Non-driving related task engagement in highly automated vehicles: How to mitigate emerging motion sickness?

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In this study, three evidence-based countermeasures to mitigate motion sickness in automated vehicles have been compared with respect to a control condition. The measures were based on visual anticipatory cues for vehicle motion or on the optimized alignment of the human body by seat adjustments. Test subjects (N = 28) experienced each condition on a 20 minutes' drive in a highly automated vehicle on a closed test track. The non-driving related task was to read a text on a handheld tablet while being exposed to automated fore-aft movements (representing stop and go traffic conditions). None of the implemented countermeasures could be shown to significantly mitigate motion sickness under the circumstances of the study. The paper finishes by discussing methodological issues and possible confounding factors.

1. Introduction

Driving automation at SAE level 3 (SAE International, 2021) and above is expected to enable non-driving related tasks (NDRT) for all passengers. At the same time a significant percentage of users will be confronted with issues of motion sickness – a phenomenon which is commonly explained by a mismatch of sensed and expected motion stimuli (Reason, 1978). In order to reduce the amount of mismatch, countermeasures of various kinds have been proposed and evaluated by researchers, e.g., elevated display positions in order to preserve as much environmental awareness as possible (e.g. Kuipers, 2018; Brietzke, 2021), peripheral visual cues indicating upcoming turn manoeuvres (Karjanto et al., 2018), anticipatory audio cues preceding fore-aft vehicle motion (Kuipers et al., 2020), compensation of horizontal accelerations by tilting/moving seats (Golding et al., 2013, Donohew & Griffin, 2009) or permanently reclined seating positions (Bohrmann & Bengler, 2019). Published studies typically report a positive (yet subtle) impact of the inspected countermeasures on the emergence of motion sickness. However, it is difficult to compare the effects of the countermeasures across publications since studies vary in type and level of applied motion dose, the recruited test sample or the way motion sickness is measured. According to the opinion of the authors there is also a lack of publications that aim to replicate the effects found in original studies. The aim of this study was to compare three implementations of evidence-based countermeasures according to the state-of-the art and to compare their effectivity in a controlled experimental setting.

2. Method

2.1 Research apparatus and motion profile

The closed-track study was based on a research vehicle allowing to fully automate longitudinal and lateral control. The motion profile was designed to represent a continuous stop-and-go traffic scenario including frequent fore-aft acceleration events with peak values of +2 m/s² and -3 m/s², respectively. The maximum speed was limited to 60 km/h and the duration of the drive was set to 20 minutes (see Fig. 1 for the longitudinal acceleration profile). Lateral accelerations were intentionally kept to a minimum.

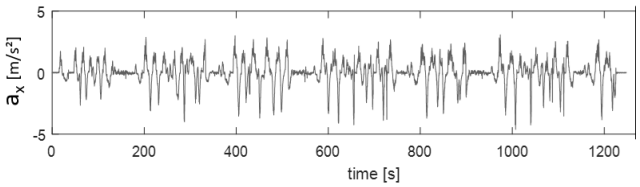

Fig 1: *Longitudinal acceleration profile representing stop-and-go traffic conditions.*

2.2 Test sample

A total of N = 28 participants (14 females, 14 males) took part in the study. Their age ranged from 23 to 47 years (M = 35.61; SD = 7.62). All participants were screened in advance for increased susceptibility to motion sickness based on self-assessment. The average score of the test sample on the MSSQ Short scale was 19.18 which represents the 75th percentile of the population (Golding, 2006). Informed consent was given by all participants in advance. Every subject could terminate the trials at any time without negative consequences.

2.3 Independent variables

The experimental study was based on a within-subject design with the following 4 conditions, presented on 4 separate days in counterbalanced order (see also Fig. 2). In all conditions, the participants were instructed to continuously read text on a handheld device.

