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Efficacy of augmented visual environments for reducing sickness in autonomous vehicles

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ABSTRACT

The risk of motion sickness is considerably higher in autonomous vehicles than it is in human-operated vehicles. Their introduction will therefore require systems that mitigate motion sickness. We investigated whether this can be achieved by augmenting the vehicle interior with additional visualizations. Participants were immersed in motion simulations on a moving-base driving simulator, where they were backward-facing passengers of an autonomous vehicle. Using a Head-Mounted Display, they were presented either with a regular view from inside the vehicle, or with augmented views that offered additional cues on the vehicle's present motion or motion 500ms into the future, displayed on the vehicle's interior panels. In contrast to the hypotheses and other recent studies, no difference was found between conditions. The absence of differences between conditions suggests a ceiling effect: providing a regular view may limit motion sickness, but presentation of additional visual information beyond this does not further reduce sickness.

1. Introduction

Major car manufacturers estimate that autonomous cars will be available for the public within the next decade. Autonomous cars are expected to improve safety, utility and comfort to passengers, while minimizing environmental impact (Gerla et al., 2014). Apart from the many inherent advantages of this technology, a potential problem that may impede its adoption is that the risk of experiencing motion sickness (MS) is considerably higher than in human-operated vehicles (Diels and Bos, 2016).

Arguably the most influential theory on MS is the Sensory Conflict Theory (SCT, Reason, 1978). According to this theory, MS results from a discrepancy between sensory cues or between expectations and sensations of motion (Diels and Bos, 2016; Duh et al., 2004; Warwick-Evans et al., 1998; Flanagan et al., 2002). Consequently, anything that limits the ability to anticipate movements potentially increases sickness. Consistent with this notion, Rolnick and Lubow (1991) found that when pairs of people are exposed to a motion, where one has control over the motion whereas the other does not, those who had no control demonstrated higher sickness scores and lower well-being ratings. More recently, Diels and Bos (2016) found that even low levels of automation led to an increase in MS, and it has already been shown that this problem will be further amplified by the introduction of novel seating arrangements that allow passengers to face each other (Salter et al., 2019). Consequently, the introduction of autonomous vehicles will require implementation of systems that mitigate MS.

According to SCT, MS should be minimal when passengers have a perfect knowledge of their trajectory. It can thus be hypothesized that providing passengers with information that aids the anticipation of motion reduces MS. Indeed, Griffin and Newman (2004) found that passengers who had a clear view on the road ahead experienced significantly less sickness than those who did not. Kuiper, Bos and Diels investigated whether the height of a display in a car affected MS scores, and thereby effectively assessed the importance of a peripheral outside view (Kuiper et al., 2018). The results showed a significant reduction in sickness scores when the peripheral view was available. Karjanto et al. (2018) presented participants with automated driving scenarios, where participants were either isolated from visual cues on vehicle motion entirely, or were shown blinking lights starting three seconds prior to a

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turn on the respective side of a central screen. It was found that MS was significantly reduced when the anticipatory visual cues were available. These findings thus illustrate that peripheral and anticipatory visual cues can mitigate MS.

In the present study, we evaluated whether these effects are additive. We hypothesized that I. providing additional visual cues that reflect the vehicle's longitudinal motion (velocity, heading and acceleration) on the vehicle's interior panels reduces MS, and II. that the efficacy of these cues increases when the cues reflect future motion. To test these hypotheses, we simulated autonomous driving scenarios. Using a motion base, participants were presented with physical cues corresponding to winding trajectories, while a Head-Mounted Display (HMD) provided a synchronized view from within a virtual car. Additional visual cues consisting of a cloud of moving particles were displayed on the vehicle's interior panels. We compared MS scores for a baseline condition without additional cues; a condition with additional cues that represented present motion; and a condition where the additional cues represented vehicle motion 500 ms in the future. Movement of the particles generates optic flow, from which heading and velocity can be estimated (Howard, 1982; Koenderink, 1986; de Winkel et al., 2018; Pretto et al., 2009). Presentation of future motion allows anticipation of the vehicle's trajectory. The color of the particles was changed in proportion to the car's acceleration; turning red during deceleration, and green during acceleration (Bergum and Bergum, 1981). This allows anticipation of the vehicle's speed.

2. Material and methods

2.1. Ethics statement

The experiment was performed in accordance with the Declaration of Helsinki. The study was approved by the ethics committee of the University of Twente (Enschede, The Netherlands; application number 18058). All participants gave their written informed consent prior to participation in the study.

2.2. Participants

Nineteen participants (mean age = 27.7, SD = 4.5, 12 females) who reported to be susceptible to MS were recruited for the study. Fourteen of them were employees of the Max Planck Institute for Biological Cybernetics; the remaining five were recruited from the institute participant database. Participants reported to be in normal health and were naive regarding experiment conditions. External participants were compensated €8 per hour.

2.3. Setup

To simulate the physical movement of an autonomous vehicle, we used a moving-base motion simulator. We first created three different tracks in MATLAB (The MathWorks Inc., Natick, United States, version R2016a). These tracks were generated as self-avoiding random walks: 100 two dimensional (x,y) data points were specified, each dependent on and proximal to the previous one. A straight stretch of three additional datapoints was added at the start to aid the automated driving software. The track was then smoothed using a three-point moving average filter and scaled by cubic interpolation to be 7.5 km long. To prevent the track from featuring overly sharp turns, a 2nd order Butterworth filter was applied, with a half power frequency of 0.05. The resulting roads are shown in Fig. 1.

