Using anticipatory vibrotactile cues to mitigate motion sickness

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Abstract *– The prevalence of motion sickness is hypothesized to increase with the use of (fully) automated vehicles, mainly because of an overall increase in passenger miles travelled. It has been reported that auditory or visual cues alerting passengers of changes in upcoming car motion can mitigate motion sickness. As such cues interfere with audio(visual) tasks that passengers may want to perform, we here investigated whether 1) anticipatory vibrotactile cues mitigate motion sickness as well, and 2) what the most effective timing of the cue is. To that end, we exposed participants to four sessions of motion sickening displacements on a linear sled. In three sessions, an anticipatory cue was presented prior to the onset of forward motion, either at 3 s, 1 s, or 0.33 s. We compared the scores on a motion sickness scale given within these sessions to the scores given in a control session with a non-anticipatory cue. Our results show that under the chosen experimental conditions, the anticipatory cues did not mitigate motion sickness, irrespective of their timing. They might be effective in more motion challenging environments with highly unpredictable displacements.*

Keywords: *anticipatory cueing, car sickness, haptic, timing*

Introduction

The introduction of various automated driving functions offers a future perspective in which cars no longer require permanent human control of driving (SAE, 2021). Potential benefits of these automated driving functionalities include safer driving, increasing road capacity, and time to engage in non-driving related tasks (Diels, 2014; Sivak and Schoettle, 2015). However, one presumed negative consequence is an increase in motion sickness prevalence (Diels and Bos, 2016; Iskander, et al., 2019). This is mainly due to an overall increase in passenger miles travelled, given that passengers experience more sickness compared to car drivers (Rolnick and Lubow, 1991; Schmidt, et al., 2020). In this paper, we focus on the question how motion sickness can be mitigated in automated vehicles.

A promising solution is based on providing passengers additional motion cues that alert a change in the car's trajectory, as such changes may induce motion sickness. These '*anticipatory cues'* could help passengers to improve their estimations of self-motion, which would minimize a neural conflict between sensory signals and their estimates suggested to cause motion sickness (see Oman, 1991; Reason, 1978). Already several studies demonstrated the effectiveness of anticipatory auditory (Kuiper, et al., 2020; Diels and Bos, 2021) or visual (Feenstra, et al., 2011; Hainich, et al., 2021) cues. However, in the context of an automated vehicle, we consider the tactile modality more suitable to present these cues. One reason is that vibrotactile cues are less disturbing to passengers who are engaged in audio(visual) tasks like reading, phoning, or watching videos. They are nevertheless attention capturing as vibrotactile warning signals reduce the reaction time of drivers in responding to critical events (Scott and Gray, 2008; Petermeijer, et al., 2015). The motive of our study was to investigate whether anticipatory vibrotactile cues can indeed be used to mitigate motion sickness.

Yusof, et al. (2020), Karjanto, et al. (2021), and Li and Chen (2022) investigated the effectiveness of anticipatory vibrotactile cues for lateral displacements (i.e., taking turns or changing lanes). Only the two latter studies reported significant reductions in motion sickness. They used different time intervals of respectively 3 and 1.2 s between the cue and onset of motion. From a practical perspective, short time intervals would be preferred as the vehicle's motion trajectory can be more accurately predicted. We therefore also wanted to investigate how many seconds in advance of motion onset anticipatory vibrotactile cues are most effective.

To summarize, in our study we first wanted to confirm if anticipatory vibrotactile cues mitigate motion sickness. Our second research question then was on the most effective timing of the cue. To that end, we subjected participants to four sessions of sickening displacements on a linear sled. These sessions only differed in the timing of vibrotactile stimulation. In three anticipatory sessions, a vibrotactile cue was always presented prior to the displacement, thereby alerting participants of its onset. In a control session, the cue was always presented after the onset of the displacement, thereby useless for anticipating motion.

Methods

Participants

We recruited 20 participants between 18 and 61 years old from the Vrije Universiteit Amsterdam. We only included participants who were in overall good health, reported to have experienced car sickness in the last five years, and had no (self-known) vestibular disturbances. We obtained ethical approval from the institutional review board of TNO, which is where the experiment was realized.

Motion stimuli

In all sessions, we exposed participants to 15 minutes of fore-aft displacements on a linear sled (Figure 1a). Each displacement had an amplitude of 7.2 m and consisted of a fast forward acceleration followed by a slow backward motion (Figure 2). The start of consecutive displacements was randomly varied between 12 and 20 s, wherefore the exact onset of the next displacement was unpredictable without anticipatory cue.

