the experimental participants has been presented below in Table 3:

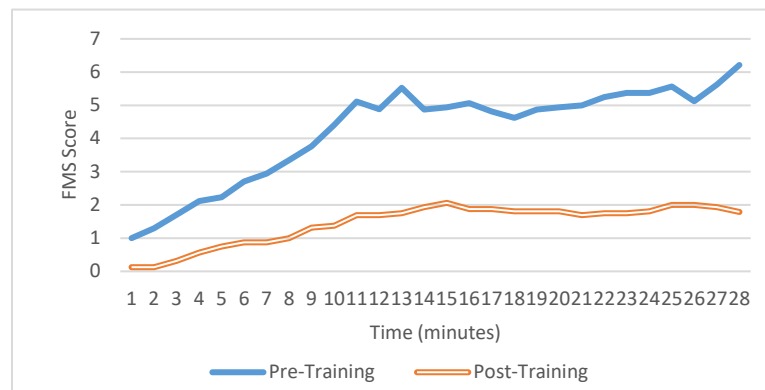*Table 3 Exploratory Analysis of Motion Sickness for the Experimental Group*

Motion Sickness category	Pre-Training Mean	Pre-Training SD	Post-Training Mean	Post-Training SD	Δ Mean
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

For the experimental group, the average total SSQ score decreased by 58.50% from 46.87 to 19.45 $t(14)=5.456$, $p<0.01$. All SSQ subscales were also significantly reduced where nausea decreased by 68.08% $t(14)=5.924$, $p<0.01$, oculomotor decreased by 41.97% $t(14)=3.956$, $p<0.01$ and disorientation decreased by 56.89% $t(14)=2.866$, $p<0.01$. This data has been plotted graphically below in Figure 7:
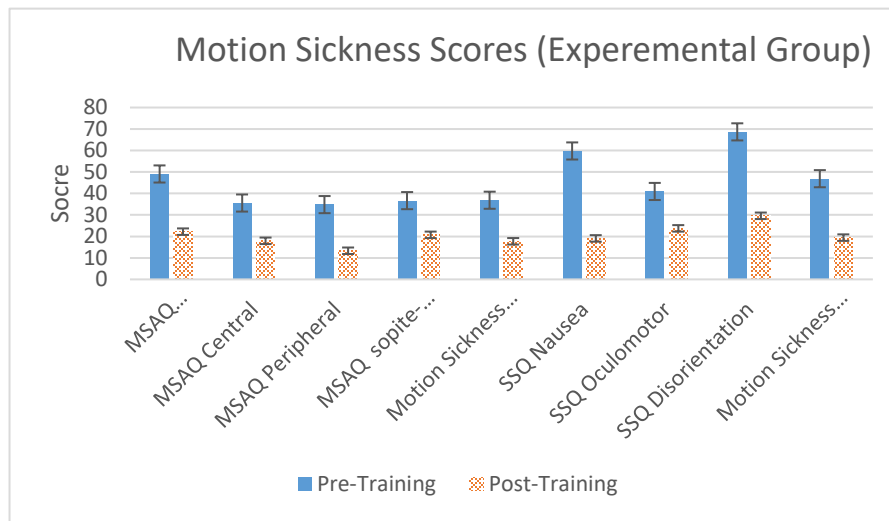
Figure 7 SSQ Scores On-Road Study Experimental Group
Error Bars: Standard Deviation

For the experimental group, FMS peak score reduced from an average of 7.8 to just 3.1 (a 53.03% reduction) which was proven to be statistically significant $t(14)=4.817$, $p<0.01$. Average FMS score per minute for the experimental group is presented below in Figure 8:

Figure 8 FMS Scores Throughout the On-Road Driving Scenario (experimental group)

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 4:

Table 4 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
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

SSQ total score increased by 3.70%, nausea decreased by -6.66%, oculomotor increased by 4.44% and disorientation increased by 29.16%. None of these changes were significant according to a Paired T-test where $p>0.05$ in all cases. The control group results are presented graphically in
Figure 9:

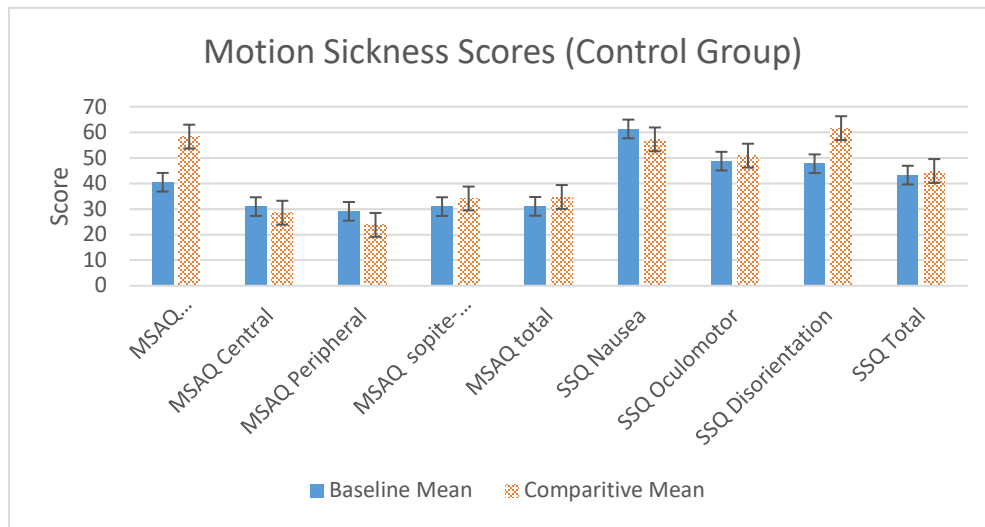*Figure 9 SSQ Scores On-Road Study Control Group*
Error Bars: Standard Deviation

Looking at the FMS scores for the control group, there was no significant change in FMS peak between pre and post training period $t(6)=0.460$, $p=0.662$. Average FMS score per minute for the experimental group is presented below in Figure 10:
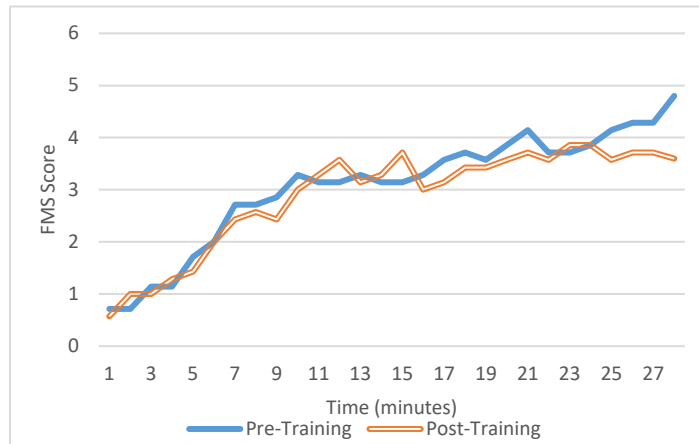

Figure 10 FMS Scores Throughout the On-Road Driving Scenario (control group)

Group data (i.e., control and experimental 'groups') for the on-road study have been individually analyzed using paired t-tests. However a more robust method using 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 variable. The SSQ total 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. However, given the uneven groups it is understood that the M Test is not necessarily robust, so this can be 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) ($F1,20) = 14.203$, 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 11 below, it is clear that the experimental group significantly reduced their scores where the control group did not.
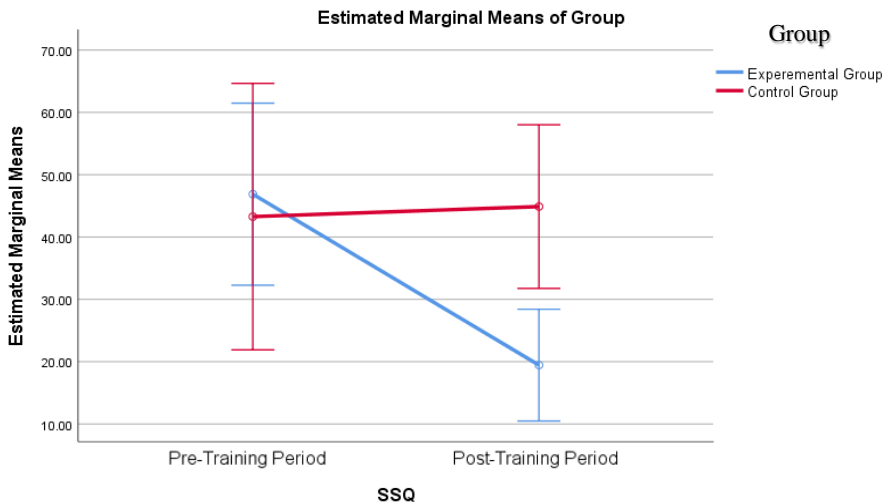

