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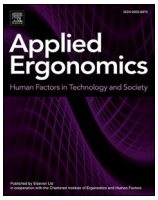

Validation of a moving base driving simulator for motion sickness research

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ABSTRACT

Increasing levels of vehicle automation are envisioned to allow drivers to engage in other activities but are also likely to increase the incidence of Carsickness or Motion Sickness (MS). Ideally, MS is studied in a safe and controlled environment, such as a driving simulator. However, only few studies address the suitability of driving simulators to assess MS. In this study, we validate a moving base driving simulator for MS research by comparing the symptoms and time course of MS between a real-road driving scenario and a rendition of this scenario in a driving simulator, using a within-subjects design. 25 participants took part as passengers in an experiment with alternating sections (slaloming, stop-and-go) with normal and provocative driving styles. Participants performed Sudoku puzzles (eyes-off-road) during both scenarios and reported MIsery SCale (MISC) scores at 30 s intervals. Motion Sickness Assessment Questionnaire (MSAQ) scores were collected upon completion of either scenario. Overall, the results indicate that MS was more severe in the car than in the simulator. Nevertheless, significant correlations were found between individual MS in the car and simulator for 3 out of 4 MSAQ symptom categories ($0.48 < r < 0.73$, $p < 0.02$), with a strong overall correlation ($r = 0.57$, $p = 0.004$). MS onset times were similar between the car and the simulator, and sickness fluctuations as a result of driving style showed a similar pattern between scenarios, albeit more pronounced in the car. Based on observed similarities in MS, we conclude these simulator results to have relative validity. We attribute the observed reduction of MS severity in the simulator to the downscaling of the motion by the Motion Cueing Algorithm (MCA). These results suggest that, at least in eyes-off-road conditions, findings on MS from simulator studies may generalize to real vehicles after application of a conversion factor. This conversion factor is likely to depend on simulator and MCA characteristics.

1. Introduction

Automated vehicles are expected to minimize vehicle environmental impact, increase passenger comfort and enhance safety (Gerla et al., 2014). A potential hindrance to widespread adoption of automated vehicle technology is the occurrence of Carsickness or *Motion Sickness* (MS) (Diels and Bos, 2016). It has been shown that the severity of MS increases even for low levels of automation (Sivak and Schoettle, 2015). Furthermore, passengers, thus users of automated cars, are known to have an increased risk of MS compared to drivers (Rolnick and Lubow, 1991). This has been attributed to the absence of control (Dong et al., 2011) and a restricted out-the-window view (Griffin and Newman, 2004).

MS is a syndrome that typically emerges from movements such as abrupt, low-frequency periodic or unnatural accelerations by vehicles and causes discomforting symptoms (e.g. headaches, sweating, dizziness, fatigue, nausea, vomiting (Lackner, 2014)). Around 60% of the population has experienced MS symptoms, whereas approximately one third has vomited from car travel before the age of 12 (Griffin and Erdreich, 1991). Although several theories have been proposed (McNally and Stuart, 1942; Steele, 1970; Reason and Brand, 1975; Treisman, 1977; Riccio and Stoffregen, 1991), the exact causes of MS are still under investigation. To ensure acceptance (Biocca, 1992) and widespread use (Sivak and Schoettle, 2015) of (future) automated vehicles, it is of paramount importance to address the problem of MS. This, in turn, requires understanding of the etiology of MS.

To study MS in the context of driving and to understand and predict how and when it develops, ideally driving tests would be performed under naturalistic driving conditions. However, considering the high costs of naturalistic driving studies; the impossibility of creating

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identical experimental conditions on repeated experimental trials and for multiple participants; and safety and ethical concerns that arise from experimenting with humans in real traffic, such studies are often not feasible. Here, driving simulators could present a solution. A driving simulator is a tool, designed to (re)create the motion cues one may experience while driving and consists of a visualization system, which may be augmented by other modalities, such as a moving base platform. As a simulator offers i.a. controllability over external variables and reproducibility (de Winter et al., 2012) and ensures the safety of participants, it has the potential to be an ideal environment for research and training. However, due to differences and ambiguities in cues experienced by passengers in a simulator relative to a real car, *Simulator Sickness* (SS) may arise. SS therefore complicates whether and to what extent findings of sickness in a simulator generalize to real vehicles (Bellem et al., 2017). Hence, the validity of driving simulators to study MS is not known.

Fundamental differences exist between MS in self-driving cars and SS. Firstly, although sickness in a simulator can originate from stimuli analogous to Carsickness, it can also develop as a result of technological constraints limiting simulator fidelity. Examples are the limitations on a simulator's ability to reproduce actual vehicle motion, imposed by the motion envelope of a motion-base and the choice of Motion Cueing Algorithm (MCA), and factors that determine the realism of the artificial imagery, such as the resolution, intensity, brightness, Field of View (FoV), and scene contents of the visualization modality (Bellem et al., 2017; Kolasinski, 1995; Jäger et al., 2014; Fleming Seay et al., 2001; Correia Grácio et al., 2014; de Winkel et al., 2018; Bos et al., 2021). In the remainder of this study, the term SS will be used to refer to the complicated combination of sickness originating from both these ambiguous factors and vehicle-replicated stimuli, obtained in a driving simulator. Secondly, according to the most prominent theory of MS, the Sensory Conflict Theory (Reason and Brand, 1975), MS results from a conflict between sensations of motion and expectations of motion, based on previous experience. Research has shown that conflicts can arise when these experiences, which are typically based on car driving experience, are not updated for the simulator movements and environment. For example, whereas there is a *negative* correlation between MS susceptibility in cars and age (or years of driving licensure) (Kennedy and Lilienthal, 1994; Schmidt et al., 2020; Paillard et al., 2013), there appears to be a *positive* correlation between age and SS susceptibility (Kawano et al., 2012; Kennedy and Lilienthal, 1994; de Winter and Kuipers, 2017). Thirdly, it is unsure whether MS and SS share the same symptomatology. Whereas Gavgani et al. (2018) show high correspondence specifically for nausea scores between a real and artificial environment during advanced stages of sickness, studies by Kennedy et al. (2010) and Stanney et al. (1997) show differences in symptom profiles where, in contrast to MS, nausea appears to be but a secondary symptom for SS.