To generate the actual motion profiles, we used CarSim software (Mechanical Simulation Cooperation, Ann Arbor, United States). CarSim provides an automatic driver which was used to drive around the generated tracks. The automatic driver accelerated from 0–50 km/h at the onset of the track, and was set to drive at a constant velocity of 50 km/h for the remainder of the track. The driver slowed down before going around corners and at the end of the track. It also decelerated three times, from 50 km/h to 30, 20 or 10 km/h, and accelerated again to the original speed after five seconds. Each profile was approximately 10 min long.

To generate inertial motion cues from these profiles, we used an eMotion 1500 hexapod motion simulator (Bosch Rexroth AG, Lohr am Main, Germany). The motion profiles generated in the previous step were passed to the simulator control software, and translated into motions using the built-in washout filter. Road rumble with an intensity proportional to the simulated car's velocity was added to the motion profiles to increase realism.

For the visual cues of the virtual environment, we used custom software written to work with the Unity game engine (Unity Technologies, San Francisco, United States, version Unity 4.2.2f1). The software created a visual environment for each of the generated roads. Each environment consisted of a flat plane populated with trees that encompassed the road (see Fig. 2). Visual motion cues were generated by moving a camera through the virtual environment in synchrony with the motion simulator. Visual motion cues were presented to the participants using an HTC Vive (HTC Cooperation, New Taipei City, Taiwan) head-mounted display (HMD). This HMD has a refresh rate of 90 Hz, a resolution of 2160 × 1200 (1080 × 1200 per eye), a horizontal field of view of 100° and a vertical field of view of 110°, therefore it provides a pixel density of approximately 11 pixels per degree. For head tracking, an HTC lighthouse system was used, which allowed the transformation of participants' head movements into corresponding translations and rotations of the virtual camera. To correct for the simulator's motion, we measured and subtracted its motion from that of the HMD on participant's heads (which is equal to the sum of head and simulator motion). This was done using the program OpenVR-InputEmulator (matzman666, 2018). This program can alter the received input from VR devices and has a built in function to compensate for the specific motion registered by one device, which in this case was a Vive controller strapped to the simulator.

To further increase the realism of the simulation, engine noises proportional to the simulated car's velocity were added to the simulation. The noises were generated in the Unity game engine, and played back over wireless noise-canceling headphones.

The experimental logic and communication between the different systems were implemented in Simulink (The MathWorks Inc., Natick, United States, version R2016a).

2.4. Stimuli

The independent variable in the present study was the nature of the information presented on interior panels of the virtual car. There were three different levels of the visual environment: (1) no additional visual information (control condition; Fig. 2, left panel); (2) additional information on present motion; and (3) additional anticipatory information relating to future motion. An impression of the latter two conditions is given in the right panel of Fig. 2.

In the latter conditions, this information was presented in the form of virtual Earth-stationary particles surrounding the car. Cameras facing outwards captured the particle flow around the vehicle while progressing along the track. The captured video was shown on panels on the doors, between the backseats and on the floor of the car. The particles visible on the panels can be interpreted as an abstract representation of the outside world, as particles that were closer to the car would appear bigger and move faster (at constant speed) on the panels than those further away (Ferris, 1972). In addition to their motion, the particles gradually changed color when accelerating or decelerating, either turning green on acceleration or red on deceleration. The intensity of the color change depended on the strength of the corresponding acceleration. The relation between stop-red and go-green is known as a population stereotype, and has been demonstrated to exist in virtually everybody (Bergum and Bergum, 1981).

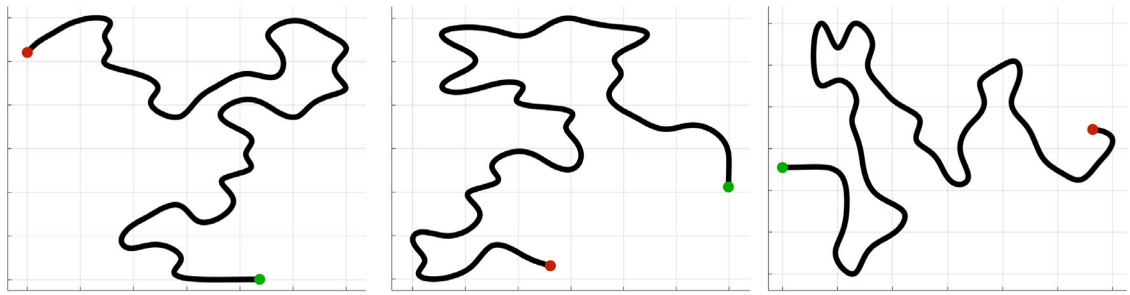

Fig. 1. The three trajectories used for generation of the motion profiles. The green and red dots mark the starting and end points, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

