2023 IEEE 26th International Conference on
Intelligent Transportation Systems (ITSC)
24-28 September 2023. Bilbao, Bizkaia, Spain

2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC) | 979-8-3503-9946-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/ITSC57777.2023.10421968

Design strategies to alleviate motion sickness in rear seat passengers – a test track study*

Cyriel Diels, Pierre Dugenetet, Adrian Brietzke, and Rebecca Pham Xuan

*Abstract***— In-vehicle activities such as reading, writing or watching videos rapidly lead to signs and symptoms of motion sickness and is of particular concern in rear-seat passengers and future shared and / or automated vehicles. In this test track study, we evaluated several design strategies to alleviate motion discomfort in rear seat passengers who were exposed to a longitudinal motion profile of repeated vehicle accelerations and decelerations whilst using an e-reader. Results showed that the manipulations affecting vehicle accelerations and pitch angles failed to reduce motion sickness. Providing passengers with lateral optic flow indicating instantaneous actual vehicle speed and predictive motion cues using a visual ambient display reduced motion sickness consistency, albeit statistically non-significant. Yet, with all the above strategies combined in the wellness pack condition, a statistically significant and large (28%) reduction in carsickness was observed. Future research will benefit from exploring these possible interactions and suggest that effective motion sickness management may require a multipronged approach.**

I. Introduction

Car passengers are known to be more prone to carsickness than drivers [1]. Furthermore, trying to read, write or watch movies while being driven exacerbates matters which can make passengers feel queasy within a matter of minutes [2]. As a consequence, passengers avoid or limit themselves engaging in such activities despite being highly desirable from a leisure or commercial perspective [3].

In this study we focus on the rear seat passengers in chauffeur-driven vehicles and explore what design strategies can be employed today to alleviate carsickness and enable passengers to enjoy such activities in comfort. As an aside, note that while we confine our study to conventional vehicles, the findings are highly relevant for the design of future shared and / or automated vehicles in which all occupants will become passengers [4]. In the below, we will introduce each of the different design strategies with reference to the mechanisms hypothesized to underly their expected effectiveness.

As the name implies, motion sickness occurs when people are exposed to certain motions, in particular those in the low frequency range. Carsickness is mainly caused by horizontal accelerations due to accelerating, braking, and cornering [5,6,7]. Aggressive driving styles therefore are more likely to lead to carsickness. While driving style is largely under the control of the driver, the use of Adaptive Cruise Control (ACC) allows for some control over acceleration levels at least in car following scenarios. Hence, we here explored whether different acceleration levels generated by different ACC settings available in a commercially available production vehicle (i.e. “comfort” and “dynamic”) have the potential to alleviate carsickness.

Secondly, it is also known that alignment with the Gravito-Inertial Force (GIF) vector has the potential to reduce motion sickness [8]. This, at least to some extent, also explains the relative immunity of drivers to motion sickness when cornering. Unlike passengers, drivers lean into the corner actively aligning their head and body to the resulting GIF vector with passengers moving in the opposite direction. Similarly, we here explored the potential of tuning the suspension by imposing maximum damper current in effect minimizing the vehicle’s and subsequently occupant’s pitch movement during accelerations and decelerations. Compared to the default suspension setting, the tuning better aligns the passenger body/head towards the GIF vector.

Thirdly, sickness occurring for example while reading in a car is attributed to conflicting sensory cues [2,9]. Whilst the vestibular system perceives the vehicle’s physical motion, our eyes reading the text, typically held on our laps, perceive a stable stationary interior environment. We here explored the potential of providing the rear seat passenger with a visual pattern providing lateral optic flow to indicate instantaneous actual vehicle speed and creating the illusion of a “see-through door” with the intent to reduce these visual-vestibular conflicts.

In addition, such ambient visual displays may also be used to provide passengers with predictive cues warning of upcoming motion. The inability to anticipate future motion on behalf of passengers increases the likelihood of discrepancies between expected and sensed motion and underlies the causation of motion sickness. Whilst many specific parameters remain largely unexplored, providing passengers with predictive motion cues has already been shown to have the potential to provide an elegant and effective method to reduce motion sickness [9,16,17].