To the best of our knowledge, the relation between SS and MS, and consequently the ecological validity of simulator studies on MS, has only been considered in three studies. On a theoretical level, Bos et al. (2021) argue that it is impossible to study actual Carsickness in a fixed-base simulator, due to the absence of inertial motion. Sickness as a result of exposure to a fixed-base simulator environment, needs to be referred to as Visually Induced Motion Sickness (VIMS). Empirical studies of simulators including a motion-base have provided some evidence for similarities between MS and SS. Kuiper et al. (2019) report that MS and SS are similar, but only evaluated symptoms in one scenario for blindfolded subjects exposed to highly predictable oscillatory motions. Gavgani et al. (2018) exposed subjects to both a visual sickness scenario in virtual reality and a (different) vestibular stimulation, and reported mostly similarities between MS and VIMS.

In the present study, we aim to determine the validity of a driving simulator for MS research in the context of automated driving. Specifically, we intend to delineate the relation between MS as it is experienced by individuals during naturalistic driving and SS as it is reported by the same individuals when presented with a rendition of the naturalistic driving scenario in a moving base simulator. We study conditions of being driven with eyes-off-road. Hence, we exclude the role of outside vision and road preview and its effect on expected motion and exclude aspects of visual motion quality. We aim to quantify simulator validity in studying self-driving Carsickness regarding:

1. Are symptoms of SS different from MS?
2. Does a relationship exist between individual sensitivities to MS and SS?
3. Are temporal aspects (time to onset, increase and decrease, amplitude) of MS and SS comparable?

To account for the existence of large individual variability in susceptibility (Lackner, 2014), we performed a within-subjects experiment, where participants were exposed to passive, eyes-off-road driving scenarios both in a real car and in a moving base driving simulator. The scenarios consisted of alternating periods of normal and provocative driving. We collected data on individual susceptibility using the Motion Sickness Susceptibility Questionnaire (MSSQ (Golding, 1998)) prior to the experiment; we monitored the time courses of sickness severity in relation to the variations in driving style during playback of the scenarios using the MIsery SCale (MISC (Bos et al., 2005)); and we characterized the nature of sickness experiences, by administering the Motion Sickness Assessment Questionnaire (MSAQ (Gianaros et al., 2001)) at the conclusion of both scenarios. We address our research objectives by comparing data obtained from both scenarios.

2. Methods

2.1. Ethics statement

The experiment was performed in accordance with the Declaration of Helsinki. The study was approved by the Human Research Ethics Committee of Delft University of Technology (Delft, The Netherlands; application number 1765). All participants gave their written informed consent prior to participation in the study.

2.2. Participants

In total, 25 participants took part in the experiment (mean age = 25.3 years, std = 3.4 years). Of the 25 participants, 7 were female and 18 were male. Both students and employees from Delft University of Technology participated in the study. All participants were in possession of a valid driver's license, had normal or corrected-to-normal vision, reported no vestibular disorders and had either no simulator driving experience at all (72%) or had never driven the simulator setup used in this experiment. All participants were asked to refrain from recreational drug consumption, including alcohol and caffeine, for 24 h prior to the experiment.

2.3. Apparatus

2.3.1. Car

A Hyundai Kona Electric (2019), equipped with automatic transmission, three levels of regenerative braking, Virtual Engine Sound System, and cruise control has been used for the experiment. The inside temperature was kept constant at 18 °C. The experimental setup of the car scenario with the Hyundai on the route can be seen in Fig. 1 (left). Participants were seated in the passenger seat and the researcher drove manually. Accelerations, rotations and GPS fix position were recorded with a 6 Degree of Freedom (DoF) Xsens MTi-G-700 accelerometer, which was located at the passenger seat H-point. Accelerometer data were sampled at 400 Hz.

Fig. 1. The Hyundai Kona on the Valkenburg track (left) and the Cruden motion-base driving simulator (right), both in starting position (I) of the route.

2.3.2. Simulator

Fig. 1 (right) shows the Cruden driving simulator. This CE-Certified simulator consists of an AS2 (eM6-640-1500) 6 DoF hexapod motion-base, of which the specifications are shown in Table 1. On top the platform, a vehicular cabin is mounted which features a car seat and controls and is surrounded by a semicircular projection screen. Auditory road and wind noise are provided by three surrounding speakers. Audio levels were set to provide a subjective match with the experience in the car during pilot sessions by the experimenter, but were not matched in terms of dB. Dedicated Cruden Panthera software integrates vehicle dynamics, vision, audio, and motion platform control.

2.3.2.1. Motion Cueing Algorithm. The *classical MCA*, often used as a baseline for other MCAs (Stahl et al., 2014), is used in this study to map vehicle accelerations on the simulator workspace.

The MCA first order high pass frequencies are 12 rad/s (1.9 Hz) and 9 rad/s (1.4 Hz), for longitudinal and lateral motion respectively, which is above the peak sickening frequency of 0.2 Hz (McCauley et al., 1976). Longitudinal and lateral scaling gains of 0.7 and 0.5, respectively, were used. Motion from on-road driving scenarios transferred to a driving simulator 1:1 is often perceived as too intense (Correia Grácio et al., 2014), and scaling factors of 0.5–0.75 are found to be most realistic (Bellem et al., 2017; Fischer and Schwan, 2010; Pretto et al., 2009). Tilt coordination was not implemented, as the driving scenario in the present study consisted mainly of quick slaloming and stop-and-go manoeuvres. Here tilt coordination would not significantly contribute to improved simulations, whereas it may introduce false cues. Atop the MCA, an adaptive washout algorithm (i.e., the Direct Workspace Management algorithm (Veltena, 2014)) is applied to prevent the platform from reaching the workspace boundaries (i.e., hitting the endstops). Participants in the simulator were seated in the driver's seat, as no passenger seat is present. The difference in position and perceived accelerations was compensated for by adding an offset to the lateral distance from the sensor in the virtual world (Center of Gravity of the vehicular cab), to the H-point of the subject, within the MCA.

2.3.2.2. Visualization modality. The simulator visualization system consists of 3 Norxe AS 101–1007 P1+ WQXGA IR projectors with a resolution of 2560 × 1600 and a refresh rate of 120 Hz. Their brightness is 3000 lm. The projectors create a surrounding vision with a radius of 3 m, a projection height of 2.2 m and FoV of 200° horizontally and 50° vertically. Additionally, three LCD displays on the place of the side and rear-view mirrors simulate mirror images.

2.4. Stimuli

The closed-track route that was driven (and virtually recreated for the simulator condition) is located at Valkenburg Airport in the province of South-Holland, the Netherlands. The one-way route (from point I to XIII) as shown in Fig. 2 is 2.5 km long and has an approximate road width of 3 m.