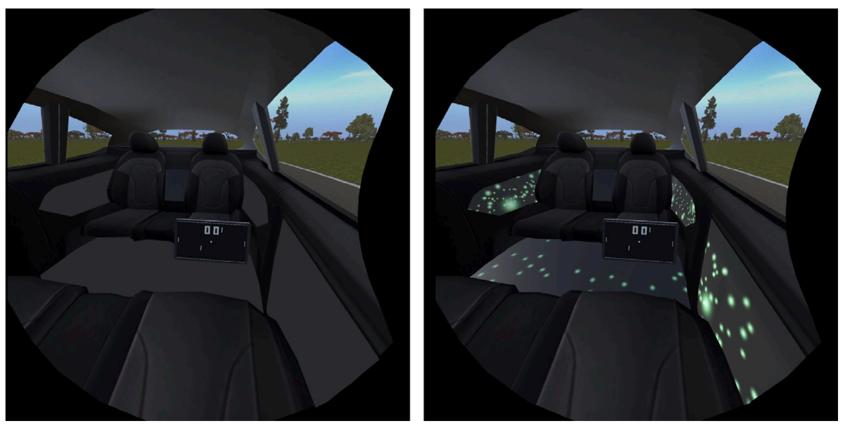

Fig. 2. Monocular screenshot of the participants' view through the HMD. The left panel shows the control condition without additional information on the virtual vehicle's motion; the right panel shows conditions where additional information was presented. Note that it is not possible to visualize the difference between present and future motion information statically.

In the condition where future motion was shown, the virtual cameras that captured the car's environment were looking 500 ms ahead in the simulation motion profile. This value was based on pilot studies that were performed with the experimenters as participants. A shorter interval was indistinguishable from real-time, whereas a larger one was perceived to bear no relation to the trajectory.

Note that in the condition with present movement information, the cues presented on the interior panels can be regarded as an extension of what is seen through the window. In the condition with future cues, the cues provide information that can be used to anticipate future motion; the colors inform of oncoming acceleration or deceleration, and the trajectory can be derived from the optic flow.

2.5. Task

The participants were seated facing rear-wards in the virtual car so that they did not have a view on the road ahead. In the interior of the visual virtual car, a tablet-like screen was presented at knee-height that featured the video game Pong (1972). Participants were instructed to play this game, which they were able to do using a hand held Xbox 360 (Microsoft, Redmond, United States) controller. The purpose of playing Pong was to present them with a task that resembles activities that may be performed in autonomous vehicles and to ensure the additional visual cues appeared in the periphery. The tablet-like virtual screen also featured a red light. The experimenter flashed this light briefly at two-minute intervals within each trial, starting immediately at the onset of the trial. Every time the light turned on, participants had to rate their MS using the FMS (see 2.6.2 Fast Motion Sickness Scale).

2.6. Questionnaires

Questionnaires were used to assess participants' sensitivity to MS (1), their experienced MS level during (2) and after (3) the simulation, and to debrief the participants (4).

2.6.1. Motion sickness susceptibility questionnaire

To determine the participants' sensitivity to MS, the shortened version of the Motion Sickness Susceptibility Questionnaire was used (MSSQ: Golding, 2006). It is divided in two parts, both including nine items asking about the experience of MS in different scenarios (e.g., in cars, on funfair rides). Responses to the items can be scored from zero to three (0 = never felt sick, 3 = frequently felt sick). The first part is concerned with experiences before the age of 12; the second part with the last 10 years.

2.6.2. Fast motion sickness scale

During the experimental trials, MS was assessed with the Fast Motion Sickness Scale (FMS, Keshavarz and Hecht, 2011), which originally ranges from zero to 20 (0 = not nauseous, 20 = I am about to vomit) and can be applied verbally. In the present experiment the scale was mistakenly taken to start at a value of one. Because it was made clear to the participants that the scores should range between no symptoms (1) and frank sickness (20), this was not corrected. The participants were instructed to report their FMS score verbally each time the red light on the virtual tablet was flashed.

2.6.3. Simulator Sickness Questionnaire

After each trial, the Simulator Sickness Questionnaire (SSQ, Kennedy et al., 1993) was administered to measure the MS experienced by participants. The SSQ includes 16 4-point scale items (0 = no MS, 3 = severe MS), covering three symptom clusters (nausea (SSQ-N), oculomotor impairment (SSQ-O) and disorientation (SSQ-D)).

2.6.4. Evaluation questionnaires

At the end of the experiment, participants filled out an evaluation questionnaire that consisted of two parts. The first part contained 10 7-point Likert scale items about the quality of the simulation (e.g., “Did braking feel real?”), while the second part contained 10 questions about the perceived utility of visual cues (e.g., “Did you pay attention to these visualizations?”). In the second part, seven questions could be answered on a 7-point Likert scale ranging from “Not at all”(1), to “Undecided”(4), to “Very much”(7), and three were open questions. All questionnaires were available in English and German. The English version of the questionnaire is available as supplementary material in Appendix A.

2.7. Procedure

Prior to the actual experiment, participants were informed of the study goals and task by written instruction. Participants were informed that the study was on MS and that they would experience three different driving simulation scenarios. No information was given on the nature of the differences between conditions. Participants who agreed to participate were required to provide written informed consent.