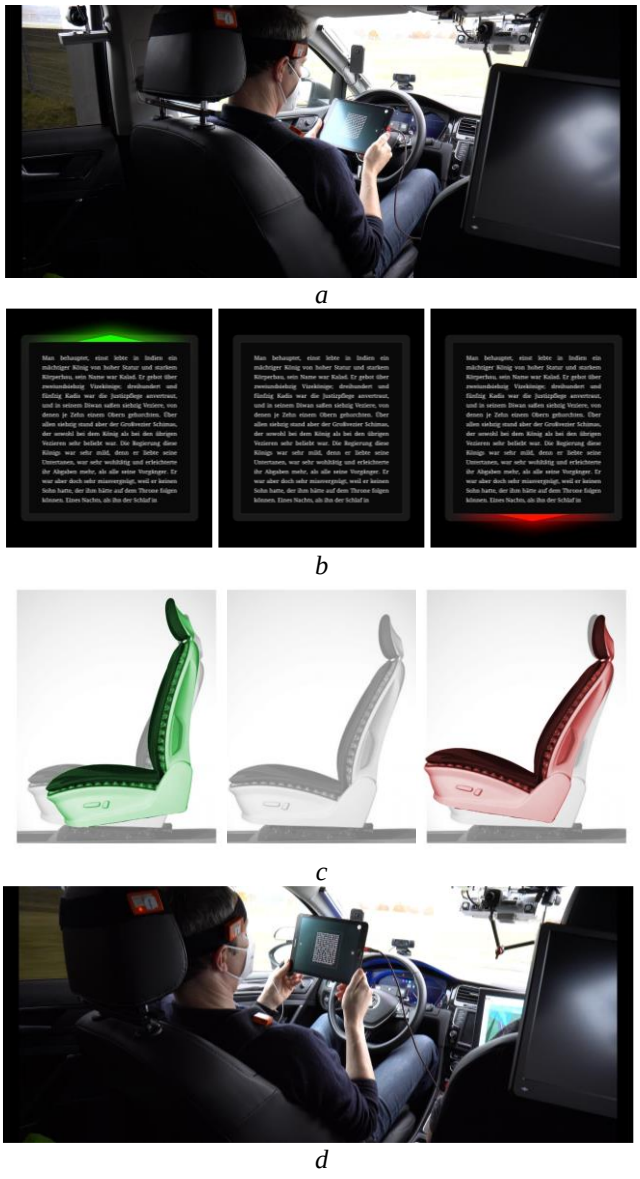

Fig. 2. *Experimental conditions (see details in the text)* ***(a)*** *Control condition,* ***(b)*** *visual anticipatory cues,* ***(c)*** *dynamic seat adjustments,* ***(d)*** *permanently reclined seating*

2.3.1 Control condition

The subject was seated on the driver's seat behind the steering wheel in an upright sitting position (inclination angle of backrest: 25°; see Fig. 2a).

2.3.2 Visual anticipatory cues

The subject received dedicated visual cues below and above the text box on the handheld tablet (see Fig. 2b), preceding the actual onset of vehicle acceleration/deceleration by 1.3 seconds. The brightness of the visual cues was linked to the level of the upcoming acceleration (from transparent to full brightness). All other aspects were identical to the control condition.

2.3.3 Dynamic seat adjustment

In this condition the seat moved along a curved trajectory in longitudinal direction (cf. forward swing movement for braking, backward swing movement for accelerating). This dynamic seat movement was implemented as a pre-programmed adjustment of three seat actuators (forward-backward, tilt and backrest angle). The resulting inclination angles for the backrest were 30° (neutral position), up to 20° for positive vehicle acceleration and up to 40° for negative vehicle acceleration (see Fig. 2c).

2.3.4 Permanently reclined seating position

Participants were instructed to read the text while the backrest of the seat was permanently set in a reclined position (inclination angle of backrest: 40°; see Fig. 2d). Subjects could use the headrest while reading on the handheld device.

2.4 Dependent variables

The main dependent (subjective) variable was based on differences between pre and post scores of the Motion Sickness Assessment Questionnaire (Delta MSAQ) according to Gianaros et al., 2001. The questionnaire was administered before and after all test drives.

2.5 Test procedure

Each of the four trials started with a pre-drive questionnaire and basic instructions, followed by a 20 minutes' drive in the research vehicle. During the drive the participants were requested to continuously engage in the reading task. In order to monitor the development of motion sickness in real time, test subjects indicated their current level of motion sickness on a 10-point rating scale every 2 minutes. The safety driver sitting next to the participant was instructed to terminate the trial whenever the participant wishes or when the reported motion sickness level exceeded the value of 6. A post-drive questionnaire with interview followed in the office next to the test track location.

3. Results

3.1 General effects on motion sickness mitigation

In order to compare the level of emerged motion sickness between the experimental conditions, the distribution of Delta MSAQ scores is analysed (see Table 1 and Fig. 3). A Friedman test (conducted with SPSS Statistics 26) did not reveal any significant differences between the experimental conditions ($\chi^2(3) = 4.79$, $p = 0.188$, $N = 28$).