Table 1
Specifications of the Cruden 640 hexapod motion system performance with accelerations based on the standard generic dynamic frame payload (800 kg).

Axis	Position	Velocity	Acceleration
Surge	−0.48 m–0.60 m	0.8 m/s	13 m/s^2
Sway	±0.50 m	0.8 m/s	13 m/s^2
Heave	±0.41 m	0.6 m/s	14 m/s^2
Roll	±23.8°	35°/s	500°/s^2
Pitch	−23.7°–26.0°	35°/s	500°/s^2
Yaw	±25.4°	40°/s	800°/s^2

2.4.1. Car scenario

The route that was driven (Fig. 2) consisted of an alternating sequence of *normal* and *provocative* driving styles. The normal driving style was applied one way (i.e., from point I-XIII), and provocative driving the other way (i.e., from point XIII-I). During normal driving, a constant speed of 30 km/h was maintained with the help of the car's cruise control function. Consequently, driving one way lasts approximately 5 min and turns along the route resulted in lateral accelerations of approximately 4 m/s^2. Provocative driving was implemented to introduce variation in the time course of MISC scores, with the intent to facilitate the comparison of sickness between the simulator and car. During provocative driving, lane changes (slalom) and deceleration/acceleration behaviour (stop-and-go) behind a slower vehicle were replicated in an alternating pattern. These manoeuvres belong to the most frequently occurring in future automated driving (Bellem et al., 2016) and show a strong correlation with self-reported sickness scores (Roe et al., 2007). The slalom motion was performed between point XI and IX at a constant driving speed of 20 km/h. Stop-and-go driving was implemented between point XIII and IX and between IX and I, by driving at speeds varying between 10 and 20 km/h. Both maneuvers were performed at a frequency of 0.2 Hz, which is thought to be the peak frequency for MS sensitivity (McCauley et al., 1976; Persson, 2008). A metronome was used by the driver to maintain this frequency. These manoeuvres result in accelerations of respectively 1 and 2 m/s^2. At the ends (point I and XIII) of the route, a three-point-turn was performed.

One-way normal and provocative driving epochs were alternated 3 times each, or until a stopping criterion was reached. At the end of the driving sequence, a 5 min rest period was introduced. In total, there was thus a maximum of 7 time epochs (i.e., normal driving, provocative driving, normal, provocative, normal, provocative, rest) with a total duration of 38 min.

2.4.2. Simulator scenario

By means of available OpenStreetMap geodata; an elevation map obtained from Shuttle Radar Topography Mission (NASA); and an overlay of recorded GPS position data obtained from the accelerometer during the real-road driving, an artificial trajectory was created that closely resembled the route in the actual environment. A 3D environment suitable for driving was created from these data using MathWorks' VectorZero RoadRunner 2019.0.5 software. Driving layers and object files exported from RoadRunner were imported into Unity 2019.4

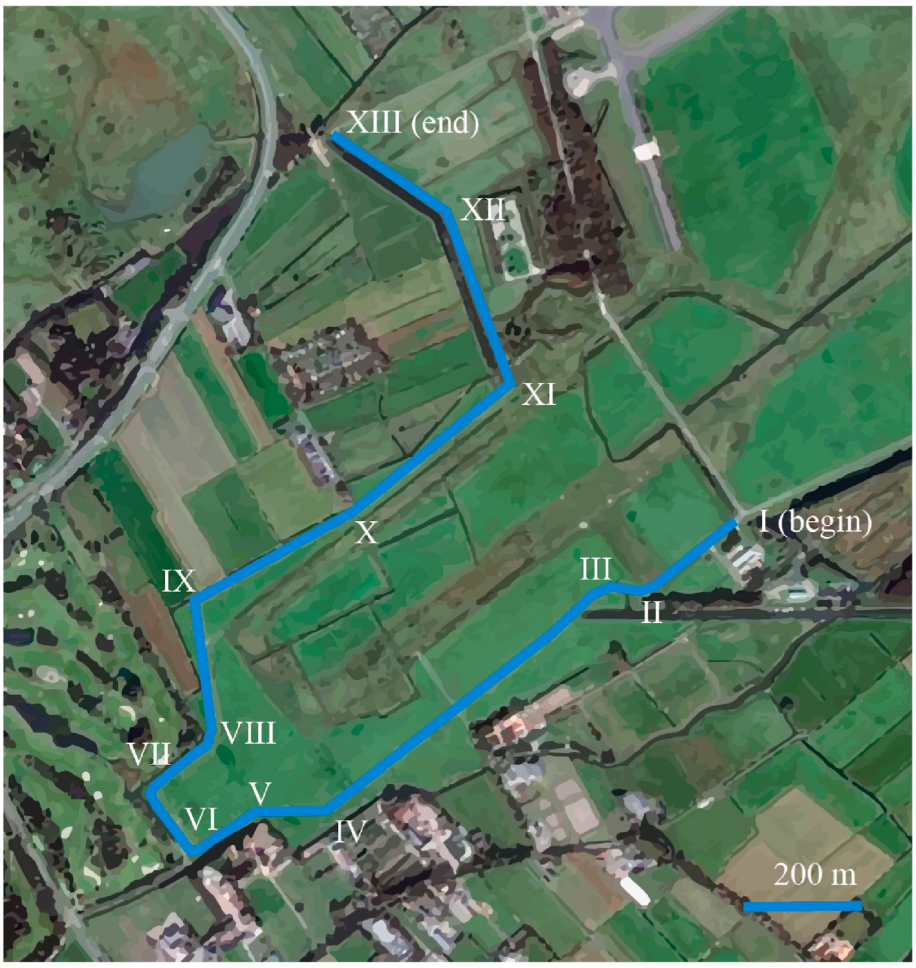

Fig. 2. The 2.5 km route section driven in both scenarios that is located at Valkenburg Airport. The map is obtained from Space Office Netherlands (Satellietdataportaal).

software. Since the presence of peripheral visual cues is said to influence sickness (Moss and Muth, 2011; Karjanto et al., 2018), these are ideally also present in the simulated world, and care was taken to replicate the visual reality as close as possible, as can be seen in Fig. 3. The Unity scene was then imported into the dedicated Panthera 2021B software. The recreated route was driven using Cruden's 6 DoF vehicle model and recorded at 1000 Hz to be played back to participants as the experimental simulator scenario. The parameters (e.g., regenerative braking force) of the model were tuned to ensure that participants would be exposed to acceleration stimuli which are as close as possible to those in the real car. A detailed analysis of the similarity in terms of physical motion cues between the simulator and car scenario is available as supplementary material in the online appendix, Section *A1. Consistency of motion stimuli*. This analysis showed that the vehicle motion in simulator driving closely matched the real-world driving, whereas the amplitude of platform motion cues was significantly reduced in the simulator.