First, participants filled out the MSSQ. They were then brought to the motion simulator, and were given a verbal reiteration of the written instructions. Then they were given the HMD, earplugs to suppress operating noises of the simulator, the headphones and the Xbox controller. After all equipment was set-up, an experimental trial was started. On each trial, a participant experienced one of the three visual conditions in combination with one of the three tracks. Each participant experienced each visual condition and track once. The specific combination of visual condition and tracks was counterbalanced between participants. During the trials, participants reported their FMS score at two minute intervals, cued via a blinking virtual LED on the tablet also used to play Pong. The first report was provided upon the start of the trial to establish a baseline. Each trial took approximately 10 min, or until an FMS score of 15 was attained. Each visual condition was administered on a separate day to ensure participants could fully recover from any MS symptoms.

After completion of each trial, participants filled out the SSQ. Upon completion of the experiment, participants filled out the evaluation questionnaire.

3. Results

3.1. Evaluation of motion sickness susceptibility

We evaluated MS susceptibility to ensure there would be a reasonable likelihood that MS would be induced by the experimental conditions. To this end, we set as a criterion that the MSSQ score should be above the 50th percentile, as per (Golding, 2006). In addition, we found that despite initial screening, some participants did not develop any measurable MS. It was found that out of the 19 participants initially recruited, seven did either not meet the selection criterion for the MSSQ or did not report any sickness. Subsequent data analyses performed either including or excluding these participants did not yield any different conclusions.

Table 1
Factor loadings of questions that related to a single factor termed ‘simulation realism’, as per a Confirmatory Factor Analysis.

Item	Factor loading
1. Did the simulation in general feel realistic?	0.776
2. Did you feel like you were sitting in a car?	0.767
4. Did you have the feeling that you were going backwards?	0.279
5. Was the sound realistic?	0.300
6. Did accelerating feel real?	0.857
7. Did braking feel real?	0.832
8. Did making a turn feel real?	0.334
9. Did going straight at constant speed feel real?	0.491
10. Did what you see match with what you felt?	0.287

3.2. Evaluation of simulation realism

The experiment’s ecological validity was evaluated using 10 questions designed to assess simulation realism. As a basic validation, we performed a Confirmatory Factor Analysis (CFA, Kline, 2005) with one factor, which we assume represents the construct of ‘simulation realism’. Fitting this model was done with the lavaan package in R (Rosseel, 2012). The model with a single factor did not fit the data of all items well, as indicated by a test of the null-hypothesis that the model fit the data perfectly ($\chi^2(35) = 55.000, p = 0.017$). We then removed the item with the smallest factor loading (3), which resulted in acceptable model fit ($\chi^2(27) = 26.470, p = 0.493$). This procedure thus indicated that nine items corresponded to this single factor (Table 1).

As an overall indication of the perceived realism, we fitted a linear model to the scores for the listed items. This model included an intercept and participant as a random effect. Participant was included as a random effect to account for the fact that individual participants contributed multiple data points (i.e., one for each item). The value 4, which corresponds to participants being undecided on whether the simulation was realistic or unrealistic, was subtracted from the scores. Then, if the intercept is found to be significantly larger than 0, this indicates that participants found the simulation realistic. The value of the intercept was 1.556 ($t(18) = 8.669, p < 0.001$). We therefore conclude that participants found the simulation reasonably realistic.

3.3. Analysis of motion sickness scores

The maximum value of the FMS scores, FMS_{max}, was taken as a representation of the experienced MS on each trial. The SSQ (specifically SSQ-N) and FMS_{max} should represent the same construct, and therefore the scores should be correlated (Keshavarz and Hecht, 2011; Shahal et al., 2016), which was found to be the case: FMS_{max} correlated with the total SSQ score SSQ_{total} (Spearman $\rho = 0.682, p < 0.001$), as well as with its subscales (SSQ-N: $\rho = 0.658, p < 0.001$; SSQ-O: $\rho = 0.579, p < 0.001$; SSQ-D: $\rho = 0.572, p < 0.001$). Spearman correlation coefficients between 0.50–0.70 may be considered a moderately strong relationship (Mukaka, 2012).

We fitted mixed-effect models to the SSQ_{total} and FMS_{max} data (‘score’) separately to check for consistency of the findings. The models had the following form (in Wilkinson notion Wilkinson and Rogers, 1973):

$$\text{score} \sim 1 + \text{visualization} + (1|\text{participant}). \quad (1)$$

Here, the ‘1’ represents an intercept; ‘visualization’ represents the type of visual cues presented on the car’s interior panels, and ‘$(1|\text{participant})$’ represents a random effect (random intercept) for participant, to account for individual variability. It should be noted that variability in responses can also be introduced by the choice of track and trial number (through habituation), which could be modeled by including effects for these factors as well. Fitting such models did not yield different conclusions. However, for the SSQ data this did cause problems due to overfitting. Because the randomization of conditions

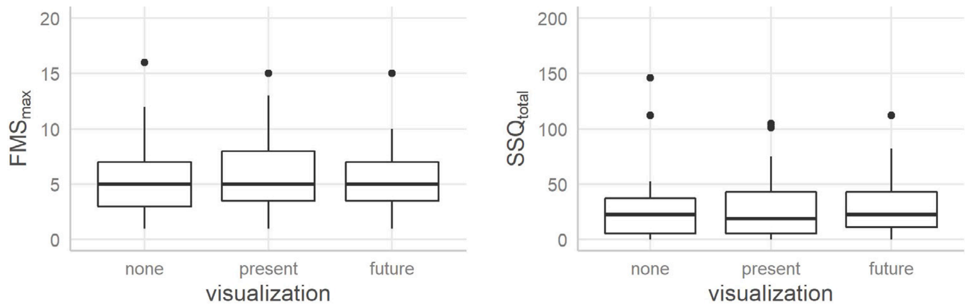

Fig. 3. Boxplots showing the FMS_{max} (left panel) and SSQ_{total} (right panel) scores per experimental condition. No significant differences were found.