Table 1: *Descriptive statistics for Delta MSAQ scores across experimental conditions*

Condition	Mean	*SD*	Median	Min	Max
Control	14.68	18.67	6.60	-2.78	68.75
Visual cues	13.72	15.08	8.68	-0.69	51.39
Dynamic seat	11.76	15.86	7.64	-13.19	61.11
Reclined seat	12.00	18.12	3.13	-4.17	76.39

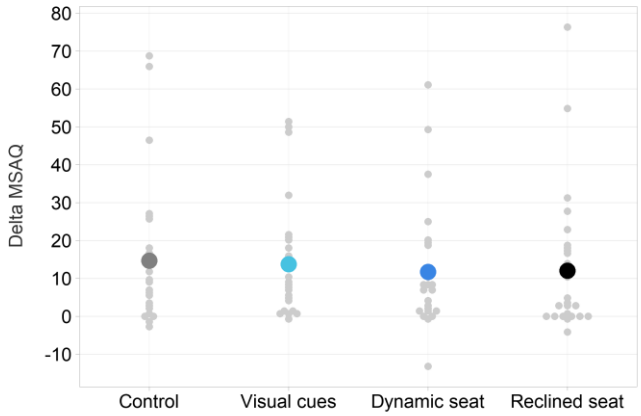

Fig 3: *Distribution of individual scores for Delta MSAQ. Coloured circles indicate the mean value for each experimental condition.*

3.2 Inter-individual differences

Figure 4 shows the effectiveness of all three countermeasure conditions in relation to the control condition by comparing the increase/decrease of the MSAQ scores on an individual level. This explorative analysis highlights the large inter-individual differences: Each countermeasure seems to mitigate motion sickness for single participants (see negative values/green cells in Fig. 4), but not consistently across the test sample. Conversely, there is a clear indication that all countermeasures have the potential to increase motion sickness compared to the control condition (see positive values/red cells in Fig. 4). This result is also reflected in the verbal statements after the test drive.

ID	Visual cues	Dynamic seat	Reclined seat
1	-2.08	-4.86	-5.56
2	-0.69	0.00	0.00
3	-6.25	-5.56	-18.06
4	4.17	-9.72	-13.89
5	-17.36	-16.67	-34.72
6	10.42	13.89	6.25
7	-16.67	-6.94	-9.72
8	6.25	4.17	4.17
9	2.08	-2.78	-6.94
10	-1.39	-0.69	-2.08
11	2.78	0.00	0.00
12	-4.17	6.94	4.86
13	9.03	13.19	-2.78
14	-11.81	-38.89	-2.78
15	-8.33	-24.31	-8.33
16	20.14	-12.50	-11.81
17	-22.92	-14.58	-13.19
18	-2.08	5.56	-2.78
19	1.39	2.08	27.78
20	3.47	0.69	0.69
21	-17.36	-31.25	7.64
22	6.94	4.86	1.39
23	-5.56	-6.25	-6.25
24	10.42	0.69	-6.94
25	3.47	14.58	8.33
26	-0.69	15.97	7.64
27	6.25	0.69	0.00
28	3.47	9.72	2.08

Fig 4: *Individual impact of countermeasures compared to the control condition (in terms of differences between Delta MSAQ scores).*

3.3 Relationship between self-reported motion sickness susceptibility and motion sickness occurrence

Pearson correlation coefficients were computed to assess the linear relationship between the MSSQ Short scores and Delta MSAQ scores for each experimental condition:

- Control condition: $r(26) = .15$, $p = .460$
- Visual anticipatory cues: $r(26) = .38$, $p = .047$
- Dynamic seat adjustment: $r(26) = .30$, $p = .125$
- Reclined seating position: $r(26) = .19$, $p = .327$

4. Discussion and conclusion

This study was designed to (1) replicate existing findings for selected measures aiming to mitigate motion sickness in automated vehicles and (2) to compare their effectiveness in a controlled setting. Although great care has been taken to control for potential confounding factors (e.g., within subject design, same time of day, full permutation of trials, standardized instructions) the positive effects of the countermeasures found in related studies (see chapter 1) could not be confirmed under the circumstances of this study. Statistically, this can be explained by minor differences between means and especially by large differences between individual responses within the experimental conditions. But what are the determining factors that may explain the large variance within each experimental condition? Apart from the spread of self-reported susceptibility to motion sickness, the large variance within the experimental conditions may also result from intra-individual (day-to-day) variations in motion sickness susceptibility or from individually different reactions to the countermeasures presented in the experiment. In order to control for the day-to-day effect, several measurements for identical conditions would be needed. On the other hand, verbal feedback also indicates that differences in means could be enlarged by improving the implementation of countermeasures. Both aspects should be carefully considered for follow-up studies. After all, providing effective means to mitigate motion sickness is crucial to enable NDRTs in highly automated vehicles.

5. Acknowledgments

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