2.5. Task

Since we are interested in MS as it would occur in a real-life scenario, for instance when driving in an automated car, participants in this experiment were considered passengers.

Being a representative non-driving task people may engage in during automated driving, we chose a Sudoku Puzzle. This task is familiar to many people, it needs little explanation and is considered a cognitive task (Ashlesh et al., 2020). Participants were asked to minimize the amount of time spent looking outside and to focus on the puzzle while being driven in the car or simulator. To enhance the task motivation, a prize in the form of a € 15 voucher was awarded to the participant who

Fig. 3. Snapshots of the visual content in the car (left) and artificially created visuals in the simulator (right).

filled out most squares of the puzzle correctly.

MS was monitored using two subjective methods. During presentation of the scenarios, participants provided numerical ratings reflecting their overall sickness level using the MIsery Scale (MISC (Bos et al., 2005)). The MISC is a one-dimensional ordinal rating scale ranging from 0 (no symptoms) to 10 (vomiting), and may be assumed to reflect monotonously increasing levels of sickness (de Winkel et al., 2022). At the conclusion of each scenario, participants filled out the Motion Sickness Assessment Questionnaire (MSAQ (Kennedy et al., 1993; Gianaros et al., 2001)). The MSAQ features 16 symptoms that may each be rated with a number between 1 (not at all) to 9 (severe). The scores are divided into 4 categories: Gastrointestinal (nausea, vomiting), Central (lightheaded, dizzy, spinning), Peripheral (sweaty, feeling warm) and Sopite-related (irritated, drowsy, tired). Whereas the MISC allows for the creation of a sickness time course, the MSAQ provides detailed information about various symptoms and consequent symptom profiles.

2.6. Procedure

Prior to participation, each participant filled out an (online) Motion Sickness Susceptibility Questionnaire (MSSQ (Golding, 1998))-Short form. The mean MSSQ of 13.1 (std = 11.4) indicates a percentile conversion of 57. The MSSQ was not used for participant selection.

Participants were then randomly assigned to participate either first in a simulator session and then in a car session, or vice versa. The experimental sessions were performed on different days, with multiple days in between (mean = 13.2 days, std = 6.7 days), to counteract effects of expectancy, habituation and Mal Debarquement (Hain et al., 1999). A within-subjects design was chosen, as it allowed us to account for the large interpersonal variability typically observed in MS studies (Lackner, 2014).

During the briefing preceding both scenarios, participants were first familiarized with the MISC, after which they were seated in the car/simulator and the scenario was started. Participants were then allowed to start filling out the Sudoku puzzle. During the scenario, participants were cued by the researcher to write down their MISC level on a response sheet every 30 s. After each three-point-turn manoeuvre (points I and XIII), that is, after each change of driving style, MISC levels were entered on a new row of the response sheet. This allowed synchronization of MISC time courses for the car and the simulator scenarios.

Each scenario was terminated either after completion of the 6 normal/provocative driving epochs, or when MISC = 7 (rather nauseated) was reached, or when termination was requested. This level is deemed an ethically appropriate termination point for the experiment. At this point, the 5 min rest period was started, during which MISC level was also monitored.

Directly after the rest period, participants filled out the MSAQ.

2.7. Data analyses

2.7.1. Data processing

Four metrics related to the MISC scores, and two metrics related to the MSAQ scores are calculated:

Individually averaged MISC is an average calculated for each participant over the total exposure, preceding the rest period. In this calculation, the participant's final MISC level is padded with MISC = 7 for the remaining time, if a participant requested termination of the experiment prematurely. This method has been used by various other studies (Webb and Griffin, 2003; Griffin and Newman, 2004; Irmak et al., 2021b) and tries to account for the difference in exposure durations between subjects.

Time-to-MISC represents the time to all (0–7, i.e., 8/11) sickness levels possible in this study. The time to onset of these levels is assigned the maximum value when a certain MISC level is never reached.

Mean MISC refers to the average of MISC levels of all participants for every time step during the full motion excitation in both scenarios. Again, in case of premature termination, data are padded with MISC = 7 for the remainder of the scenario duration. The rest period is left out of this calculation as the onset time of this epoch varies between participants.

MISC rate provides an indication of how sickness has increased or decreased in a time epoch. The rate is calculated by subtracting two time points (being the points I and XIII in Fig. 2) for each epoch within a scenario, and dividing by the epoch's duration.

From MSAQ data, we calculate a **Total MSAQ** and **Subscale MSAQ** scores (Irmak et al., 2021a; Gavgani et al., 2018; Yusof, 2019; Gianaros et al., 2001), which is done respectively as:

$$\text{Total} = \frac{\text{total points}}{144} \cdot 100 \tag{1}$$

$$\text{Subscale} = \frac{\text{subscale total}}{\text{number of subscale items} \cdot 9} \cdot 100, \tag{2}$$

2.7.2. Statistical analyses

The validity of driving simulator studies is often interpreted as the ability to accurately represent research outcomes of real-world driving (Wynne et al., 2019). Various methods to assess the validity of a simulator have been proposed (Blana, 1996; Leonard and Wierwille, 1975), of which the most common assessment distinguishes between absolute and relative validity (Blaauw, 1982). *Absolute validity* occurs when research outcomes of a simulator match with outcomes obtained in a real vehicle in absolute terms. In statistical terms, absolute validity would be supported by (strong) correlations and the absence of significant differences between conditions. *Relative validity* occurs when outcomes of a simulator match those of a real vehicle qualitatively, but are of a different order, direction or magnitude. In statistical terms, relative validity would be supported by (strong) correlations in the presence of significant differences between conditions.

Analyses of correlation were performed for each dependent variable to assess the strength and direction of the association between sickness observed in the car and simulator. Cross-correlation (R_{XY}) or coherence (C_{xy}) was calculated when comparing patterns of sickness between both scenarios over time. Pearson correlation is used when data is normally distributed; Spearman's ρ correlation test is used otherwise.