Table 2
Factor loadings of questions that related to a single factor termed 'utility', as per a Confirmatory Factor Analysis.

Item	Factor loading
12. Did you like the visualizations in the interior elements?	0.550
13. Did you pay attention to these visualizations?	0.681
14. If applicable, do you think the visualizations reduced your symptoms of motion sickness?	0.716
15. Do you think they could help others with motion sickness?	0.858
21. Do you think it would be helpful to include visualizations of this kind in an autonomous car?	0.627

should already minimize any confounding effects of these factors in the analysis, we chose not to include them in the model.

The FMS scores were verbally provided on a scale from 1 to 20 at two-minute intervals during trials. The lowest score recorded was 1, and the maximum was 16. The mean score was 5.667. No significant differences were found among the different experimental conditions $F(2, 32.861) = 0.585, p = 0.563$ (see Fig. 3, left panel). The estimated marginal mean values were 5.526, 5.895 and 5.579, for the visualizations 'none', 'present', and 'future', respectively.

There were also no significant differences between the experimental conditions for the SSQ ($F(2, 36.000) = 0.167, p = 0.847$), nor for its subscales (SSQ-N: $F(2, 36.000) = 0.210, p = 0.812$, SSQ-O: $F(2, 36.000) = 0.224, p = 0.801$, SSQ-D: $F(2, 36.000) = 2.095, p = 0.138$). The data for the SSQ score, split per condition, are shown in Fig. 3, right panel. The theoretical range of the SSQ_{total} is between 0 and 235.620 (Kennedy et al., 1993). The lowest observed score recorded was 0, and the maximum was 145.86. The mean score was 30.839. The estimated marginal mean values were 31.888, 29.920 and 30.707, for the visualizations 'none', 'present', and 'future', respectively.

3.4. Evaluation of visual cue utility

As was done for the evaluation of simulation realism, we assessed whether the items on the second part of the questionnaire related to a latent 'utility' construct using CFA. Open questions (16, 17, 19) and Likert scale items relating to the answer on these open questions (18, 20) were excluded from this analysis. The χ^2 test indicated that the model with the remaining questions included did not fit the data well ($\chi^2(9) = 17.888, p = 0.0362$). We then removed the item (11) with the smallest factor loading, which resulted in acceptable model fit ($\chi^2(5) = 6.097, p = 0.297$) The remaining items and factor loadings are shown in Table 2.

As an overall indication of the perceived utility, we again fitted a linear mixed-effects model including only an intercept and participant as a random effect. The middle score (4) was subtracted such that the model intercept could be interpreted as a measure of general utility. The value of the intercept was 0.872 ($t(17.934) = 3.694, p = 0.002$). We therefore conclude that participants found the visuals somewhat useful.

Apart from the above questions, there were three open questions. In the first open question (item 16), we asked participants whether they had paid special attention to any particular aspect of the visual cues, and if they did, to what aspect. Seven individuals said they did not concentrate on anything in particular, four focused on both the movement and the change of color of the particles, and seven others reported to focus either on the change of colors (5) or the movement of the particles (2). The remaining person's answer was not related to the visual cues.

In the second open question (item 17), we asked participants to indicate what they thought was represented by the motion of the particles. Here, approximately two-thirds of the participants (12/19) related the movement of the particles to car motion. These participants on average scored 5.333 (SD = 1.371) on the following Likert-scale question (item 18) whether they thought understanding this was intuitive.

In the final open question (item 19), we asked participants to indicate what they thought was represented by the change of color of the stimuli. Here, again approximately two-thirds (11 out of 19) understanding was correct, with an average score of 5.00 (SD = 1.843) on the corresponding Likert-scale question (item 20) on intuitiveness of the color change.

Data analyses performed excluding the participants who appeared to have misunderstood what was represented by the motion of the particles and/or color change did not yield any different conclusions.

4. Discussion

Previous research has shown that providing passengers with additional visual information can decrease conflict between visual and vestibular cues (Feenstra et al., 2011; McGill et al., 2017), which is a known cause of MS. We used a moving base motion simulator and virtual reality to immerse participants in a scenario where they were a passenger in an autonomous vehicle; seated in a self-driving car, facing backwards, and playing a game on a tablet. We then evaluated whether additional visual cues that represent a vehicle's longitudinal velocity and acceleration could be used to alleviate MS symptoms. Data analyses did not show any differences between visualization conditions. Therefore, the hypotheses that I. providing additional visual motion cues that reflect the vehicle's motion (velocity, heading and acceleration) reduces MS, and II. that the efficacy of these cues increases when the cues provide information about future motion, are not supported by the data. These findings are surprising, considering that a number of previous studies do report beneficial effects of such cues (Feenstra et al., 2011; McGill et al., 2017; Karjanto et al., 2018; Kuiper et al., 2018).