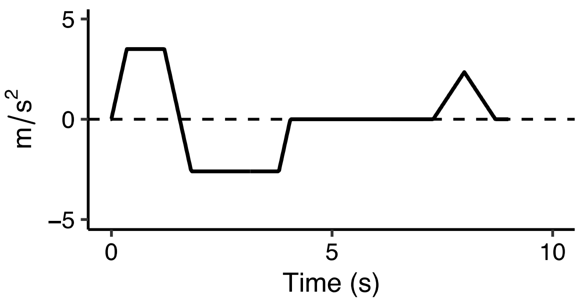

Figure 2: Acceleration profile of one displacement

Vibrotactile cues

The vibrotactile cues were presented via the seat pan and consisted of six actuators turned on simultaneously for a duration of 150 ms. In the three anticipatory (A) sessions, the cues were predictive and presented either 3 s (AL), 1 s (AM) or 0.33 s (AS) in advance of motion onset. As the vibrotactile cue could have an effect on its own, we wanted to keep the control session (C) as similar as possible and also presented a cue in this session. This cue was presented after motion onset at a varying interval from 2 to 6 s (to reduce any predictability associated

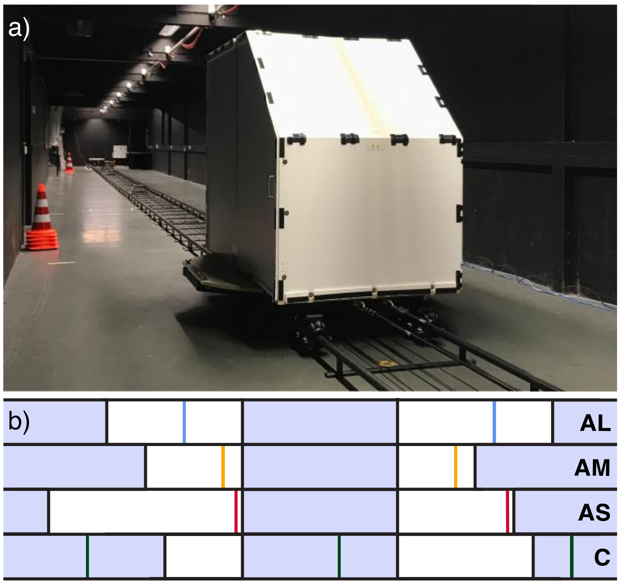

Figure 1: a) The linear sled that was used in this experiment. The enclosed cabin prevented visual and somatosensory (airflow) cues on motion. b) Schematic overview of the timing of vibrotactile stimulation for the four sessions. Cues are represented by the coloured thin vertical bars, the periods of sled displacements in blue, and stationary periods in white. The alignment of the first full motion shown is chosen arbitrarily

with this cue) and therefore non-informative about the onset of motion. The order of sessions was counterbalanced between participants. The presentation of the cues in relation to the motion profile is presented in Figure 1b.

Motion sickness

To evaluate the effectiveness of the cue, we asked participants for a Motion Illness Symptoms Classification (MISC, Table 1, developed by Bos, et al., 2005; renamed by Reuten, et al., 2021) at one-minute intervals during the sessions.

Table 1: Motion Illness Symptoms Classification scale

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, … but no nausea	vague	2
	little	3
	rather	4
	severe	5
Nausea	little	6
	rather	7
	severe	8
	retching	9
Vomiting		10

Procedure

The four sessions were split across two days. On the first day, we informed participants about the experimental protocol, after which they signed an informed consent form. We instructed them that the cue would be presented prior to the onset of forward motion in some sessions, and during the motion in some other sessions. They subsequently performed a familiarization trial on the sled of three displacements (< 1 minute). We always provided a 10-minute break afterwards, even though none of the participants reported to experience motion sickness from this short trial. After the break, participants started the first session, with a second session following after an hour of resting time. A week later, they performed the remaining two sessions at the same time of day. Participants could only start a session if they rated a MISC 0 or 1 at t=0. They received study credits or a monetary award for their participation in the study.

Data analysis and statistics

We will here present our results based on the statistical analysis as used in Kuiper, et al. (2020). We accordingly evaluated the effectiveness of the anticipatory cues by performing a two-way repeated measures ANOVA with factors time (16 levels) and session (AL, AM, AS, C) on the provided MISC scores. Missing values as the result of a stop-criterium (MISC $\geq$ 6) were substituted with the last rated value.