Differences between conditions were assessed using Linear (Mixed-Effect) Models, where each dependent variable is modeled as a function of the fixed categorical factors *order* (first car or first simulator, to account for order effects), *driving style* (normal or provocative) and *scenario* (car or simulator). *Participant id* was included as a random effect and *time* as a constant effect. As the latter effects were not relevant for the present research questions per se, we do not present an evaluation in the results section. ANOVA is then performed on the fitted models. For metrics of which residuals are found to violate the assumption of normal distributed noise, the Aligned Rank Transform (ART) (Wobbrock et al., 2011; Elkin et al., 2021) ANOVA was used. In contrast to classic nonparametric statistical tests (e.g. Friedman) or rank transformations (e.g. Rank Transform), ART ANOVA allows for multiple factors and their interactions to be analyzed. The ART ANOVA procedure is as follows: For each raw dependent variable, residuals are computed. Then, estimated effects are computed for main and interaction effects. Afterwards, the aligned response is calculated by adding the results of the previous steps. The fourth step is to assign averaged ranks to columns of aligned observations. Lastly, a Linear Mixed Effect Model including all main and interaction effects can be used to perform a full-factorial ANOVA (Littell et al., 1998). Note that conclusions based on findings from either the ART ANOVA or regular ANOVA did not differ qualitatively.

For all tests, we consider as significant $p < 0.05$. When more than one statistical test per dependent variable is used, the chance of committing a Type I error increases, thus increasing the likelihood of coming about a significant result by chance. A Bonferroni correction is then applied to adjust for the number of comparisons. All analyses were performed and visualized using MATLAB R2020b software.

3. Results

3.1. MISC

The raw MISC data for each participant and for both scenarios are shown in Fig. 4. From these individual figures, it may be observed that (1) the highest MISC scores occur in the car scenario, (2) there are considerable interpersonal differences in terms of sickness susceptibility: Some participants reached high levels of sickness within minutes, whereas others endured the complete drive without reporting any symptoms, and (3) the sensitivity to the provocative epochs varies, as some participants' sickness levels increase during provocative driving (coloured areas) and decrease during normal driving (white areas), whereas driving style does not appear to influence ratings for others. The number of participants wishing to terminate the experiment due to nausea (MISC = 7, or a request to prematurely end the experiment for two participants, at MISC = 5 and MISC = 6), was 14 (58%) at the end of the car drive and 0 (0%) for the simulated drive. Except for participant 3, all dropouts occurred during provocative driving epochs.

3.1.1. Individually averaged MISC

The Individually averaged MISC score (mean ± std) was 3.43 ± 1.94 for the car and 1.33 ± 1.26 for the simulator. There is a correlation of $r = 0.57$ ($p = 0.004$) between the average MISC in the car and simulator. A two-way ANOVA (scenario × order) showed that Individually averaged MISC values are higher in the car than in the simulator [$F(1,44) = 30.23$, $p = 0.000$]. There are no effects of order ($p = 0.817$) nor an interaction effect between order and scenario ($p = 0.210$). This result provides support for the conclusion of relative validity between the car and the simulator.

3.1.2. Time-to-MISC

The Time-to-MISC for each MISC level is visualized in Fig. 5. Data for participant 13, who jumped from MISC = 2 to MISC = 6 in one timestep, could not be used for these boxplots. It can be seen that subsequent Time-to-MISC levels increase almost linearly for both scenarios. However, from the (constant) offset in times between scenarios, it can be inferred that these subsequent times are shorter in the car. Lower intercepts for the car drive also indicate that the real-road drive was experienced as sickening more quickly than in the simulator.

A three-factor ANOVA (MISC level × scenario × order) showed that Time-to-MISC differs significantly between MISC levels [$F(6,308) = 17.14$, $p = 0.000$]. Also, it takes participants significantly longer to reach certain sickness levels in the simulator, as compared to the car [$F(1,308) = 4.80$, $p = 0.029$], for original $p < 0.05$. However, this finding becomes non-significant after Bonferroni correction. Cross-correlation on the averaged outcomes for both scenarios shows a very strong significant correlation of $R_{XY} = 0.97$ between the car and the simulator at 0 lag. There were no other significant main or interaction effects. The non-significant difference (after Bonferroni correction) between the Time-to-MISC in the car and the simulator and the strong correlation, indicate absolute validity.