A possible explanation for the findings can be derived by taking together two recent studies: Karjanto et al. (2018) investigated whether anticipatory visual cues could be used to mitigate MS in an autonomous vehicle. Participants were seated in a partition of a specially prepared vehicle. This partition was visually isolated from the rest of the vehicle as well as from the vehicle's surroundings. Inside, the partition featured a seat and a centrally placed display, 1.2m in front of the seat. Surrounding the display was a visualization system called the

Peripheral Visual Feedforward System (PVFS). The PVFS consisted of two arrays of blue LED lights, placed 30° to the left and right of the central screen. These arrays would light up in upward sweeps for three seconds prior to a turn, on the matching side of the screen. Using a Wizard of Oz approach, their participants were presented with two automated driving scenarios that lasted between eight and nine minutes each, and either included the PVFS or not. During these scenarios, the participants watched videos on the central screen. Various measures of MS were recorded. The results indicated that MS was significantly reduced when the PVFS was on, and it was concluded that presentation of the additional visual information could indeed mitigate MS.

Kuiper, Bos and Diels investigated whether positioning of a display either at the height of the windscreen or glove compartment affected MS scores, and thereby effectively assessed the importance of a peripheral outside view (Kuiper et al., 2018). They placed participants on the passenger side of a car, and drove them along sinusoidal trajectories for periods of 15 min; either with the display in the lower or higher position, while the participants performed a task on the display, and reported their level of sickness at one-minute intervals using the MISC scale (Bos et al., 2005). The results showed a significant reduction in sickness scores when the peripheral view was available.

These studies thus suggest that providing *some* visual information rather than no visual information at all is beneficial with respect to MS, and also that this benefit can be achieved by simply providing an outside view. The present results contribute to these findings by showing that if there is an additional effect of augmented visual stimuli on MS, the effect is at best small. This is in line with a previous study that found no differences in motion sickness during fore-aft oscillations on a linear sled when participants were either blindfolded or shown different visualizations (Butler and Griffin, 2006). Taken together, these results therefore suggest there may be a ceiling effect to how much MS can be mitigated by providing visual information, and that the mere presence of an outside view could be sufficient.

4.1. Limitations

The use of an HMD and moving base motion simulator provided full control of the visualizations and ensured that participants could be exposed to identical stimulation. However, the choice of apparatus and stimulus design also present a number of potential limitations.

First, the HMD that was used provided a horizontal field of view of 100°. It can be contested whether this device provides peripheral stimulation. Stimulation of the peripheral visual field may be of particular importance because motion information appears to be transduced most efficiently via peripheral vision (e.g., Brandt et al., 1973; Held et al., 1975; Berthoz et al., 1975; Osaka, 1988; Pretto et al., 2008, 2009; de Winkel et al., 2018). In a comprehensive review, Strasburger et al. (2011) note that in perimetry (i.e., measuring the field of view), the central visual field is considered to be 60° in diameter. However, functional differences in form recognition already occur at 2° eccentricity, therefore we may consider as *peripheral vision* anything outside these 2°. In the aforementioned study by Karjanto et al. (2018), the visualizations were shown at approximately 30° eccentricity. In the present study, stimuli were also presented beyond the 60° range, and in that sense they can be considered peripheral. Still, it should be noted that the field of view in humans extends beyond 180°, and the present data do not allow any conclusions about the efficacy of cues presented in the far-periphery. Similarly, another concern that is particular to studies performed in motion simulator environments is that motion bases generally cannot reproduce vehicle motion one-to-one. This can potentially introduce various kinds of false and missing cues (Cleij et al., 2017). Mismatches between the desired vehicle motion and actual simulator motion constitute sensory conflicts, as they imply mismatches between visual and inertial cues. MS that arises due to such mismatches particularly is known as simulator sickness. Although causes of mismatches in a simulator can thus be distinct from those in a real vehicle, the nature of the sensory conflicts leading to sickness is the same (Bles et al., 1998). It cannot be excluded that the present results differed from previous studies (Karjanto et al., 2018; Kuiper et al., 2018) due to this distinction.

