Transportation Research Part F: Psychology and Behaviour 105 (2024) 196–205

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

journal homepage: www.elsevier.com/locate/trf

Anticipatory cues can mitigate car sickness on the road

A.J.C. Reuten [a,b,*], I. Yunus [c,d], J.E. Bos [b,a], M.H. Martens [e,f], J.B.J. Smeets [a]

[a] Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
[b] Defence, Safety and Security, TNO, Soesterberg, The Netherlands
[c] Department of Safe Vehicle Automation, Volvo Car Corporation, Gothenburg, Sweden
[d] Department of Engineering Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden
[e] Mobility and Built Environment, TNO, Helmond, The Netherlands
[f] Department of Industrial Design, Eindhoven University of Technology, Eindhoven, The Netherlands

ARTICLE INFO

Keywords:
Automated driving
Anticipation
Motion sickness
Self-driving cars
Sensory conflict

ABSTRACT

Car passengers experience much more car sickness than car drivers. We assume that this is because drivers can better anticipate the car's motions. Does helping passengers to anticipate the car's motions then mitigate car sickness? Indeed, laboratory studies have shown that anticipatory cues which announce one-dimensional motions of a linear sled mitigate sickness to a small extent. Does this mitigation generalize to real car driving? We tested this in a car ride on a test track along a trajectory involving lane changes, accelerations, and decelerations. We show that vibrotactile cues mitigated car sickness in passengers. Auditory cues were less effective. The mitigating effect of the vibrotactile cue was considerable: a 40% decrease in car sickness symptoms, a larger effect than we found in the laboratory. Automated vehicles can predict their own motion very well. They could thus provide vibrotactile cues to mitigate car sickness in their passengers.

1. Introduction

The lifetime incidence of car sickness may be as high as 58% (Reason & Brand, 1975), and predominantly concerns car passengers rather than drivers (Schmidt et al., 2020). As the majority of car occupants currently are drivers (Armoogum et al., 2014; BTS, 2023; TSGB, 2022), the number of car travelers susceptible to car sickness will multiply following a human-to-automated driving transition (reviewed by Iskander et al., 2019). Additionally, this transition will include a phase of conditional or high driving automation during which the system could require a take-over of vehicle control (SAE, 2021). Motion sickness, an umbrella term for car sickness, sea sickness and other variants, has been observed to impair human performance (Bos, 2004; Dobie, 2019; Matsangas et al., 2014). Needing to take over vehicle control whilst feeling car sick could thus potentially compromise road traffic safety (Diels & Bos, 2016). For these reasons of comfort and safety, it is essential to find a solution to mitigate car sickness in passengers.

Understanding why car drivers experience less car sickness compared to car passengers provides a starting point for finding a solution. Whereas passengers are passively subjected to the car's motions, drivers actively control them. Rolnick and Lubow (1991) demonstrated that participants in active control of self-motion reported less motion sickness compared to yoked participants passively exposed to the same stimulus. The sensory conflict, or more specifically, neural mismatch theory may provide an explanation for this observation (Oman, 1982; Reason, 1978; Reason & Brand, 1975). The theory proposes that motion sickness develops following a

* Corresponding author at: Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands.
E-mail address: anna.reuten@tno.nl (A.J.C. Reuten).

https://doi.org/10.1016/j.trf.2024.07.006
Received 20 January 2024; Received in revised form 27 May 2024; Accepted 8 July 2024

neural mismatch between integrated vestibular, visual, and somatosensory signals on self-motion, and expectations or predictions thereof as generated by an internal model. During active self-motion, efference copies resulting from motor commands may be used by this internal model to predict afferent sensory output. This could minimize a possible neural mismatch and consequently mitigate motion sickness. The decreased susceptibility of car drivers might thus be explained by their advantage to anticipate self-motion. Finding a way for passengers to better anticipate passive self-motion may accordingly mitigate car sickness.

Automated vehicles can predict their own motion very well, and should be able to respond to unexpected situations quickly. They could provide cues to alert passengers of upcoming driving manoeuvres such as braking or overtaking. Several studies investigated the effectiveness of *anticipatory cues* using visual (de Winkel et al., 2021; Feenstra et al., 2011; Hainich et al., 2021; Karjanto et al., 2018, 2021), auditory (Diels & Bos, 2021; Kuiper et al., 2020; Maculewicz et al., 2021), or tactile (Karjanto et al., 2021; Kremer et al., 2022; Li & Chen, 2022; Reuten et al., 2023, 2024; Yusof et al., 2020) stimuli. A limitation of visual and auditory cues is that they could interfere with tasks that passengers of fully automated vehicles may want to perform. Examples include listening to music, reading, and watching videos – tasks that occupy the auditory and/or visual modality (Detjen et al., 2020; Pfleging et al., 2016; Schmidt et al., 2020). Passengers could accordingly miss a cue (Meng & Spence, 2015) or feel disturbed by it (Diels & Bos, 2021). Visual cues could moreover aggravate, rather than mitigate motion sickness (Karjanto et al., 2021; Stauffert et al., 2020). Providing cues via the tactile modality may therefore be more desirable in automated vehicles. Studies differ regarding their conclusion on the effectiveness of tactile cues: some report a significant reduction in motion sickness (Karjanto et al., 2021; Li & Chen, 2022) whereas others do not (Kremer et al., 2022; Reuten et al., 2023, 2024; Yusof et al., 2020). We argued that the statistical power of our studies was too low (Reuten et al., 2024). An internal meta–analysis of our studies, including a study on auditory cues (Kuiper et al., 2020), showed that anticipatory cues are overall effective in mitigating motion sickness (Reuten et al., 2024). All of these studies were performed in the same laboratory, in which we exposed participants to one–dimensional motion in fore-aft direction on a linear sled. The goal of the current study is to investigate whether the mitigating effect of anticipatory cues generalizes to real car driving.

Here we expose participants sitting in the back seat of a car to trajectories resembling those of everyday car driving, including variations in speed and direction of motion at irregular intervals. It is more difficult to anticipate upcoming motion when it consists of multiple degrees of freedom. Anticipatory cues may therefore be of greater benefit to participants in the current study: their predictions of upcoming motions are prone to larger errors compared to those of participants in the laboratory subjected to one–dimensional motion. To increase the predictive value of the anticipatory cues, we will use directional cues that indicate the (initial) direction of upcoming accelerations. Despite the possible added value of receiving anticipatory cues for more variable motion, variability in driving behaviour may result in some part of the motion being unannounced by the cues, which could lessen their effectiveness. We investigate three research questions in our study. Our first question is whether anticipatory auditory and vibrotactile cues mitigate car sickness in passengers during real car driving. Our second question is whether one of the cues is more effective. Our third question is how users experience anticipatory cues during a real car drive. Car passengers might consider the cues helpful but too intrusive, which could limit their effectiveness as a solution.