Figure 11 Estimated Marginal Means for Pre and Post MSAQ Score Control Vs Experimental
Error Bars: 95% CI

5. Discussion

There were two primary aims of this paper as detailed by RQ1 and RQ2, namely if it is possible to increase visuospatial ability through training, and whether or not this increased visuospatial performance would decrease motion sickness susceptibility and severity. To assess this, a two part user trial was devised. Part 1 included a use of a driving simulator, and Part 2 used a different set of participants for an on-road study – the total sample size was 44. Baseline motion sickness susceptibility and baseline visuospatial performance were assessed for participants in both studies before a 14-day visuospatial training period commenced – where participants trained their visuospatial skills using a novel pen and paper visuospatial training pack. After training, comparative motion sickness and comparative visuospatial performance were measured. Through the careful design of methodologies for both Part 1 and Part 2 it was considered that visuospatial skill was the only independent variable and only factor, in relation to motion sickness susceptibility, which was changed between the two exposures. The methodology provided a direct comparison of motion sickness state before and after visuospatial skill training. Hormone change throughout the female menstrual cycle was the only known significant factor that may affect motion sickness, but could not be controlled for either Part 1 or Part 2.

The data collected and presented in this paper shows how visuospatial skill, as measured by the Mental Rotation Test (MRT) was significantly improved for participants after completing the 14-day visuospatial training tasks in both Part 1 and Part 2 of the study. With an average improvement in visuospatial skills of 40.38% it is with good confidence that it can be concluded that participant's visuospatial abilities were improved through this training pack (RQ1). The control group used in Part 2 of this study confirmed that visuospatial performance change was indeed linked to the training pack provided where the control group received no training pack and there was no significant change between their visuospatial performance in the 14 day period. Further analysis of the two MRT test used, showed there was no difference in baseline scores between the two tests, showing they were of equal difficulty and therefore assures validity in the experimentation. No literature was found directly proposing methods for self-led visuospatial training. Although some research has previously measured how people commonly involved with CAD [26] and videogame exposure [25] have increased visuospatial ability. Some research associated with directed visuospatial training involved a 10-week, 20 hour programme whereby teachers led classes for (10-12 year olds). Through their spatial reasoning training method, a significant increase in mental rotation of 23% was observed [54]. Despite a lack of similar studies to compare the effectiveness of this training

pack to, it is thought that this was a reasonably strong effect, however, it is sill believed there is significant room for further improvement.

For Part 1 of this study it was shown that visuospatial training reduced participant dropouts due to severe motion sickness by 46%. If removing participants who did not improve their visuospatial ability (as is perhaps more suitable to address RQ2), this reduction in dropouts increases to 60%. This was the first indication that training visuospatial performance may reduce motion sickness. A reduction in dropouts is considered to be a very strong indicator of reducing motion sickness, where the objective action of no longer being able/willing to tolerate an environment is less open to subjective bias than a questionnaire. Looking to other research concerned with simulator dropouts, one study developed both a participant screening process (to remove those who are known to be highly susceptible to motion sickness) and an enhanced familiarisation process, again aimed to reduce sickness [55]. This research was successful for reducing participant dropouts across a sample of 625 participants by 8% (from 24.5% to 16.6%) through the application of the screening criteria. Further, the familiarisation method reduced dropouts from 37.5% to 18.75% (a 18.75% reduction) with a sample of 20 participants per group. Comparing these results to the visuospatial training method, the visuospatial appears to produce a greater reduction in dropouts. During the on-road study (Part 2 of this research), only one participant ended the study early, where at 13 minutes into the drive they reached an FMS score of 17 out of 20. This same participant, after visuospatial training completed the entire drive with a peak FMS score of just 7. It is likely that more dropouts were seen in the simulator as it is more of an extreme environment, which is unfamiliar to many. Participants were likely to have more experience in traveling in a car as a passenger, and therefore were more habituated to, and understanding of the road study.