Second, the efficacy of the stimuli can be questioned: on the one hand, it can be questioned whether the motion stimuli were sufficiently provocative, and on the other hand, whether the visualizations were suitable to mitigate sickness. The provocativeness of the stimuli can be judged from the sickness responses. The actual FMS (Fig. 3, left panel) and SSQ scores (Fig. 3, right panel) averaged about $\frac{1}{4}$ and $\frac{1}{8}$ of the scales' ranges, respectively. This means that levels of frank MS were not achieved. However, it is not the case that no sickness was introduced; the scores obtained in the present study are in fact comparable to scores obtained in two recent studies that are quite similar to the present. In the study by Karjanto et al. (2018), participants were driven for slightly shorter periods of time than in the present study (8 to 9 min), and overall Motion Sickness Assessment Questionnaire (MSAQ, Gianaros et al., 2001) scores of 10.4 were found. The MSAQ is comparable to the SSQ. Overall MSAQ is expressed as a percentage, which implies sickness levels of about $\frac{1}{10}$ of the scale's range were achieved, which is in fact below the present levels. In the study by Kuiper et al. (2018), participants were driven along sinusoidal trajectories for about 15 min, and sickness scores of 2.8 on the MISC-scale (Bos et al., 2005) were achieved (Kuiper et al., 2018), which is about $\frac{1}{4}$ of the scale's range (0–10). Although the MISC is explicitly related to specific symptoms, whereas the FMS is not, the symptoms are arranged from 'no problems' to 'vomiting', and in that sense the scales are comparable. Consequently, these scores are similar to those observed presently. Nevertheless, sickness scores could be increased in driving simulator environments like the present by increasing the duration of stimulation, for instance from the present 10 min to 20 min, and/or tracks could be designed that include low frequency vertical oscillations (approx. 0.2 Hz), as these have been demonstrated to be particularly provocative (McCauley et al., 1976; Golding et al., 2001; Kuiper et al., 2018). The visual cues were designed to exploit knowledge of how humans normally perceive self-motion from visual stimulation, namely via optic flow (Howard, 1982; Koenderink, 1986; de Winkel et al., 2018; Pretto et al., 2009), and by the common association between stop-red and go-green (Bergum and Bergum, 1981). Subjective evaluations of the stimuli, obtained by questionnaires, indicated that the majority of the participants also understood the purpose of the stimuli, had found them reasonably intuitive, and appreciated their presence. Despite this, it is possible that certain features limit their efficacy. For instance, adding visual cues to the interior of a vehicle that are predictive of future movements may actually pose a conflict with visual information on present movements seen through the windows. Such visual–visual mismatches also have the potential to increase MS (Keshavarz et al., 2011). In this respect, it is also interesting to consider stimulation of alternative sensory modalities, for example by providing auditory or tactile stimuli (Van Erp, 2005). We also cannot rule out the possibility that explicit instructions on the nature of the stimuli could enhance their efficacy, although for the present study the conclusions did not change when those participants who appeared to have misunderstood the visual stimuli were excluded from the analyses.

A final potential limitation unrelated to the apparatus is the number of participants. A small sample may not provide sufficient statistical power for small effects to become significant, and is more susceptible to outliers. The fact that we did not observe a significant effect therefore does not mean that no effect exists. However, we can conclude that if there is an effect, it is at best small. In addition, the pattern of mean scores between conditions did not suggest any trend indicative of possible mitigation of sickness due to the experimental manipulations. This conclusion also did not change when we performed the analyses on subsets of the data; excluding from the analyses participants who either did not develop any sickness, who reported a general low susceptibility to MS, or who appeared to have misunderstood the visual stimuli. Given that the present visualizations provided a richer visual environment than in previous studies, the present observations therefore suggest that providing additional visual information beyond an outside view does not further reduce sickness in a meaningful way.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Bergum, B.O., Bergum, J.E., 1981. Population stereotypes: An attempt to measure and define. In: Proceedings of the Human Factors Society Annual Meeting, Vol. 25. Sage Publications, Sage CA: Los Angeles, CA, pp. 662–665.

Berthoz, A., Pavard, B., Young, L., 1975. Perception of linear horizontal self-motion induced by peripheral vision (linearvection) basic characteristics and visual-vestibular interactions. Exp. Brain Res. 23 (5), 471–489.

Bles, W., Bos, J.E., De Graaf, B., Groen, E., Wertheim, A.H., 1998. Motion sickness: only one provocative conflict?. Brain Res. Bull. 47 (5), 481–487.

Bos, J.E., MacKinnon, S.N., Patterson, A., 2005. Motion sickness symptoms in a ship motion simulator: effects of inside, outside, and no view. Aviat. Space Environ. Med. 76 (12), 1111–1118.

Brandt, T., Dichgans, J., Koenig, E., 1973. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. Exp. Brain Res. 16 (5), 476–491.

Butler, C.A., Griffin, M.J., 2006. Motion sickness during fore-and-aft oscillation: Effect of the visual scene. Aviat. Space Environ. Med. 77 (12), 1236–1243.

Cleij, D., Venrooij, J., Pretto, P., Pool, D.M., Mulder, M., Bülthoff, H.H., 2017. Continuous subjective rating of perceived motion incongruence during driving simulation. IEEE Trans. Hum.-Mach. Syst. 48 (1), 17–29.

de Winkel, K.N., Kurtz, M., Bülthoff, H.H., 2018. Effects of visual stimulus characteristics and individual differences in heading estimation. J. Vis. 18 (11), 9.

Diels, C., Bos, J.E., 2016. Self-driving carsickness. Applied Ergon. 53, 374–382.

Duh, H.B.-L., Parker, D.E., Philips, J.O., Furness, T.A., 2004. Conflicting motion cues to the visual and vestibular self-motion systems around 0.06 hz evoke simulator sickness. Hum. Factors 46 (1), 142–153.

Feenstra, P., Bos, J.E., van Gent, R.N., 2011. A visual display enhancing comfort by counteracting airsickness. Displays 32 (4), 194–200.

Ferris, S.H., 1972. Motion parallax and absolute distance. J. Exp. Psychol. 95 (2), 258.

Flanagan, M.B., May, J.G., Dobie, T.G., 2002. Optokinetic nystagmus, vection, and motion sickness. Aviat. Space Environ. Med. 73 (11), 1067–1073.

Gerla, M., Lee, E.-K., Pau, G., Lee, U., 2014. Internet of vehicles: From intelligent grid to autonomous cars and vehicular clouds. In: Internet of Things (WF-IoT), 2014 IEEE World Forum on. IEEE, pp. 241–246.