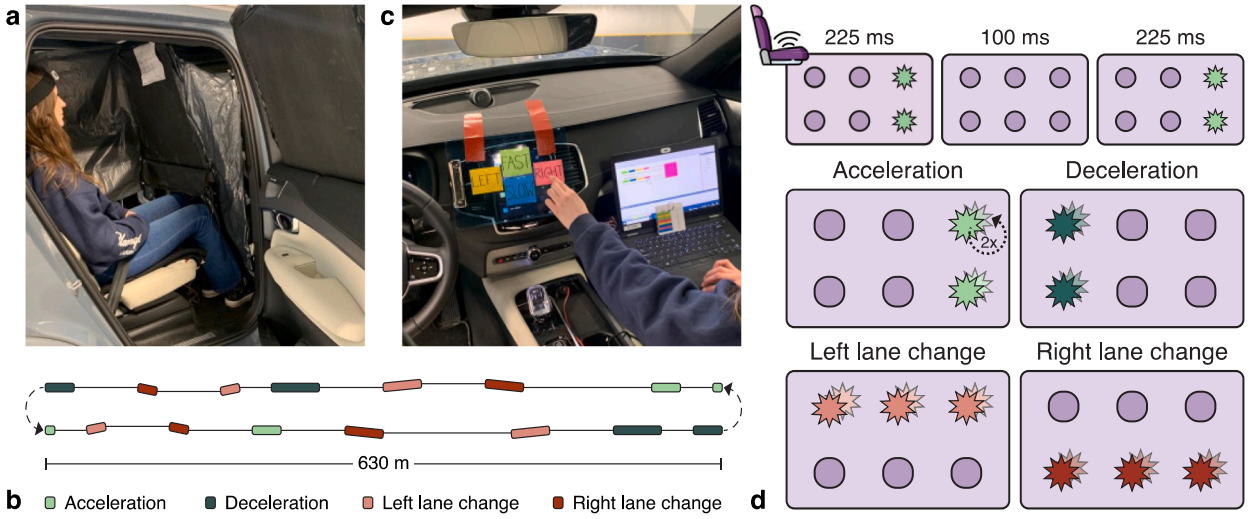

Fig. 1. **a.** Participants sat in the back seat of a car without outside view. We instructed them to keep their head upright, to keep looking straight ahead, and to keep their eyes open. **b.** Example of two driving sequences, connected by low velocity U-turns. Driving manoeuvres (coloured bars) were separated by intervals of 5 or 10 s driving at constant speed (black lines). Long bars correspond to a manoeuvre performed at 40 km/h, short bars to ones at 20 km/h. **c.** The setup used to trigger the cues and to coordinate initiation of the corresponding driving manoeuvre. **d.** Schematic representation of the presentation of vibrotactile cues (top view). The upper half represents the spatial and temporal representation of the vibrotactile cue indicating an accelerating manoeuvre. The row of motors positioned near the knees vibrated for 225 ms. After 100 ms without vibration, there was a second vibration burst of 225 ms of the same row of motors. The bottom half illustrates the row or column of motors activated for each driving manoeuvre. Each cue followed the same temporal pattern as in the top panel. All cues thus lasted 550 ms in total.

2. Methods

We asked participants to take part in three sessions in which they were sitting in the back seat of a car without outside view. A trained driver performed scripted driving manoeuvres that were unpredictable in onset, speed, and direction. In one session, there were no anticipatory cues (control session). In the other two sessions, either an auditory or vibrotactile cue announced the upcoming manoeuvre (anticipatory sessions). To determine if the cues mitigated car sickness, we compared the development of self-reported car sickness symptoms in each anticipatory session to that in the control session. We quantified the reduction in car sickness using the same analysis approach as in our prior studies performed on a linear sled (Reuten et al., 2023, 2024).

2.1. Participants

We intended to recruit a sample larger than in our prior cueing studies to increase statistical power. Because of limited resources, we could however only recruit 15 participants. One participant could not be included in the results because he dropped out after the first session, resulting in a sample size of 14 participants ($M = 34$ years old, 7 females). All participants were Volvo Cars employees who had not participated in studies on anticipatory cueing before. Participants could participate if they had experienced symptoms of motion sickness in the last five years and were in overall good health according to self-report, which included to not suffer from vestibular disorders. We asked participants to fill in the Motion Sickness Susceptibility Questionnaire (MSSQ-short; Golding, 2006) from which we observed that the susceptibility of our sample fell within the 59th percentile, which is within one standard deviation of the general population mean. The study received ethical approval from the Swedish Ethical Review Authority (reference number: 2022-07311-01).

2.2. Motion apparatus and stimulus

We performed the study at a test track (the Hällered Proving Ground in Sandhult, Sweden) to prevent interference from other traffic. We used a left-hand drive Volvo XC90 in which participants sat in the back seat diagonal to the driver. Because vision on the road ahead is known to modulate car sickness (Griffin & Newman, 2004), we used opaque materials to block outside view (see Fig. 1a). Natural daylight entered the car via the rear window, leaving the sitting area moderately lit. Participants could hear engine noises as we did not manipulate auditory information. We set the air conditioning to 20°C with nonzero but minimal airflow.

All sessions consisted of 16 sequences of driving manoeuvres performed at a straight 630 m long track (Fig. 1b). We included the following manoeuvres: accelerations, decelerations, left lane changes, and right lane changes. Drivers practiced performing the manoeuvres with verbal instructions from two experimenters driving along in the test sessions. Moreover, drivers trained to reach a peak acceleration of 2 m/s^2 as guided by direct feedback from an accelerometer. This value corresponded for accelerations and decelerations to a change in speed of 20 km/h in 3 s. Accelerations corresponded to speed increases from 0 to 20 km/h or 20 to 40 km/h; decelerations corresponded to speed decreases from 40 to 20 km/h or 20 to 0 km/h. As our test track was 630 m, we limited maximum speed to 40 km/h because driving at higher speeds would take up a substantial portion of the available track distance. Lane changes consisted of a lateral acceleration immediately followed by a slightly lower deceleration lasting about 3 s in total, resulting in a 3 m lateral displacement. Both left and right lane changes were performed at 20 and 40 km/h. Given that each type of manoeuvre was performed at two speeds, the number of driving manoeuvres totalled to eight. We separated the manoeuvres by pseudorandom intervals of 5 or 10 s driving at constant speed (20 or 40 km/h) to reduce the predictability of motion onset.

To prevent participants from anticipating the next manoeuvre from memory, we predefined four sequences with a different order of the driving manoeuvres (see Supplementary Table S1). Three of the sequences contained all eight manoeuvres, implying that the deceleration to 0 km/h occurred at the end. We created one sequence in which the car also decelerated to 0 km/h halfway the sequence, instead of accelerating to 40 km/h. The lower average speed in this sequence would result in a shorter distance travelled, implying that the car would stop before the starting position of the next sequence. Because the other sequences covered the maximum track distance available, we used longer intervals of driving at constant speed in this sequence. This resulted in a longer sequence duration (~109 s) in comparison to the other three sequences (~74 s). We repeated the four sequences four times, totalling to 16 sequences per session. We created three variations of the order of the 16 sequences and exposed all participants to each variation once – distributing the variations approximately equally across the anticipatory and control sessions. Sequences were connected by verbally announced left U-turns that were performed at minimal driving speed (<5 km/h). We used three drivers throughout the experiment. All participants performed at least two sessions with the same driver. Throughout the experiment, drivers received feedback about the uniformity of their driving behaviour based on the recordings from an accelerometer.