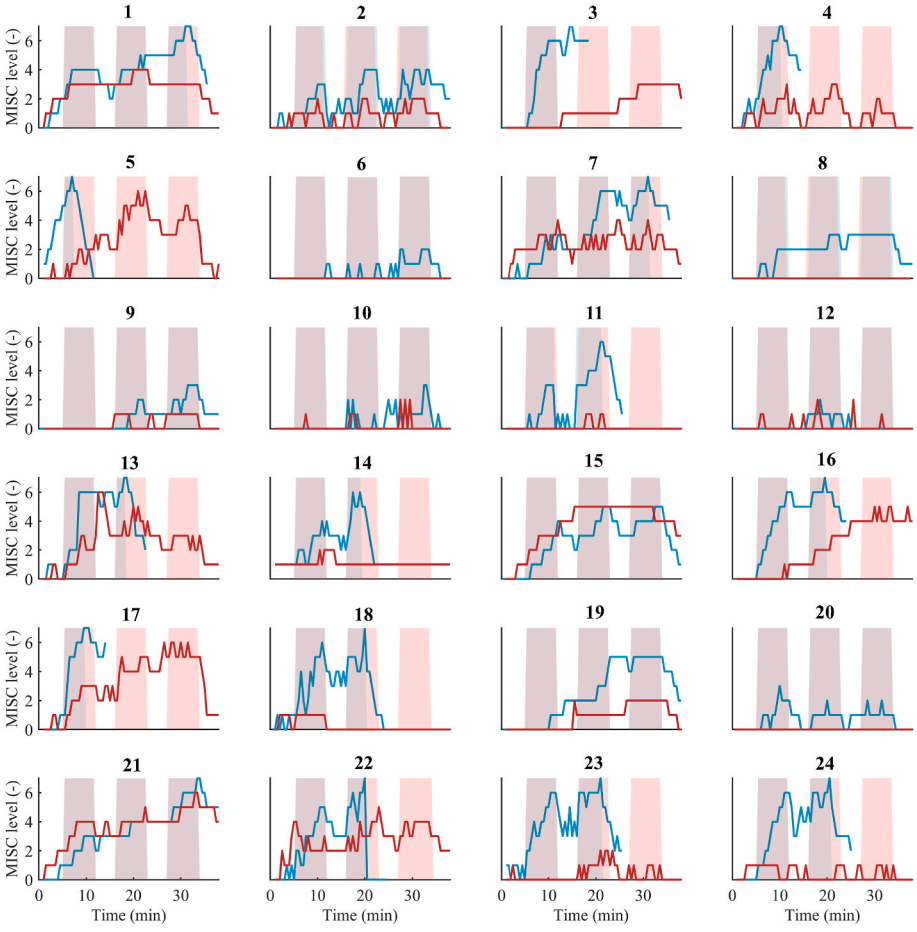

Fig. 4. Individual sickness responses for the car (blue) and simulator (red) of 24 participants. MISC levels for participant 25 have not been recorded for one scenario and are thus left out. The x-axes represent time and the y-axes MISC score (0–7). Red areas denote provocative driving sections in the simulator scenario; blue areas denote provocative driving in the car scenario. When coloured areas overlap, this indicates that periods of normal/provocative driving match, time-wise, between scenarios. From this, it can be seen that there is at most 1 min variability in the on- and offset of different driving styles between scenarios. Every exposure is ended with a 5 min rest period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

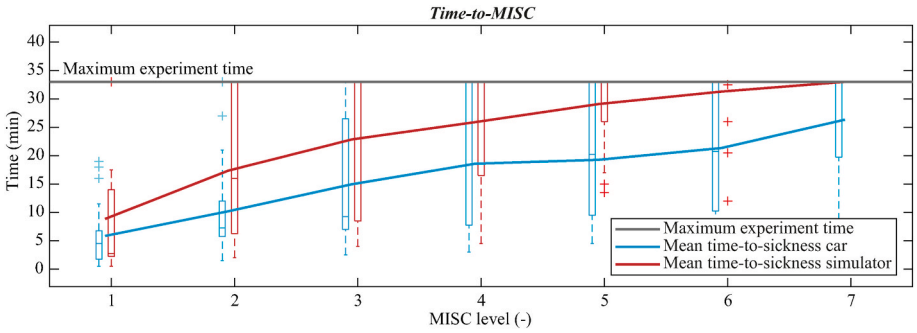

Fig. 5. Time-to-MISC for 24 participants for each of the 8/11 MISC levels used in this study. MISC levels for participant 25 have not been recorded for one scenario and are thus left out. Bold lines represent subject averages per scenario. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers. Outliers are plotted individually with the '+' marker symbol.

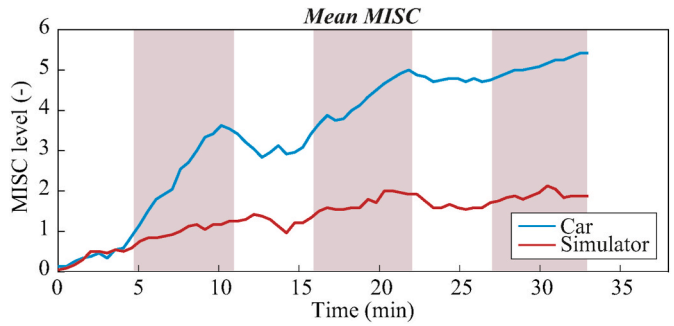

Fig. 6. Mean MISC group response versus time (min) for the car (blue) and the simulator (red) during normal (white) and provocative (coloured) driving. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1.3. Mean MISC

The Mean MISC over all participants at each time step is visualized in Fig. 6. It can be observed that Mean MISC scores for the two scenarios are comparable during the first time epoch (0–5 min), further increase during the provocative driving sections (coloured areas), and decrease or plateau during normal driving for the car scenario. For the simulator scenario, a similar but less noticeable effect is present. Overall, Mean MISC scores are higher in the car than in the simulator. As a result of padding prematurely ended trials with a maximum of MISC = 7, and in particular the car condition stretching to this maximum, Fig. 6 may suggest lower averages than would be observed if participants would have been allowed to continue.

As residuals were found to be non-normal, a two-way ART ANOVA (scenario × order) was conducted. This analysis showed that Mean MISC values were significantly higher in the car than in the simulator [$F(1,259) = 297.55$, $p = 0.000$]. A very strong significant cross-correlation of $R_{XY} = 0.96$ was found at 0 lag. There were no other significant effects. The combination of a significant difference and a strong correlation between the car and the simulator, indicates relative validity for the Mean MISC metric.

3.1.4. MISC rate

The MISC rate for each time epoch in the experiment is shown in Fig. 7. The figure suggests that MISC respectively increases and decreases during provocative and normal driving. This effect appears strongest for the car scenario. The rest time epoch shows a steeper decrease of sickness for the car scenario. As residuals were found to be non-normal, a three-way ART ANOVA (driving style × scenario × order) was conducted. The rest epoch was not included in this analysis. The MISC rate was significantly higher in the car than in the simulator [$F(1,248) = 7.07$, $p = 0.008$], and differed depending on driving style [$F(1,248) = 19.15$, $p = 0.000$]. Further analysis revealed that MISC rate was significantly higher during provocative driving for the car scenario, than for the simulator scenario [$F(1,248) = 14.60$, $p = 0.000$], but almost equal between scenarios during normal driving. No other significant effects were found. Cross-correlation analysis between averaged MISC rates shows a very strong positive correlation of $R_{XY} = 0.95$ at a lag of 0. The combination of a significant difference between rates of sickness in the car and the simulator and strong correlations indicates relative validity for this metric.

3.2. MSAQ

3.2.1. Total MSAQ score

The Total MSAQ score (mean ± std) in the car is rated with 42.5 ± 17.7 and for the simulator as 26.5 ± 16.4. A two-way ANOVA

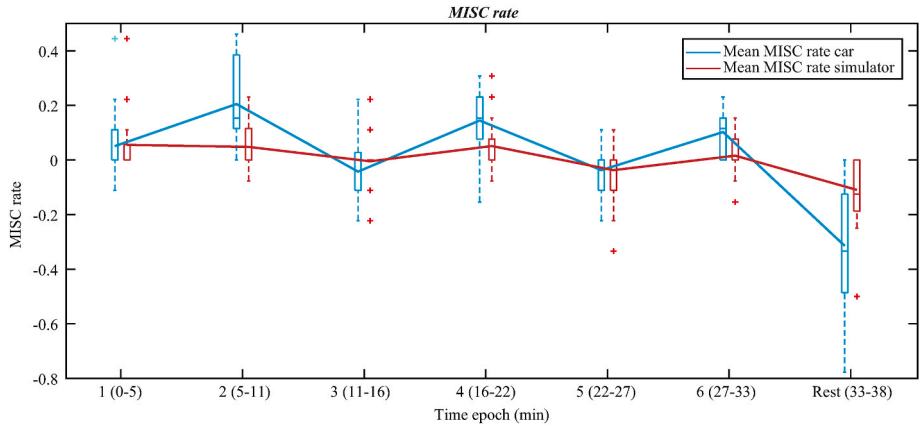

Fig. 7. MISC rate per time epoch for 24 participants, bold lines represent subject averages per scenario. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers. Outliers are plotted individually using the '+' marker symbol.