Participant dropouts in simulator studies is a significant drawback of simulator-based research projects, where it wastes time and money if participants have to end the study early. Some studies have reported dropout rates of 59% [56] and up to 71% [57] (p.259). Although these are considered high, a 'rule of thumb' in driving simulator studies is to expect approximately 25% of participants to dropout due to severe motion sickness. Further to time/money, the known sex effect on motion sickness results in another drawback, where a resulting data set (after dropouts) is likely to contain an unrepresentative sample. This unrepresentative sample is also a reason why a motion sickness focused exclusion criteria should be used with caution, where it is likely more females will be excluded from studies than males. It is therefore beneficial to see that training visuospatial skills reduces dropout rates in simulator trials and proposes a possible solution to this problem. A 14-day training period may not be viable for some purposes, but with further refinement of a training method, the scope for application may be developed.

In Part 1 of this study, the simulator trials, SSQ scores decreased by an average of 46.95% after the visuospatial training period for the group. The subcategories also each saw a decrease in average scores, Nausea by 40.36%, Oculomotor by 46.94%, and Disorientation by 53.11%. All of these findings were proven statistically significant and are considered to be strong results comparative to other motion sickness research studies. To support these SSQ findings, the real-time measure of motion sickness using the FMS scale saw a significant reduction in FMS peak scores of 22%. Both the FMS and SSQ are pre-validated and effective methods of measuring motion sickness state, however, as with many questionnaires, their reliability is dependent on subjectivity. For instance, one persons 'minor' discomfort, may be another persons 'severe'. This factor was controlled somewhat through the repeat-measure study design however, where the change in score was of more interest than the absolute scores.

Due to the reversal of afferent and efferent motion cues, there are differences between motion sickness profiles in simulators and in rea 'real-world' environments (such as carsickness). Specifically, simulators are thought to have a greater oculomotor discomfort aspect, which is logical considering the presence of large display screens. The data indicated that indeed oculomotor discomfort was greater in the simulator trial compared to the on-road trial. However, direct statistical comparison is not possible due to the drastically different scenarios (Part 1 involved participants driving in a simulator, Part 2 involved participants as passengers and the driving route was different to the simulator route). It is interesting to note however that the largest difference in the SSQ subscale scores for both baseline and post-training score is in the Nausea subscale. It was previously discussed that the Nausea scale was a good indicator of propensity to drop out of a trial due to motion sickness [4] so comparing the dropout rates from the simulator to the real-world study, this appears to be in support of this idea. Looking at baseline scores, the profiles of motion sickness appear to be the same where the subcategories can be ranked as D>N>O for both scenarios. This profile is in disagreement with the profiles explained in previous research [58], however this does bode well for comparability between the two scenarios in Parts 1 and 2.

Part 2 of this study looks to see if the reduction in motion sickness due to visuospatial skill, as observed in the simulator, is transferable to the 'real-world' as the profiles in motion sickness may suggest. The scenario devised in Part 2 somewhat imitated the experience of a fully autonomous vehicle, where participants could sit and be driven around. Looking at the experimental group, it was seen that visuospatial training was responsible for a reduction in average total SSQ scores of 58.50%. Again, the subcategories were all also reduced: Nausea by 68.08%, Oculomotor by 41.97% and Disorientation by 56.89%. All of which were significant. The real-time measurement of motion sickness using the FMS also showed a significant reduction of 53.03% for the experimental participants. Further to this, it was shown that for the control participants (i.e., those who received no training), their motion sickness

scores remained statistically unchanged. The scale of these findings was initially unexpected, where due to the visual nature of the visuospatial training it was expected that the on-road drive, with relatively little visual demand may not benefit quite as much, compared to the simulator. It is noted as somewhat of a limitation to this project that the control group was not a true 'control' where they completed no exercises at all whereas the experimental group did complete training tasks. Ideally the control group should have completed a 14-day pen and paper training period for completely unrelated tasks – this ensuring the experience was the same but the tasks completed would be unrelated to visuospatial skills. However, as neither the control or experimental group knew about the groups or the purpose of the trial there is unlikely to be any significant effect of this.