2.3. Anticipatory cues

In the two anticipatory sessions, participants received either auditory or vibrotactile cues which announced upcoming driving manoeuvres. We based the design of our cues on the results of an office pilot study in which we asked colleagues' opinions about the clarity and comfort of various auditory and vibrotactile cues. For the auditory cues, we selected voice recordings of a female voice in a British accent. We used short words (550 ms) to alert the participants: "fast" to indicate accelerations, "slow" to indicate decelerations, "left" to indicate left lane changes, and "right" to indicate right lane changes. To present the vibrotactile cues, we used a seat cushion in which six small (approximately 5 x 20 mm) eccentric rotatory mass vibration motors were embedded across two columns aligned with the upper legs and three lateral rows. Each cue consisted of two 225 ms vibrations bursts of one row or column of motors, with 100 ms

between the two bursts (Fig. 1d). We used the row positioned close to the knees and that close to the hips to indicate accelerations and decelerations respectively. Vibrations of the column of motors beneath the left and right upper leg indicated left and right lane changes respectively.

Following the predefined manoeuvre sequence, the experimenter in the front seat (same person throughout all sessions) activated the cues manually by clicking the corresponding button in a custom-made software program. About half a second after the cue had ended, the experimenter tapped a card of the corresponding manoeuvre on a clipboard mounted on top of the centre console to prompt the driver to initiate the manoeuvre (Fig. 1c). In conclusion, the onset of each cue was approximately 1 s prior to the start of the manoeuvre. This anticipatory interval was preferred in our previous study (Reuten et al., 2023) and has been shown effective in other cueing studies (e.g., Hainich et al., 2021; Kuiper et al., 2020; Li & Chen, 2022).

2.4. Procedure

Participants performed the three sessions in a random order, with each possible order performed by at least one participant. Sessions were separated with a minimum of 1 and maximum of 9 days, except for two participants for whom the duration between two sessions was limited to several hours due to time constraints in their schedule. Prior to starting the first session, we provided participants the opportunity to read an information letter about the experiment. After answering any questions, we asked them to sign an informed consent sheet and to fill out the MSSQ-short. For each session, we drove participants to a test track located five minutes away from the office. During this short journey, participants sat in the front passenger seat with outside view to minimize the risk of developing car sickness.

After arriving at the test track, participants moved to the back seat diagonal to the driver where they received additional instructions. We explained participants how to use the Motion Illness Symptoms Classification scale we used throughout the experiment (MISC; Bos et al., 2005; Reuten et al., 2021). We also described the four types of driving manoeuvres the car would perform. Prior to starting an anticipatory session, we let participants hear or feel all four cues two times. The first time, we explained which manoeuvre the cue announced. The second time, we asked participants to indicate which manoeuvre they thought the cue announced. All participants performed this task without errors. Lastly, we instructed participants to keep their head upright, to keep looking straight ahead, and to keep their eyes open. After the instructions, we asked participants to rate a pre-test MISC score. All ratings were MISC ≤ 1 with a single exception of MISC $= 2$ for one participant in one session. We aborted a session when a participant rated MISC ≥ 7. After each session and at the end of the experiment, we asked participants to fill out a user experience questionnaire at the office.

2.5. Data collection

Our main focus was on the development of car sickness symptomatology during the sessions. The MISC is a single value self-report rating scale that is based on the progression of motion sickness symptoms, with a severity grading within each symptom class (Table 1). We asked participants to verbally indicate their MISC score right after each sequence, just before the turn, using the MISC. Motion sickness ratings were thus never made whilst receiving an anticipatory cue. Additionally, we collected acceleration data of the car and the head motion of the participant (the latter not analysed in this paper). We used an OxTS RT3000 IMU to measure the car's accelerations, which was configured to provide an estimation of the accelerations acting on the participant.

To gain more insight into the user experience of the anticipatory cues, we asked participants to complete a questionnaire after each session and at the end of the experiment. After each session, we asked participants to indicate if and when they noticed the cues (multiple-choice). If they had noticed cues, we asked them to indicate how many times those were presented (multiple-choice); and to evaluate them along several user experience dimensions (Likert scale). At the end of the experiment, we asked participants if they realized that the cues had always been presented at a fixed moment relative to the onset of the driving manoeuvres (multiple-choice); which cue they preferred to announce upcoming driving manoeuvres (multiple-choice); to rank the sessions from most to least favourite (rank); if they would want to use the cue they preferred in their (self-driving) car (multiple-choice); and how much money they would be willing to spend extra on a car preventing car sickness (open-ended).

Table 1
The Motion Illness Symptoms Classification (MISC) used to assess motion sickness symptomatology (Bos et al., 2005; Reuten et al., 2021).

Class description		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, yawning, headache, tiredness, sweating, stomach / throat awareness, burping, blurred vision, salivation,	vague	2
… but no nausea	little	3
	rather	4
	severe	5
Nausea	little	6
	rather	7
	severe	8
	retching	9
Vomiting		10

2.6. Data analysis

To determine the effectiveness of the anticipatory cues, we use the same data analysis approach as in our prior studies (Reuten et al., 2023, 2024). Using this approach, we can quantify the reduction in the development of car sickness in each anticipatory session relative to the control session in one value: R. This allows for an easy comparison of the effectiveness of anticipatory cues (or other interventions) between experimental sessions and studies. For each cue, we determine R using the steps described below.