Results

The MISC scores gradually increased with time, and this increase followed a similar pattern across the four sessions (Figure 3). The data seem to indicate a slight advantage (lower MISC values) for the anticipatory sessions AL, AM, AS relative to the control session C. An ANOVA with Greenhouse-Geisser correction indicated a significant main effect of the factor time, with F (1.9, 35.2) = 53.98, p < .001, partial η^2 = 0.74, but did not show a significant main effect of session (p = 0.842) or interaction effect (p = 0.905). This implies there was no significant advantage of the cue in any anticipatory session.

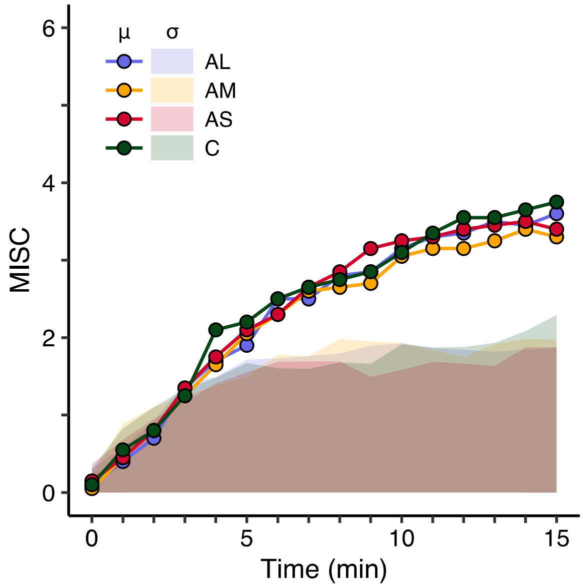

Figure 3: The development of MISC scores averaged across participants for each of the four sessions. The filled areas represent standard deviations in these averages. AL = 3 s anticipatory interval, AM = 1 s anticipatory interval, AS = 0.33 s anticipatory interval, C = control session with cue after motion onset

Discussion

We here investigated the use of anticipatory vibrotactile cues as a potential solution to car sickness, specifically in the context of an automated vehicle. In addition to previous studies, we not only investigated if anticipatory vibrotactile cues mitigate motion sickness, but also their most effective time interval. In three sessions with different anticipatory time intervals, a vibrotactile cue alerted participants of the motion onset of a linear sled. The same vibrotactile cue was presented after motion onset in a control session. In contrast to our expectations, we did not find a difference in the motion sickness scores between the anticipatory and control sessions. We conclude that the anticipatory vibrotactile cues did not mitigate motion sickness under the conditions used in our study. This interpretation aligns with the results of a more complex data analysis approach described in a preregistration of the study (https://doi.org/10.17605/OSF.IO/SYVU9).

Kuiper, et al. (2020) performed an analogous experiment on anticipatory auditory cueing using the same linear sled with a similar experimental protocol. They also included 20 participants comparable in motion sickness susceptibility, who reported similar levels of motion sickness in the control session. Their auditory cue generated a 17% reduction of the last rated MISC score in the experiment, whereas we obtained an average (non-significant) reduction of 9%. This suggests that anticipatory cues presented via the auditory modality may be more effective. There is however an essential difference between the two studies. In our study, we wanted to isolate the effect of the anticipatory time interval on the effectiveness of the vibrotactile cue. We accordingly only varied the displacements in their onset, not in their direction, as both factors individually contribute to the motion sickness response (Kuiper, et al., 2019). This possibly resulted in a more predictable motion profile compared to Kuiper, et al. (2020), who did vary displacement direction. In fact, some of our participants indicated it became easier to anticipate the displacements after having performed a couple of sessions, which was in line with a small order effect we observed. Our study was performed under highly controlled circumstances with repetitive motion. It may be possible that anticipatory cues generate larger beneficial effects when upcoming motions are harder to predict. This might explain why the (directional) anticipatory vibrotactile cues in previous studies were effective, since they used displacements unpredictable in both onset and direction (Karjanto, et al., 2021; Li and Chen, 2022).

Given the mixed results of our and previous studies investigating the use of anticipatory vibrotactile cues, it seems that they are not effective in all circumstances. More research is required to decide under what conditions they can contribute to a solution against car sickness. We intend to perform future studies to investigate the added value of directional cues, together with a comparison of the effectiveness of different anticipatory cueing modalities.

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