Gianaros, P.J., Muth, E.R., Mordkoff, J.T., Levine, M.E., Stern, R.M., 2001. A questionnaire for the assessment of the multiple dimensions of motion sickness. Aviat. Space Environ. Med. 72 (2), 115.

Golding, J.F., 2006. Predicting individual differences in motion sickness susceptibility by questionnaire. Personal. Individ. Differ. 41 (2), 237–248.

Golding, J.F., Mueller, A., Gresty, M.A., 2001. A motion sickness maximum around the 0.2 hz frequency range of horizontal translational oscillation. Aviat. Space Environ. Med. 72 (3), 188–192.

Griffin, M.J., Newman, M.M., 2004. Visual field effects on motion sickness in cars. Aviat. Space Environ. Med. 75 (9), 739–748.

Held, R., Dichgans, J., Bauer, J., 1975. Characteristics of moving visual scenes influencing spatial orientation. Vis. Res. 15 (3), 357–IN1.

Howard, I.P., 1982. Human Visual Orientation(Book). John Wiley and Sons, Chichester, Sussex, England and New York, p. 704.

Karjanto, J., Yusof, N.M., Wang, C., Terken, J., Delbressine, F., Rauterberg, M., 2018. The effect of peripheral visual feedforward system in enhancing situation awareness and mitigating motion sickness in fully automated driving. Transp. Res. F 58, 678–692.

Kennedy, R.S., Lane, N.E., Berbaum, K.S., Lilienthal, M.G., 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. Int. J. Aviat. Psychol. 3 (3), 203–220.

Keshavarz, B., Hecht, H., 2011. Validating an efficient method to quantify motion sickness. Hum. Factors 53 (4), 415–426.

Keshavarz, B., Hecht, H., Zschutschke, L., 2011. Intra-visual conflict in visually induced motion sickness. Displays 32 (4), 181–188.

Kline, R.B., 2005. Principles and Practice of Structural Equation Modeling. Guilford publications.

Koenderink, J.J., 1986. Optic flow. Vis. Res. 26 (1), 161–179.

Kuiper, O.X., Bos, J.E., Diels, C., 2018. Looking forward: In-vehicle auxiliary display positioning affects carsickness. Applied Ergon. 68, 169–175.

matzman666, 2018. OpenVR-InputEmulator. https://github.com/matzman666/OpenVR-InputEmulator/releases/tag/v1.3.

McCauley, M.E., Royal, J.W., Wylie, C.D., O'Hanlon, J.F., Mackie, R.R., 1976. Motion Sickness Incidence: Exploratory Studies of Habituation, Pitch and Roll, and the Refinement of a Mathematical Model. Tech. rep., Canyon Research Group Inc Goleta Ca Human Factors Research Div.

McGill, M., Ng, A., Brewster, S., 2017. I am the passenger: How visual motion cues can influence sickness for in-car vr. In: Proceedings of the 2017 Chi Conference on Human Factors in Computing Systems. ACM, pp. 5655–5668.

Mukaka, M.M., 2012. A guide to appropriate use of correlation coefficient in medical research. Malawi Med. J. 24 (3), 69–71.

Osaka, N., 1988. Speed estimation through restricted visual field during driving in day and night: naso-temporal hemifield differences. In: Vision in Vehicles II. Second International Conference on Vision in Vehicles. Applied Vision AssociationErgonomics SocietyAssociation of Optometrists.

Pong, 1972. https://en.wikipedia.org/w/index.php?title=Pong&oldid=905511379.

Pretto, P., Ogier, M., Bülthoff, H.H., Bresciani, J.-P., 2009. Influence of the size of the field of view on motion perception. Comput. Graph. 33 (2), 139–146.

Pretto, P., Vidal, M., Chatziastros, A., 2008. Why fog increases the perceived speed. In: Proceedings of the Driving Simulation Conference. pp. 223–235.

Reason, J.T., 1978. Motion sickness adaptation: a neural mismatch model. J. R. Soc. Med. 71 (11), 819–829.

Rolnick, A., Lubow, R., 1991. Why is the driver rarely motion sick? the role of controllability in motion sickness. Ergonomics 34 (7), 867–879.

Rosseel, Y., 2012. Lavaan: An r package for structural equation modeling. J. Stat. Softw. 48 (2), 1–36, URL http://www.jstatsoft.org/v48/i02/.

Salter, S., Diels, C., Herriotts, P., Kanarachos, S., Thake, D., 2019. Motion sickness in automated vehicles with forward and rearward facing seating orientations. Applied Ergon. 78, 54–61.

Shahal, A., Hemmerich, W., Hecht, H., 2016. Brightness and contrast do not affect visually induced motion sickness in a passively-flown fixed-base flight simulator. Displays 44, 5–14.

Strasburger, H., Rentschler, I., Jüttner, M., 2011. Peripheral vision and pattern recognition: A review. J. Vis. 11 (5), 13.

Van Erp, J.B., 2005. Presenting directions with a vibrotactile torso display. Ergonomics 48 (3), 302–313.

Warwick-Evans, L., Symons, N., Fitch, T., Burrows, L., 1998. Evaluating sensory conflict and postural instability. theories of motion sickness. Brain Res. Bull. 47 (5), 465–469.

Wilkinson, G., Rogers, C., 1973. Symbolic description of factorial models for analysis of variance. Appl. Stat. 392–399.