We first calculate the reduction in MISC scores between the anticipatory (A) and control (C) session at each turn (t) and individual participant (i) by

$$R_{ti} = \frac{(C_{ti} - A_{ti})}{(C_{ti} + A_{ti})} \tag{1}$$

This relative reduction value facilitates the interpretation of the effectiveness of the cues as the distribution of R is symmetrical around zero (indicating no effect), with a maximum value of 1 ($A_{ti} = 0, C_{ti} \neq 0$) and mimum value of -1 ($A_{ti} \neq 0, C_{ti} = 0$). We do not determine R_{ti} for pre-test measurements and cannot determine R_{ti} for sequences without data (i.e., after reaching the stop-criterion). Also, when $C_{ti} = A_{ti} = 0$, it is impossible to determine R_{ti}. This is not problematic for our analysis as we weigh the data as explained below; undefined R_{ti} values will receive a weight of zero. Because participants typically rate MISC 0 or 1 at the beginning of a session, R_{ti} will have a value of -1, 0 or 1 for the first sequences. To take account of the resolution of R_{ti} when determining the average reduction across a session, we weigh each of the 16 obtained R_{ti} values by the sum of the two underlying MISC scores. Consequently, R_{ti} values that are calculated on higher MISC scores will receive a larger weight

$$w_{ti} = C_{ti} + A_{ti} \tag{2}$$

We can then calculate the average reduction per participant i by

$$\overline{R}_i = \frac{\sum_t w_{ti} R_{ti}}{\sum_t w_{ti}} = \frac{\sum_t (C_{ti} - A_{ti})}{\sum_t w_{ti}} \tag{3}$$

and at each turn t by

$$\overline{R}_t = \frac{\sum_i w_{ti} R_{ti}}{\sum_i w_{ti}} = \frac{\sum_i (C_{ti} - A_{ti})}{\sum_i w_{ti}} \tag{4}$$

Equation (3) indicates that $\overline{R}_i$ is proportional to the sum of MISC score differences between the anticipatory and control session. To express the overall reduction generated by the cue across all turns and participants, we again consider the resolution of R_{ti} using

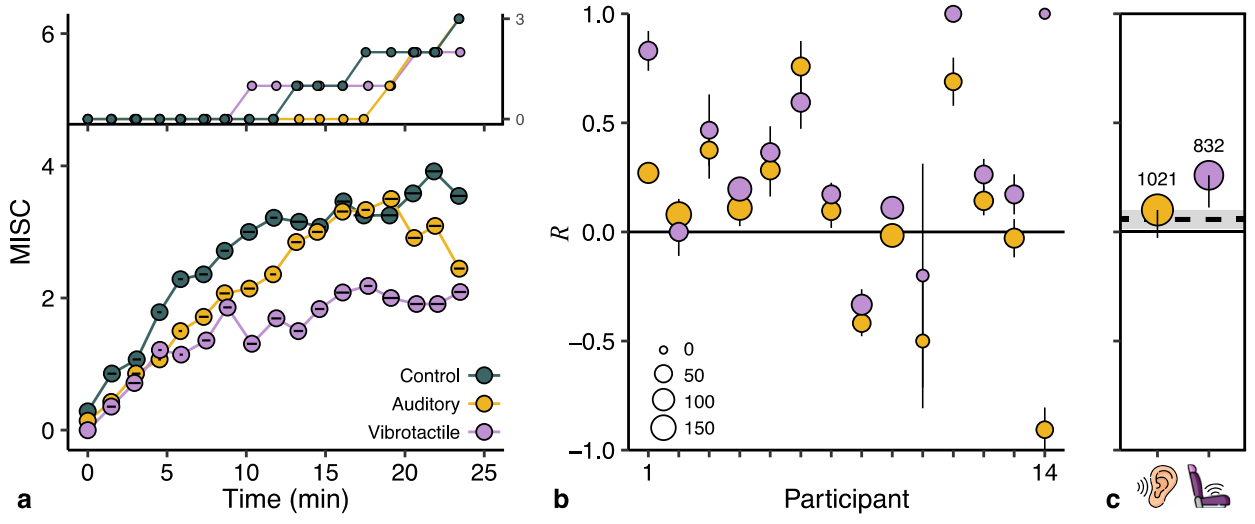

Fig. 2. a. The development of car sickness during each session as a function of time. The (small) horizontal error bars represent the standard deviation of the cumulative duration of the sequences. After a participant reached the stop-criterion (frequency in inset), they do not longer contribute to the average of that session as we did not replace missing data, resulting in a decrease of the average MISC. If the stop-criterion was reached in the control session, we excluded the data of this participant on the corresponding sequences in the anticipatory sessions (similar to R in the other panels). **b.** The reduction in car sickness for individual participants ($\overline{R}_i$) in the two anticipatory sessions in comparison to the control session. Error bars are 95% confidence intervals. **c.** The overall reduction in car sickness across all sequences and participants for each cue. Coherent with our one-sided analysis, we plot 95% one-sided confidence intervals. The dashed line represents the overall reduction of anticipatory cues we found in the laboratory, with the grey band representing their 95% confidence interval. In panels b and c, the size of a data point reflects its weight, corresponding to the sum of MISC scores underlying the data (see legend).

$$\overline{R} = \frac{\sum_t \sum_i w_{ti} R_{ti}}{\sum_t \sum_i w_{ti}} = \frac{\sum_i w_i \overline{R}_i}{\sum_i w_i}, \text{ with } w_i = \sum_t w_{ti} \tag{5}$$

To translate this final value into a more intuitive measure, we provide a conversion of R to a percentual decrease in MISC score (i.e., $S = (1 - A/C) \times 100$) in Supplementary Figure S1. Note that we use the measure R instead of a percentage change as exchanging C and A only results in a change of sign of R. This makes it suitable for averaging: if C and A are drawn from a random distribution, the average of R will be zero, whereas the average of S will become negative.

2.7. Statistical analysis

Our first question is whether our anticipatory auditory and vibrotactile cues mitigated car sickness. For both cues, we accordingly performed a weighted one-sided t test ($\alpha = 0.05$) on the $\overline{R}_i$ values (each weighted by w_i) to determine whether the overall reduction $\overline{R}$ was larger than zero (corresponding to no reduction). We express the confidence of our estimates of $\overline{R}$ in one-sided 95% confidence intervals (coherent with our one-sided analysis) using bootstrapping of $\overline{R}_i$ and corresponding weights. Our second question is whether one cue was more effective in mitigating car sickness. We hence performed a weighted paired samples t test ($\alpha = 0.05$) between the $\overline{R}_i$ values (each weighted by w_i) of the auditory and vibrotactile session. We here determine 95% two-sided confidence intervals calculated with bootstrapping of R_{ti} and corresponding weights to express the confidence of our estimates of $\overline{R}_i$. Our last question focused on gaining insight into the user experience of anticipatory cues during a real car ride. We analysed the results of the user experience questionnaire using visualizations of descriptive statistics without performing statistical tests.

3. Results

Before answering our research questions, in Fig. 2a we present an impression of the overall behaviour: the average MISC score across participants at each turn as a function of the average cumulative sequence duration (see Supplementary Figure S2 for the raw data per participant). The duration of the sequences was comparable across participants in all sessions: in Fig. 2a, the horizontal error bars within each data point are small. They indicate the standard deviation across participants of the cumulative duration of the driving sequences until that data point. The pattern of MISC scores suggests a reduction in car sickness in both anticipatory sessions compared to the control session, with a larger reduction for the vibrotactile cue.