Finally, this study provided an opportunity to evaluate a more integrated approach to the management of motion sickness and not only study the different strategies in isolation, but bring them together in an overall “wellness pack”. This approach was inspired by the observation that there are no silver bullets and motion sickness management is likely to require a multipronged approach. This study represents one of the very few examples implementing such an approach.

*Research supported by Bentley Motors and Volkswagen AG.
C. Diels is with the Royal College of Art, London, SW11 4NL, UK (corresponding author to provide phone: +44 (0)20 7590 4491; e-mail: cyriel.diels@rca.ac.uk).
P. Dugenetet is with Bentley Motors, Crewe CW1 3PL, UK.
A. Brietzke and R. Pham Xuan are with Group Innovation, Volkswagen AG, 38440 Wolfsburg, Germany.

II. Methods

A. Participants

A total of 16 participants were recruited and were between 30 and 60 years old, in good state of health and reported to have experienced symptoms of motion sickness at least once in the last five years and had a Motion Sickness Susceptibility Questionnaire (MSSQ-short [10]) percentile of 70%ile or higher. By excluding participants who hardly suffer from motion sickness, we aimed at maximizing the chance to find differences between the experimental conditions. The above-average motion sickness susceptibility of our sample has to be taken into account when generalizing to the general population. All 16 participants completed five experimental sessions. Half the participants were female, who were on average both younger and more sensitive to motion sickness as measured by the MSSQ-short. The study was conducted in accordance with the 1964 Declaration of Helsinki, and the study protocol was approved by the Royal College of Art Ethical Committee. All participants gave their written informed consent before participation and were reimbursed for their participation.

B. Test vehicle

The study was performed using a large Sports Utility Vehicle (SUV) (2019 Bentley Bentayga with automatic gearbox and v8 engine, left-hand drive). The vehicle was a pre-production engineering vehicle representative of the series intent. The participant was seated in the left-hand rear seat behind the driver. The visual feedback system consisted of and ambient display implemented using 3 horizontal LED strips integrated into the door card (see Fig 1). The LED strips were located to allow the passenger to focus on the reading task while receiving motion information peripherally using the ambient LED display. The strips were covered with a black mesh and appeared to be integrated with the door card. In response to prevailing COVID19 conditions, a transparent safety screen was attached to the rear of the driver's seat to protect drivers and passengers. The Misery Scale (MISC) was attached to the screen and was available at all times for participants to refer to. The car's air conditioning system was set to automatic with a 21°C temperature setting.

C. Experimental conditions

A total of five different conditions were tested each consisting of a unique combination of settings related to the ACC (dynamic vs. comfort), suspension (default vs. tune), and lighting (on vs. off). Table 1 shows settings for each of the three variables for each of the five conditions.

Adaptive Cruise Control (ACC): The level of acceleration was varied by using two Bentley ACC settings, i.e. the Comfort and Dynamic ACC settings. Compared to the Dynamic setting, the RMS and Maximum acceleration in the Comfort setting was reduced by 10.6 and 16.6%, respectively. Since motion sickness is dependent on the level of acceleration, the dynamic setting was expected to induce higher levels of motion sickness.

Suspension: The standard default suspension setting was compared to a modified suspension setting that was tuned to align the passenger's body/head towards the Gravito Inertial Force (GIF) vector, hypothesized to reduce motion discomfort. This was achieved by modifying the damper setting (i.e. max damper current) to minimize pitch during acceleration / deceleration. Compared to the default setting, in the tuned setting the RMS of the pitch angle was reduced by 14%.

Figure 1. Top: Lead and test vehicle on test track performing stop-and-go manoeuvre. Bottom: LED display placement and test setup in the test vehicle with participant holding the e-reader in the lap. *Left*: red LED signal indicating upcoming deceleration; *Middle*: blue LED pattern congruent with vehicle speed; *Right*: green LED signal indicating upcoming acceleration.