It is not possible to directly compare the difference between simulator and on-road motion sickness as the two tasks (driving a simulator in Part 1, and being driven on the road in Part 2) are not directly transferable. Therefore it cannot be known the extent to which the scenario may be impacting severity of motion sickness. However, the effect of training visuospatial ability has been proven to be impactful for both motion sickness in simulators and in cars. The finding that this effect was useful for both on-road and simulator-based motion sickness is of significance for future research. Because it is known that this effect is useful and comparable for both environments, it is recommended that future refinement of this method can use simulators for the majority of experimentation, which are quicker, cheaper, safer and more convenient that on-road studies.

This is the first time that this effect has been evidenced and stands as a starting point for what may become a larger field of study. At this point the reason for this observed effect is unknown and we may only hypothesise about the underlying mechanism responsible for this relationship between visuospatial skills and motion sickness. It is possible that visual dependency plays a role in this effect, where visual dependency is the term for when people rely to a greater extent on their visual system for identifying motion instead of their vestibular or somatosensory systems – see [59] Previous research in this field is sparse – although one paper was identified discussing motion sickness susceptibility and impact of visual-cues to motion sickness onset [60] which links motion sickness susceptibility and visual dependency somewhat. It is conceivable therefore to consider that through reducing visual dependence (though, say, training visuospatial skill to enhance somatosensory dependence) one may be able to reduce susceptibility to motion sickness. In fact previous literature has discussed how repeat visual motion stimuli can reduce visual dependence and manage (somewhat) postural sway [61]– although the debate around postural sway and motion sickness is still ongoing.

It may also be possible that an enhanced ability to resolve conflicting motion cues 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 [62]. This highlights the consideration 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.

6. Conclusion

The user trials reported in this paper, are the first to confirm the link between visuospatial ability and motion sickness. This paper also shows that not only is there an empirically proven link between the two, but that training of visuospatial ability actually leads to a reduction in motion sickness. The importance of this finding is remarkable for both academia considering the contribution this project makes to our understanding of motion sickness, but also to the automotive industry especially given the increased research emphasis on motion sickness with the growth of driverless, or self-driving cars. We have shown that it is possible to improve visuospatial skill through pen and paper training task, and that this improvement was directly responsible for a large, and statistically significant, reduction in motion sickness, both assessed by severity (as indicated by three independent motion sickness scales) and onset likelihood (as indicated by dropout rates).

The scope of this project was focused on the automotive industry, and considered applications to driving simulator use and automated vehicles. However, it is conceivable that that this relationship may be transferable to other industries. The applications of this finding may help in the management of space sickness and sea sickness and other motion sickness states. Applications may include military simulator training or ship crew members (amongst others) to reduce subjective discomforts and improve job performance through mitigating motion sickness-induced performance degradation.

Further fundamental research will need to be conducted to understand the psychophysiological mechanism through which this effect leads to the motion sickness reduction. It is possible an enhanced ability to understand movement and motion (visuospatial ability) aids the brain in resolving any sensory conflicts between what motion is being observed, and what motion is being experienced. The visuospatial training method used this research was proven to be effective. However, this method may not be the optimal solution to visuospatial training where it is likely more research will reveal more efficient and effective ways of improving visuospatial performance. Fundamental questions also remain about if MRT are the best visuospatial training tool, if 15 minutes a

day over two weeks is the optimal combination, and also if active engagement in the task is even needed. It may even prove to be that with an enhanced method of visuospatial training, motion sickness can be reduced even further.

Visuospatial training, as developed in this research, provides an invaluable method through which people may be able to reduce their personal susceptibility to motion sickness in their personal lives. This affect is independent of 'design features' and may prove to be a useful alternative to anti-sickness medication. This paper has ultimately shown that visuospatial skill can be trained, and such training is an effective method to reduce motion sickness.

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