To answer our first question, we used our measure R to quantify the reduction in car sickness for each cue per participant (Fig. 2b). The resulting $\overline{R}_i$ values differ considerably between participants, but most participants received some benefit from both cues (both data points are above zero). For both cues, $\overline{R}_t$ did not vary systematically across the sequences of a session (Supplementary Figure S3). As the cues generated a constant effect, it is meaningful to express the effectiveness of each cue in one value. On average, the overall reduction appears larger for the vibrotactile cue (Fig. 2c). The weighted one-sided t test indicated that the vibrotactile cue significantly mitigated

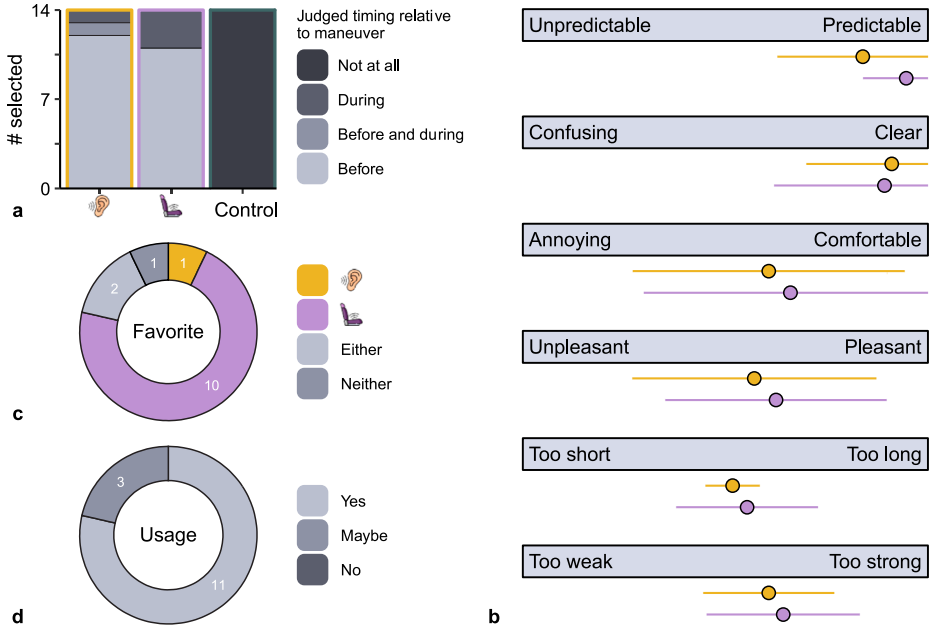

Fig. 3. Results of the user experience questionnaire in which participants **a.** indicated if and when they thought anticipatory cues were presented, **b.** evaluated the cues along several user dimensions, **c.** indicated which cue they preferred to announce upcoming driving manoeuvres, and **d.** if they would want to use their favourite cue in their (automated) car.

car sickness, with $\overline{R} = 0.26$ ($t = 2.8$, $p = 0.014$). The reduction generated by the auditory cue was not significantly larger than zero, with $\overline{R} = 0.10$ ($t = 1.9$, and $p = 0.085$).

To answer our second question, we tested whether the two cues differed in the generated reduction of car sickness. In line with visual inspection of the data, the weighted paired samples t test indicated that the vibrotactile cue generated a significantly larger reduction in car sickness compared to the auditory cue, with a weighted $\overline{R}$ difference of -0.13 ($t = -2.6$, $p = 0.021$).

In addition to these planned comparisons, we explored whether the effectiveness of the cues in the current study differed from that in our prior laboratory studies performed on a linear sled. We therefore plot the results from an internal meta–analysis on the overall effect of anticipatory cues ($\overline{R} = 0.06$; Reuten et al., 2024) with their 95% confidence interval in Fig. 2c. The confidence interval of the auditory cue overlaps, whereas that of the vibrotactile cue falls above the upper bound of the overall effect. This suggests that our vibrotactile cue was more effective in mitigating car sickness during a real car drive compared to anticipatory cues in the laboratory.

To answer our third question, we investigated the responses to the user experience questionnaire. The results indicated that all participants had noticed the auditory and vibrotactile cues for all driving manoeuvres. The majority of participants also correctly indicated that the cues were presented before the onset of each manoeuvre (Fig. 3a). Unsurprisingly, no participant indicated to have noticed cues in the control session. After the experiment, we asked participants if they realized that the cues had always been presented at a fixed moment relative to the onset of the manoeuvres. Twelve participants indicated they did in both anticipatory sessions, the two other participants indicated they did only in the vibrotactile sessions.

On the whole, participants rated both cues positively along several user dimensions (Fig. 3b). The cues helped participants to predict the onset of the manoeuvres and the message they conveyed was clear. In terms of comfort and pleasantness, the cues were rated acceptable on a group level. The standard deviation on these dimensions was however large, indicating that participants disagreed concerning these aspects. The duration of the cues was rated neutral, with more variability in responses for the vibrotactile cue. The intensity of the cues was appropriate, with responses tending towards being too strong rather than being too weak. In Supplementary Figure S4, we present the results of some exploratory analyses on the relationship between several user dimensions as well as their relationship with $\overline{R}_i$.

By far the most participants expressed a preference for the vibrotactile cue (Fig. 3c). They reported that this cue was more intuitive and easier to understand, as well as less intrusive and annoying compared to the auditory cue. When asking participants to rank the sessions from most to least favourite, we obtained a corresponding overall ranking: 1) vibrotactile session, 2) auditory session, and 3) control session. A frequency table on the rankings can be found in Supplementary Table S2.

The majority of participants would want to use the cue they preferred in their (automated) car (Fig. 3d). Several participants mentioned that a cueing system should be optional in use and implemented as a turn-on/turn-off function. The amount of money participants were willing to pay for a car preventing car sickness varied between €0 and €4400, with an average of €513.

4. Discussion

In prior laboratory studies, we demonstrated the potential of anticipatory cues as a solution to mitigate motion sickness under controlled experimental conditions for one–dimensional motion. Does their effect generalize to real car driving? We exposed participants sitting in the back seat of a car without outside view to three sessions of unpredictable driving manoeuvres. In two anticipatory sessions, either auditory or vibrotactile cues announced whether the car would accelerate, decelerate, make a left lane change, or a right lane change. Using the same analysis approach as in our previous studies (Reuten et al., 2023, 2024), we determined the reduction in the development of self-reported car sickness in each anticipatory session relative to a control session without cues. The results indicate that the vibrotactile cues mitigated car sickness (Fig. 2c). Auditory cues were less effective (Fig. 2b) and generated no mitigation overall (Fig. 2c). In accordance with the results on the effectiveness of the cues, participants expressed a clear preference for the vibrotactile cue (Fig. 3c). The reduction in car sickness they generated was larger than the overall reduction generated by anticipatory cues in the laboratory (Fig. 2c). The mitigating effect of our vibrotactile cue translates to a 40% reduction in car sickness symptoms (Supplementary Figure S1).