TABLE I. Overview of experimental conditions

	Parameter		
Conditions	***ACC***	***Suspension***	***Lighting***
Control	Dynamic	Default	Off
ACC	**Comfort**	Default	Off
Suspension	Dynamic	**Tune**	Off
Lighting	Dynamic	Default	**On**
Wellness pack	**Comfort**	**Tune**	**On**

Lighting: The vehicle was equipped with an ambient lighting display which consisted of three RGBW-LED strips attached to the left rear door card and ran across the length of the interior door as illustrated in Fig 1. As mentioned, the LED strips were covered by a perforated black leather mesh to appear more integrated with the vehicle interior. Each strip consisted of 144 LEDs per meter. The visual pattern was created by activating 6 adjacent LEDs with 6 inactive LEDs in between. The visual pattern was linked to the vehicle dynamics and, in effect, created a see-through door in that the pattern was representative of the optic flow pattern that would be perceived form the outside environment if the door card would be transparent. The visual flow pattern was linked to the vehicle dynamics using information from the Controlled Area Network (CAN) bus. The speed of the light was proportional to the longitudinal speed of the vehicle. Smooth movement of the visual pattern was enabled by the consecutive activation of LEDs. The direction of the LED lights was programmed to simulate the natural optic flow, i.e. forward motion of the vehicle corresponded to movement of the visual pattern from front to rear of the vehicle. For acceleration up to ±2 m/s², the color of the LED light was blue.

In addition to the real-time vehicle speed, the ambient display also provided predictive motion cues. This was achieved by illuminating all LEDs for a duration of 2s (pulse). Anticipation of upcoming acceleration or decelerations was enabled by the different speed and distance sensors available on-board. The feedforward time lag, defined by the time between the pulse trigger and the peak of the subsequent longitudinal acceleration, was 500-2000ms depending on the driving condition. Predictive cues were presented on average at 0.5 and 1.5 seconds ahead of braking (red) and accelerating (green), respectively. Variability in the exact timing ranged from 500-1500ms (acceleration) and 100-1000ms (deceleration). During vehicle braking, as defined by decelerations below -2 m/s², the LED lights turned from blue to red. Likewise, during vehicle accelerations, as defined by accelerations above 2 m/s², the LED lights turned from blue to green.

C. Motion recording

Triaxial vehicle acceleration and rotational velocity were measured continuously using the integrated accelerometer located in the middle of the vehicle. Vehicle motion was measured throughout each of the individual sessions.

D. Driving trajectory

The study took place on the Horiba MIRA secure testing ground. The relevant section consisted of two two-lane motorway sections each 1.6km long and joined by banked loops. Adopting a similar method and materials as previously used by [11], the lead vehicle (VW Passat) was programmed to autonomously follow a predetermined driving profile consisting of a series of accelerations and decelerations. The automatic control of the lead vehicle ensured consistency across all conditions in terms of the vehicle dynamics. The following car carried the participant in the rear and used the Adaptive Cruise Control (ACC) to keep a constant distant to the lead vehicle. The driving profile was a slightly modified version of the profile previously used by [11].

The original profile was developed to be representative of real world driving whilst also being sufficiently provocative to avoid unnecessarily long test drives to induce an appropriate level of motion sickness. For the current study the profile had to be adjusted to accommodate the available length of the particular section. Acceleration ranged from – 3.2 m/s² to 2.7 m/s², with a maximum speed of 80 km/h. In total, each participant was exposed to the driving profile for 20 minutes in each condition. In addition, the participants were driven to and from the test section at 10 mph. The drive from and to the control center to the test section took approximately 3 minutes and was not considered to be part of the test.

E. Procedure

To limit the number of participants, the number of experimental trials, as well as the number of exposures per participant, a within-subject design was used. Participants were tested in five 20-min sessions, each testing one of the experimental conditions on five separate days with at least 24 h in between, at about the same time of the day. The order of the conditions was counterbalanced across participants.