(scenario × order) showed that scores were significantly higher in the car than in the simulator [$F(1,42) = 27.53$, $p = 0.000$]. This effect was found for all but participant 13. No significant main effect ($p = 0.744$) of order, nor an interaction effect between order and scenario ($p = 0.139$) was found. A strong correlation was found between MSAQ scores in the car and the simulator ($r = 0.64$, $p = 0.002$). The combination of significant difference and a high correlation implies relative validity for this metric.

3.2.2. Subscale MSAQ score

Table 2 shows Subscale MSAQ scores for the four categories. It can be seen that for the car, the averaged symptom profile results in Gastrointestinal > Central > Sopite-Related > Peripheral. For the simulator, this profile shows Central > Sopite-Related > Peripheral > Gastrointestinal. A two-way ANOVA (scenario × order) was performed for each MSAQ subscale. Scores were significantly higher for the car than for the simulator scenario for all subscales: MSAQ-G [$F(1,42) = 23.37$, $p = 0.000$]; MSAQ-C [$F(1,42) = 15.83$, $p = 0.000$]; MSAQ-P [$F(1,42) = 9.11$, $p = 0.004$]; MSAQ-SR [$F(1,42) = 7.94$, $p = 0.007$]. No significant effects of order, or interaction with the order was found. Significant correlations between the car and simulator scores were found for 3 out of 4 subscales. These results indicate relative validity for all but MSAQ-Peripheral subscales.

4. Discussion

We investigated the validity of a moving base driving simulator for research on MS by comparing the time course and symptomatology of sickness as it occurred for participants riding as passengers in an eyes-off-road scenario in a real car, to a rendition of this scenario in a simulator. To the best of our knowledge, this is the first study where the same group of participants is subjected to sickening stimulation in a real car and in a similar simulated scenario. We quantified sickness using several commonly used metrics and evaluated whether these showed absolute, relative or no validity. For all metrics evaluated, at least relative validity may be concluded. In the following, we will interpret these findings to answer our research questions: (1) Are symptoms of SS different from classical MS? (2) Does a relationship exist between individual sensitivities to MS and SS? (3) Are temporal aspects of MS and SS comparable?

4.1. Are symptoms of SS different from classical MS?

The frequently employed MSAQ (Kennedy et al., 1993; Gianaros et al., 2001) was used to obtain a profile of sickness symptoms consisting of four categories, being Gastrointestinal (nausea, vomiting), Central (dizzy), Peripheral (sweaty, feeling warm), and Sopite-related (tired, uneasy). In this study, MSAQ scores show highest values in the Gastrointestinal category for the car scenario, and highest scores in the Sopite-related and Central categories for the simulator. These findings are in line with the studies by Kennedy et al. (2010) and Stanney et al. (1997), who concluded nausea as most prominent for the real environment but not for simulated environments. Regardless of this correspondence with previous research, we believe that different intensity of the inertial motion cues is the cause for the difference in Gastrointestinal scores between the compared conditions. This interpretation is supported by the low Individually averaged MISC scores (1.33 ± 1.26) in the simulator scenario, which indicates that the severity of symptoms had simply not progressed to a level high enough for participants to report high MSAQ nausea ratings. Moreover, when high levels of sickness *are* attained in a simulator environment, such as in a study by Gavgani et al. (2018) where most of the participant dropouts occurred around 6 min, then Gastrointestinal is also found to be the dominant category of symptoms (Gavgani et al., 2017, 2018). Even though Gastrointestinal scores are approximately twice as high in the car in our study, other categories show more similarity between car and simulator. Furthermore, strong correlations were found between the car and the simulator for Gastrointestinal, Central and Sopite-related (3 out of 4) MSAQ categories. The sole non-significantly correlated category, Peripheral, concerns feeling sweaty, clammy or warm. A possible explanation for this only odd result addresses the (outside) experimental conditions. Even though the temperature in the car was intended to be kept approximately constant for every participant, the simulator hall temperature was harder to control. Outside temperatures varied during this experiment period between $0 - 20\,^{\circ}C$, suggesting that ambient temperatures may have increased variability of scores in this category. In light of the above considerations, we conclude that symptom profiles are similar, and that absolute differences in scores are likely caused by differences in motion amplitude between scenarios.

Table 2
Total MSAQ Subscale MSAQ statistics for both scenarios, *p < 0.05 (original). **p < 0.01 (Bonferroni corrected).

	Car	**Simulator**	ANOVA	Correlation
	mean ± std	mean ± std		
Total MSAQ	42.5 ± 17.7	26.5 ± 16.4	F(1,42) = 23.53, p = 0.000**	r = 0.61, p = 0.002**
Gastrointestinal	53.5 ± 26.4	22.8 ± 19.1	F(1,42) = 23.37, p = 0.000**	r = 0.73, p = 0.000**
Central	51.6 ± 25.7	35.5 ± 24.5	F(1,42) = 15.83, p = 0.000**	r = 0.48, p = 0.020*
Peripheral	25.6 ± 17.9	18.5 ± 14.0	F(1,42) = 9.11, p = 0.004**	r = 0.18, p = 0.402
Sopite-Related	39.3 ± 20.0	29.2 ± 21.4	F(1,42) = 7.94, p = 0.007**	r = 0.61, p = 0.002**