Besides the anticipatory cues, differences in driving behaviour between the sessions could have influenced R. To rule out this possibility, we investigated the car's accelerations. We analysed the difference in the sickening component of the total of linear accelerations between each anticipatory and control session. For all sessions, we first calculated the motion sickness dose per unit of time (corresponding to the frequency weighted root mean square acceleration a_w) wherein we used the weighting W_f as recommended by ISO 2631-1 (1997). This approach accounts for participants stopping a session early as opposed to calculating conventional motion sickness dose values that increase with exposure duration (ISO 2631-1, 1997). For all participants, we then calculated the difference in a_w between each anticipatory and control session. Based on these differences, we determined a 95% confidence interval around the mean for each comparison. Both intervals included zero, indicating that there was no systematic difference in the sickening component of driving behaviour between the anticipatory and control sessions.

The smaller (and non-significant) reduction generated by the auditory cues might indicate that the auditory modality is less suited to mitigate car sickness. However, this interpretation might be incorrect when considering that the significant reduction generated by comparable auditory cues in Kuiper et al. (2020) was of equal size: $R = 0.10$ (see Reuten et al., 2023). As our sample consisted of only 14 participants, the statistical power of our study may have been too low to demonstrate a significant reduction by the auditory cue. Nonetheless, two reasons may indicate that it holds greater value to focus future research on optimizing the effect of vibrotactile cues. First, the vibrotactile cues did generate a considerable (and significant) reduction in car sickness despite our small sample. Second, participants preferred the vibrotactile cue. It was described as intuitive and easy to understand whereas the auditory cue was described

as intrusive and annoying. Vibrotactile cues may also be more desirable in the context of automated driving: they do not interfere with audiovisual tasks passengers may want to perform (Detjen et al., 2020; Pfleging et al., 2016; Schmidt et al., 2020). Even though auditory cues could possibly be effective, it may be more worthwhile to elaborate on the optimization of vibrotactile cues in future studies.

A question that we cannot answer from our study is how to explain the effectiveness of the anticipatory vibrotactile cues. We assume that their effect is not the result of possible distraction from motion sickness, as the cues had a combined total duration of only a few seconds per driving sequence. Moreover, the auditory cues with presumably similar distractive properties were not effective. The vibrotactile cues might have influenced the head or upper body motion of the passengers: tilting into the direction of centrifugal force has been shown to reduce motion sickness (e.g., Karjanto et al., 2021; Wada & Yoshida, 2016) as has minimizing pitch and roll head motion (e.g., Bles et al., 1998; Golding et al., 2003; Joseph & Griffin, 2008; Kato et al., 2021). Even though we cannot explicate the working mechanism of our anticipatory cues, in some way they contributed to reducing a neural mismatch on sensory signals on self-motion. We assume they did so by helping passengers to anticipate their self-motion. Even if reducing a neural mismatch is not the correct explanation, our main finding holds. Anticipatory vibrotactile cues can mitigate motion sickness in real car driving.

Our study shows that anticipatory vibrotactile cues can mitigate car sickness in passengers. The increased effectiveness of the cues in the present study compared to our previous studies (Reuten et al., 2023, 2024) suggests that anticipatory cues have greater value for participants when they reduce more uncertainty about upcoming motions, i.e. when the cues have more degrees of freedom. Our cues mitigated car sickness despite the fact that some part of the motion was not announced due to variability in human driving behaviour. Which motions and nuances therein should cues convey during real-life car driving? Providing car passengers information about the sharpness of a curve or the intensity of braking might enhance the effect of anticipatory cues. However, providing cues for unprovocative motion should be avoided as this could lower user acceptance and may result in passengers disabling the cueing system (Reagan et al., 2018). If found beneficial, nuances in motion parameters may be conveyed by varying the temporal and spatial aspects of a cue. For example, individuals associate shorter intervals between vibration pulses or auditory beeps with a greater sense of urgency (Edworthy et al., 1991; Meng & Spence, 2015; Van Erp et al., 2015). As the driving system's prediction accuracy is higher for accelerations in the near future, studies should consider investigating these questions for anticipatory intervals limited to a few seconds. The results from Reuten et al. (2023) suggest that the effectiveness of vibrotactile cues does not depend on their timing for intervals of 0.33, 1 and 3 s, though the statistical power of that study was limited. In any case, human limitations in the ability to detect, distinguish, and understand different cues should be considered in the design of a cueing system (e.g., Jones & Sarter, 2008; Fitch et al., 2011; Nees & Walker, 2011; Petermeijer et al., 2016; Duthoit et al., 2018).

Large scale surveys indicate that members of the public express concern about perceived risks and safety, or in a broader term those aspects relating to trust in the automated driving system (Choi & Ji, 2015; Kyriakidis et al., 2015; Schoettle & Sivak, 2014; Ward et al., 2017). Communication of the system's understanding of the environment and its planned driving manoeuvres have been proposed as a way to increase trust (Ha et al., 2020; Koo et al., 2015; Von Sawitzky et al., 2019). Besides mitigating car sickness, anticipatory cues could thus have additional advantages for passengers of automated vehicles.

In previous studies, we demonstrated the overall effectiveness of anticipatory cues in the laboratory. Here we show that the effect of vibrotactile cues generalizes to real car driving. They mitigated car sickness in passengers exposed to driving manoeuvres resembling those of everyday car driving. The mitigating effect of the vibrotactile cue was considerable: a 40% decrease in car sickness symptoms, a larger effect than we found in the laboratory. To our knowledge, our study is the first to demonstrate the effectiveness of vibrotactile cues to mitigate car sickness for both lateral and longitudinal driving manoeuvres. Automated vehicles can predict their own motion very well. They could thus provide vibrotactile cues to mitigate car sickness in their passengers. This could alleviate the expected increase of car sickness in society following the introduction of (fully) automated vehicles. To conclude, our study demonstrates the effectiveness of anticipatory vibrotactile cues as a solution to mitigate car sickness in passengers.

Ethics approval

We obtained ethical approval from the Swedish Ethical Review Authority (reference number: 2022-07311-01).

Funding

This work was supported by Volvo Car Corporation, Ford Motor Company, TNO, and the Vrije Universiteit Amsterdam. Additional funding was provided by the Amsterdam Movement Sciences via the 2020 travel grant received by the first author.

CRediT authorship contribution statement

A.J.C. Reuten: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **I. Yunus:** Writing – review & editing, Resources, Project administration, Investigation, Formal analysis. **J.E. Bos:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **M.H. Martens:** Writing – review & editing, Supervision, Methodology, Conceptualization. **J.B.J. Smeets:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank Volvo Car Corporation for their support of the PhD project of the first author. In specific, we thank Willy Tunbratt for his efforts to facilitate the study. We also thank the test drivers for driving the vehicle, and the participants for taking part in the motion sickening car drives.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2024.07.006.

References

Armoogum, J., Bonsall, P., Browne, M., Christensen, L., Cools, M., Cornélis, E., Diana, M., Harder, H., Reinau, K. H., Hubert, J.-P., Kuhnimhof, T., Madre, J.-L., Moiseeva, A., Polak, J., & Tébar, M. (Eds.). (2014). *Survey Harmonisation with New Technologies Improvement (SHANTI)*. Les collections de l'INRETS.