At the start of the first experimental session, participants received written information on the general study aims, procedures and signed the informed consent. Subsequently, the participant was informed on the symptoms of motion sickness and the usage of the Misery Scale (MISC) of motion sickness (see [12]). A printed version of the MISC was attached to the back of the front passenger seat and continuously visible to the participant. In addition, the participants were shown the e-reader and how to use it. They were also instructed to hold the e-reader in their lap during the drive and read the book throughout the duration of the test drive. Compliance was monitored by the driver and was instructed to prompt passengers in case of non-compliance. The participant then took place in the left rear seat of the vehicle and subsequently driven from the control center to the test section. Participants were not provided any information as to the experimental conditions to be experienced.

After each 20 min test session, participants were driven back to the control center. They were asked to provide the first MISC rating at the start of the test session and subsequently at 1-minute intervals throughout the test. In addition, MISC ratings were reported during the 3 min drive back to the control center and upon arrival. This time was also used to ask participants to provide any spontaneous comments regarding their experience in particular regarding the Lighting and Wellness pack given their noticeability. Participants were allowed to leave the testing ground until their MISC score reached 1, i.e. “Some discomfort but no particular symptoms”.

III. Results

A. MISC rating

Fig. 2 shows the average discomfort rating (MISC) over time for each of the five conditions. Minute 0-20 represents the actual experimental drive followed by a 3-4 min return drive to the control center and the recovery period.

As expected, motion discomfort steadily increased over the course of the 20 min experimental drive. It can also be seen that during the return drive, discomfort lingered for several minutes before rapidly declining with most participants making a full recovery within 10 minutes.

Compared to the control condition, neither the ACC or Suspension condition appeared to have much of an impact displaying approximately the same levels of discomfort. However, in the Lighting condition, discomfort appeared to stabilize somewhat during the last five minutes while the Wellness pack condition showed a considerable damping effect over the entire course of the experimental drive.

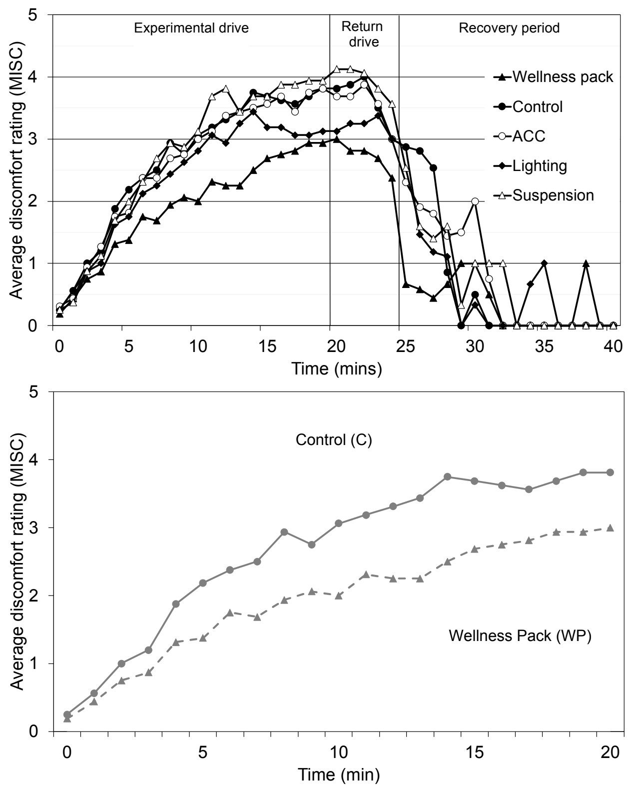

Figure 2. Average discomfort rating (MISC) over time for each of the five conditions (*top*) and separately for the Control and Wellness pack conditions with the surface areas illustrating the the Standard Error of the Mean (SEM) (*bottom*).

Statistical analyses (Wilcoxon Signed Ranks tests, 2-tailed) showed that the average MISC score over the experimental drive (t = 0-20min) in the Wellness pack conditions was significantly lower than in the Control condition ($Z = -2.558$, $p = 0.011$) and the Suspension condition ($Z = -2.556$, $p = 0.011$). Compared to the Lighting condition, the Wellness pack approached statistical significance ($Z = -1.925$, $p = 0.054$).