4.2. Does a relationship exist between individual sensitivities to MS and SS?

Individual sensitivity can be evaluated by comparing correlations of sickness levels for both the car and the simulator scenario, over the whole exposure period. Measures in this study that represent this individual susceptibility are Total MSAQ scores and the Individually averaged MISC scores, for which strong positive correlations were found. These findings imply that participants who report high levels of sickness in the simulator scenario would do so as well in the car scenario, and vice versa. This finding is in line with the study by Gavgani et al. (2018) who report a significant relation between sensitivity to VIMS and MS. A number of participants showed no, or very little response to either scenario. Also, some participants showed a sickness response only to the car scenario, but not to the simulator scenario. It has been estimated that individuals vary in terms of their sensitivity to motion sickness by up to a factor 10000 (Lackner, 2014), and several studies argue that it is inevitable that a subset of experimental participants is found to be insensitive to a given exposure (Dong et al., 2011; Perrin et al., 2013; Kuiper et al., 2019). Although there are indications that this individual variability can be partly explained by factors such as ethnicity, gender, and age, the exact causes of this variability are still unknown. For the present study, we speculate that the differential effects of the experimental conditions on sickness may be attributed to differences in motion intensity between the conditions. Specifically, it may be that a latent threshold beyond which sickness develops was not reached for those individuals who did not report sickness in the simulator scenario (Kellogg et al., 1964; Oman, 1990; Kufver and Förstberg, 1999). Taken together, the answer to the question addressed in this section is affirmative: Although levels of self-reported sickness are significantly higher in the car scenario than in the simulator, a strong relationship between scores exists on the individual level.

4.3. Are temporal aspects of MS and SS comparable?

The experimental design of the present study allowed us to evaluate the temporal aspects of sickness in the car and simulator scenarios in different ways. First, as MISC scores were monitored at regular intervals for the duration of each scenario, we could calculate the Time-to-MISC, showing how long it took to reach subsequent MISC scores in both scenarios. The analysis of this data showed that even though mean Time-to-MISC levels were unanimously higher for the simulator, with an almost constant offset (Fig. 5), the difference in onset times between MS and SS was not significant. Second, the motion stimuli were designed as a sequence of alternating epochs of normal and provocative driving. Various studies have shown that MS increases during dynamical (provocative) driving (Gruden et al., 2021; Förstberg, 2000; McCauley et al., 1976; Bellem et al., 2017) and it is known that recovery can be observed during rest or less dynamical driving periods (Irmak et al., 2021a; Oman, 1990; Bos et al., 2005). It was therefore expected that the rate at which sickness progressed would differ between the driving styles, giving rise to a distinct pattern in the MISC rate data. Comparison of the MISC rate over time between conditions then allows us to evaluate how changes in MS and SS relate to changes of the motion stimulus. These findings were in line with the expectations, showing that MISC rate was indeed higher during epochs of provocative driving. Although this effect appeared stronger in the car than in the simulator (which we again attribute to difference in motion amplitudes), the pattern distinguishing the two driving styles was present for both scenarios (Fig. 7). Lastly, it can be concluded from all above-mentioned metrics and the percentage of dropouts (58% versus 0%), that the amplitude or intensity of sickness was higher in the car, as compared to the simulator.

4.4. Limitations

Overall, the results of this study indicate the possibility to study MS in a moving base driving simulator, at least during an eyes-off-road scenario. When considering this implication, it is important to note some limitations of this study. Firstly, only questionnaire data were collected. In this respect, it has to be noted that participants' understanding of the symptoms may vary, as may their subjective judgments to the extent to which the symptoms occurred, or the scaling that they used to translate subjective experiences to numerical responses. These considerations translate into additional variability in the data. In the present study, such effects could have for instance obscured differentiating characteristics of MS and SS. One way to address this issue would be to collect objective or physiological data, which may provide converging evidence to either support or refute the present conclusions.

Secondly, whereas the results in this study imply that it may be possible to generalize findings of SS from a moving base driving simulator study to MS by means of some conversion factor, it is critical to note that such a conversion factor will depend on simulator parameters. Bos et al. (2021) argue that it is impossible to study car sickness in a fixed-base simulator. This implies that at a minimum, a simulator should offer some kind of moving base (in addition to the visualization system) in order to achieve some form of validity. It is our interpretation that the present observations of reduced symptoms in the simulator condition relative to the car condition are due to the reduced gain of the inertial motion. Consequently, there must exist a relation between the gain of mechanical motion and the validity of simulator studies. However, given that we have only tested a single simulator configuration, we cannot infer the nature of this relation. Similarly, we cannot make inferences on how validity is affected by the DoF offered by a motion base or the extent to which an given MCA is able to exploit the simulator's motion envelope. The ultimate measure will be the degree of correspondence between the generated and target inertial motion.

Lastly, there may be a point in time where the costs and risks of (experimenting with) high fidelity, high validity simulators with extensive motion workspaces, might no longer outweigh the costs of naturalistic driving studies whilst still not reaching absolute validity. When that point is reached, we have to ask ourselves if MS, or any other variable, is really not better studied in real cars.

5. Conclusion

In order to gain insight into MS, ideally it is studied in a safe environment that offers excellent reproducibility. A moving base driving simulator has the potential to provide this environment, but the validity of simulators for MS research had not been properly evaluated. The literature indicates that differences exist between sickness obtained in a fixed-base simulator (VIMS), sickness obtained in a motion-base simulator (SS) and everyday Carsickness or MS. Here, we set out to evaluate whether and how sickness in a simulator relates to sickness in a car. We did so by characterizing MS as a result of a real-road driving scenario and SS as a result of a replication of this scenario in a motion-base driving simulator. We found that symptoms between MS and SS are similar; that a strong relation exists between individual sensitivity to MS and SS; and that both types of sickness are affected by time and driving style similarly. The only prominent difference between scenarios was the reported severity of sickness. We argue that this difference can be attributed to smaller inertial motion amplitudes in the simulator, imposed by constraints of the simulator motion envelope. The observed relative validity is a promising finding, as it indicates that moving base driving simulators can be used for MS research, and that it may be possible to generalize simulator findings to the real world by means of a conversion factor. It is, however, critical to note that this factor is likely to depend on various simulator-specific properties. Attaining absolute validity may not be feasible, and will require advances in simulator motion cueing, motion envelopes and highly realistic visualizations. Until this future is realized, it is important to keep our eyes on the road ahead.

CRediT authorship contribution statement

Tessa M.W. Talsma: Conceptualization, Methodology, Software, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration. **Omar Hassanain:** Methodology, Software, Writing - Review & Editing. **Riender Happee:** Conceptualization, Writing - Review & Editing, Supervision. **Ksander N. de Winkel:** Conceptualization, Methodology, Formal analysis, Writing - Review & Editing, Supervision.

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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