Bles, W., Bos, J. E., de Graaf, B., Groen, E., & Wertheim, A. H. (1998). Motion sickness: Only one provocative conflict? *Brain Research Bulletin, 47*(5), 481–487. https://doi.org/10.1016/S0361-9230(98)00115-4

Bos, J. E. (2004). How motions make people sick such that they perform less: A model based approach. *RTO AVT Symposium on Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion*, RTO-AVT-110. Doi: 10.14339/RTO-MP-AVT-110.

Bos, J. E., MacKinnon, S. N., & Patterson, A. (2005). Motion sickness symptoms in a ship motion simulator: Effects of inside, outside, and no view. *Aviation, Space, and Environmental Medicine, 76*(12), 1111–1118.

BTS. (2023). Pocket guide to transportation 2023. *Bureau of Transportation Statistics*. https://doi.org/10.21949/1527467

Choi, J. K., & Ji, Y. G. (2015). Investigating the importance of trust on adopting an autonomous vehicle. *International Journal of Human-Computer Interaction, 31*(10), 692–702. https://doi.org/10.1080/10447318.2015.1070549

de Winkel, K. N., Pretto, P., Nooij, S. A. E., Cohen, I., & Bülthoff, H. H. (2021). Efficacy of augmented visual environments for reducing sickness in autonomous vehicles. *Applied Ergonomics, 90*, Article 103282. https://doi.org/10.1016/j.apergo.2020.103282

Detjen, H., Pfleging, B., & Schneegass, S. (2020). A Wizard of Oz field study to understand non-driving-related activities, trust, and acceptance of automated vehicles. In *Proceedings of the 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 19–29). https://doi.org/10.1145/3409120.3410662

Diels, C., & Bos, J. E. (2016). Self-driving carsickness. *Applied Ergonomics, 53*, 374–382. https://doi.org/10.1016/j.apergo.2015.09.009

Diels, C., & Bos, J. E. (2021). Great expectations: On the design of predictive motion cues to alleviate carsickness. In H. Krömker (Ed.), *HCI in Mobility, Transport, and Automotive Systems* (pp. 240–251). Springer Nature. Doi: 10.1007/978-3-030-78358-7.

Dobie, T. G. (2019). In *Motion sickness: A motion adaptation syndrome*. Springer Nature. https://doi.org/10.1007/978-3-319-97493-4.

Duthoit, V., Sieffermann, J.-M., Enrègle, É., Michon, C., & Blumenthal, D. (2018). Evaluation and optimization of a vibrotactile signal in an autonomous driving context. *Journal of Sensory Studies, 33*(1), e12308.

Edworthy, J., Loxley, S., & Dennis, I. (1991). Improving auditory warning design: Relationship between warning sound parameters and perceived urgency. *Human Factors, 33*(2), 205–231. https://doi.org/10.1177/001872089103300206

Feenstra, P. J., Bos, J. E., & van Gent, R. N. H. W. (2011). A visual display enhancing comfort by counteracting airsickness. *Displays, 32*(4), 194–200. https://doi.org/10.1016/j.displa.2010.11.002

Fitch, G. M., Hankey, J. M., Kleiner, B. M., & Dingus, T. A. (2011). Driver comprehension of multiple haptic seat alerts intended for use in an integrated collision avoidance system. *Transportation Research Part F: Traffic Psychology and Behaviour, 14*(4), 278–290. https://doi.org/10.1016/j.trf.2011.02.001

Golding, J. F. (2006). Predicting individual differences in motion sickness susceptibility by questionnaire. *Personality and Individual Differences, 41*(2), 237–248. https://doi.org/10.1016/j.paid.2006.01.012

Golding, J. F., Bles, W., Bos, J. E., Haynes, T., & Gresty, M. A. (2003). Motion sickness and tilts of the inertial force environment: Active suspension systems vs. Active passengers. *Aviation, Space, and Environmental Medicine, 74*(3), 220–227.

Griffin, M. J., & Newman, M. M. (2004). Visual field effects on motion sickness in cars. *Aviation, Space, and Environmental Medicine, 75*(9), 739–748.

Ha, T., Kim, S., Seo, D., & Lee, S. (2020). Effects of explanation types and perceived risk on trust in autonomous vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour, 73*, 271–280. https://doi.org/10.1016/j.trf.2020.06.021

Hainich, R., Drewitz, U., Ihme, K., Lauermann, J., Niedling, M., & Oehl, M. (2021). Evaluation of a human–machine interface for motion sickness mitigation utilizing anticipatory ambient light cues in a realistic automated driving setting. *Information, 12*(4), 176. https://doi.org/10.3390/info12040176

Iskander, J., Attia, M., Saleh, K., Nahavandi, D., Abobakr, A., Mohamed, S., Asadi, H., Khosravi, A., Lim, C. P., & Hossny, M. (2019). From car sickness to autonomous car sickness: A review. *Transportation Research Part F: Traffic Psychology and Behaviour, 62*, 716–726. https://doi.org/10.1016/j.trf.2019.02.020

Iso. (1997). *Mechanical vibration and shock: Evaluation of human exposure to whole-body vibration* (second ed., p. 2631). International Organization for Standardization.

Jones, L. A., & Sarter, N. B. (2008). Tactile displays: Guidance for their design and application. *Human Factors, 50*(1), 90–111. https://doi.org/10.1518/001872008X250638

Joseph, J. A., & Griffin, M. J. (2008). Motion Sickness: Effect of the magnitude of roll and pitch oscillation. *Aviation, Space, and Environmental Medicine, 79*(4), 390–396. https://doi.org/10.3357/ASEM.2196.2008

Karjanto, J., Yusof, N. M., Hassan, M. Z., Terken, J., & Rauterberg, M. (2021). An on-road study in mitigating motion sickness when reading in automated driving. *Journal of Hunan University Natural Sciences, 48*(3), 95–109.

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. *Transportation Research Part F: Traffic Psychology and Behaviour, 58*, 678–692. https://doi.org/10.1016/j.trf.2018.06.046

Kato, K., Suzuki, K., & Honda, C. (2021). Reduction of carsickness using a headrest with support to suppress head motion. *International Comfort Congress 2021 Proceedings*, 123–128.

Koo, J., Kwac, J., Ju, W., Steinert, M., Leifer, L., & Nass, C. (2015). Why did my car just do that? Explaining semi-autonomous driving actions to improve driver understanding, trust, and performance. *International Journal on Interactive Design and Manufacturing, 9*(4), 269–275. https://doi.org/10.1007/s12008-014-0227-2

Kremer, C., Tomzig, M., Merkel, N., & Neukum, A. (2022). Using active seat belt retractions to mitigate motion sickness in automated driving. *Vehicles, 4*(3), 825–842. https://doi.org/10.3390/vehicles4030046

Kuiper, O. X., Bos, J. E., Diels, C., & Schmidt, E. A. (2020). Knowing what's coming: Anticipatory audio cues can mitigate motion sickness. *Applied Ergonomics, 85*, Article 103068. https://doi.org/10.1016/j.apergo.2020.103068

Kyriakidis, M., Happee, R., & de Winter, J. C. F. (2015). Public opinion on automated driving: Results of an international questionnaire among 5000 respondents. *Transportation Research Part F: Traffic Psychology and Behaviour, 32*, 127–140. https://doi.org/10.1016/j.trf.2015.04.014

Li, D., & Chen, L. (2022). Mitigating motion sickness in automated vehicles with vibration cue system. *Ergonomics, 65*(10), 1313–1325. https://doi.org/10.1080/00140139.2022.2028902

Maculewicz, J., Larsson, P., & Fagerlönn, J. (2021). Intuitive and subtle motion-anticipatory auditory cues reduce motion sickness in self-driving cars. *International Journal of Human Factors and Ergonomics, 8*(4), 370–392. https://doi.org/10.1504/IJHFE.2021.119053

Matsangas, P., McCauley, M. E., & Becker, W. (2014). The effect of mild motion sickness and sopite syndrome on multitasking cognitive performance. *Human Factors, 56*(6), 1124–1135. https://doi.org/10.1177/0018720814522484

Meng, F., & Spence, C. (2015). Tactile warning signals for in-vehicle systems. *Accident Analysis & Prevention, 75*, 333–346. https://doi.org/10.1016/j.aap.2014.12.013

Nees, M. A., & Walker, B. N. (2011). Auditory displays for in-vehicle technologies. *Reviews of Human Factors and Ergonomics, 7*(1), 58–99. https://doi.org/10.1177/1557234X11410396

Oman, C. M. (1982). A heuristic mathematical model for the dynamics of sensory conflict and motion sickness. *Acta Oto-Laryngologica, 94*(sup392), 4–44. https://doi.org/10.3109/00016488209108197

Petermeijer, S. M., de Winter, J. C. F., & Bengler, K. J. (2016). Vibrotactile displays: A survey with a view on highly automated driving. *IEEE Transactions on Intelligent Transportation Systems, 17*(4), 897–907. https://doi.org/10.1109/TITS.2015.2494873

Pfleging, B., Rang, M., & Broy, N. (2016). Investigating user needs for non-driving-related activities during automated driving. *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia*, 91–99. Doi: 10.1145/3012709.3012735.

Reagan, I. J., Cicchino, J. B., Kerfoot, L. B., & Weast, R. A. (2018). Crash avoidance and driver assistance technologies – Are they used? *Transportation Research Part F: Traffic Psychology and Behaviour, 52*, 176–190. https://doi.org/10.1016/j.trf.2017.11.015

Reason, J. T. (1978). Motion sickness adaptation: A neural mismatch model. *Journal of the Royal Society of Medicine, 71*(11), 819–829. https://doi.org/10.1177/014107687807101109

Reason, J. T., & Brand, J. J. (1975). *Motion Sickness*. Academic Press.

Reuten, A. J. C., Bos, J. E., Martens, M. H., Rausch, J., & Smeets, J. B. J. (2024). Mitigating motion sickness by anticipatory cues. *Under Review*. Available as a preprint at https://doi.org/10.17605/OSF.IO/TZ7CA.

Reuten, A. J. C., Nooij, S. A. E., Bos, J. E., & Smeets, J. B. J. (2021). How feelings of unpleasantness develop during the progression of motion sickness symptoms. *Experimental Brain Research, 239*, 3615–3624. https://doi.org/10.1007/s00221-021-06226-1

Reuten, A. J. C., Smeets, J. B. J., Rausch, J., Martens, M. H., Schmidt, E. A., & Bos, J. E. (2023). The (in)effectiveness of anticipatory vibrotactile cues in mitigating motion sickness. *Experimental Brain Research, 241*(5), 1251–1261. https://doi.org/10.1007/s00221-023-06596-8

Rolnick, A., & Lubow, R. E. (1991). Why is the driver rarely motion sick? The role of controllability in motion sickness. *Ergonomics, 34*(7), 867–879. https://doi.org/10.1080/00140139108964831

Sae. (2021). *Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles (J3016_202104)*. Society of Automotive Engineers.

Schmidt, E. A., Kuiper, O. X., Wolter, S., Diels, C., & Bos, J. E. (2020). An international survey on the incidence and modulating factors of carsickness. *Transportation Research Part F: Traffic Psychology and Behaviour, 71*, 76–87. https://doi.org/10.1016/j.trf.2020.03.012

Schoettle, B., & Sivak, M. (2014). *Public opinion about self-driving vehicles in China, India, Japan, the U.S., the U.K., and Australia (UMTRI-2014-30)*. The University of Michigan Transportation Research Institute.

Stauffert, J.-P., Niebling, F., & Latoschik, M. E. (2020). Latency and cybersickness: Impact, causes, and measures. A review. *Frontiers in Virtual Reality, 1*, Article 582204. https://doi.org/10.3389/frvir.2020.582204

TSGB (2022). *National Travel Survey 2021: Trips by purpose, age and sex*. Transport Statistics Great Britain. https://rb.gy/k0uylb. Accessed September 23, 2023.

Van Erp, J. B. F., Toet, A., & Janssen, J. B. (2015). Uni-, bi- and tri-modal warning signals: Effects of temporal parameters and sensory modality on perceived urgency. *Safety Science, 72*, 1–8. https://doi.org/10.1016/j.ssci.2014.07.022

Von Sawitzky, T., Wintersberger, P., Riener, A., & Gabbard, J. L. (2019, June 12). Increasing trust in fully automated driving: Route indication on an augmented reality head-up display. *Proceedings of the 8th ACM International Symposium on Pervasive Displays*. PerDis '19: The 8th ACM International Symposium on Pervasive Displays, Palermo, Italy. Doi: 10.1145/3321335.3324947.

Wada, T., & Yoshida, K. (2016). Effect of passengers' active head tilt and opening/closure of eyes on motion sickness in lateral acceleration environment of cars. *Ergonomics, 59*(8), 1050–1059. https://doi.org/10.1080/00140139.2015.1109713

Ward, C., Raue, M., Lee, C., D'Ambrosio, L., & Coughlin, J. F. (2017). Acceptance of automated driving across generations: The role of risk and benefit perception, knowledge, and trust. In M. Kurosu (Ed.), *Human-Computer Interaction: User Interface Design, Development and Multimodality* (pp. 254–266). Springer Nature. https://doi.org/10.1007/978-3-319-58071-5.

Yusof, N. M., Karjanto, J., Terken, J. M. B., Delbressine, F. L. M., & Rauterberg, G. W. M. (2020). Gaining situation awareness through a vibrotactile display to mitigate motion sickness in fully-automated driving cars. *International Journal of Automotive and Mechanical Engineering, 17*(1), 7771–7783. https://doi.org/10.15282/ijame.17.1.2020.23.0578