B. Subjective experiences

In the below, we briefly present negative and positive participant comments regarding the experience across the Lighting and Wellness conditions which both featured the ambient lighting display.

Negative comments: They were awful if I looked at them they made me feel sick. I do not see the point? I got that they changed with the rhythm of the car, but why? (participant 3); Lights can be distracting when reading (participant 4); Some of the colors were garish, didn't like green and yellow (participant 6); Smaller LED's would be better (softer light) if possible (participant 15); Gentle distraction. Useful but makes it hard to concentrate on the text (participant 16).

Positive comments: All that I can add is that I can't help but feel that it helped greatly to combat my normal symptoms of travel sickness (participant 2); Not too in your face but feel it somehow helped a great deal with regards combatting symptoms of motion sickness (participant 2); Liked the blue color and how it moved with the drive (participant 8); Definitely did not feel ill and reading was easier (participant 9); I liked the pace it moved. I realized it was there but was not distracting when reading (participant 12); I could detect when the vehicle was speeding up or braking. It was distracting to begin with but after a while I forgot it was there (participant 13); Liked the lighting and felt comfortable. Only slight headache when reading (participant 9); I found it relaxing (participant 7); I find the color blue relaxing (participant 6); Useful but makes it hard to concentrate on the text (participant 16).

IV. Discussion

Corroborating earlier studies and people's lived experiences, reading in the rear-seat readily leads to passengers suffering from motion sickness. Across all conditions, motion sickness steadily increased over time but dissipated relatively quickly once the provocative motion profile ended (t = 20min) and passengers were able to look out the window again.

The different design strategies to alleviate motion sickness were not equally successful. In fact, both the ACC and Suspension conditions failed to lead to any sizeable reductions in motion sickness and suggest that larger changes in acceleration and pitch angles may be required to have an impact. Further research will be required to explore whether these, or indeed other parameters such as timing of pitch movements, may affect the levels of motion sickness.

The ambient visual display in the Lighting condition created a consistent and positive impact, albeit statistically non-significant. These findings are largely in line with previous studies and suggest that ambient visual displays may provide elegant and effective methods to alleviate motion sickness while questions remain unanswered as to the most relevant parameters including sensory modality, timing, level of information, abstraction level, and perceived integration with non-driving related activities [9]. Furthermore, earlier studies indicate that the beneficial effects of cues are not merely the effect of stimulation or distraction but can be attributed to central processes [18].

Perhaps the most surprising and significant finding was that the combined effect of all the different strategies as represented by the Wellness pack condition led to a considerable damping of the overall motion sickness levels. In fact, the wellness pack showed a 28% reduction in motion sickness, a very sizeable effect compared to results from comparable studies into single design interventions [2,14-17]. This raises the question whether the whole may be greater than the sum of its parts. Do the different countermeasures somehow interact and perhaps while not effective individually, collectively are able to considerably enhance motion comfort in rear seat passengers? This study was not designed or intended to investigate particular interactions but the findings do suggest that this may be a fruitful direction for future research. It also alludes to possible shortcomings in the current approach of designing and evaluating motion sickness countermeasures in isolation with the risk of discarding strategies that may greatly enhance comfort in the context of a more integrated, multipronged design strategy to alleviate motion sickness.

Finally, it is important to consider the subjective experiences of the different design strategies, in particular the visual ambient display which were naturally far more obvious and perceptible than the vehicle motion-based strategies. Design strategies may be effective, but without being acceptable and desirable, the implementation of such strategies may not be commercially viable. The responses showed that, despite the display being at the Proof of Concept (PoC) stage and relatively crudely implemented, participant comments were overall positive with the ambient display perceived to be beneficial, comfortable, and enjoyable while concerns around distraction and unpleasant brightness and colors point towards clear directions for future improvement and refinement.

V. Conclusion

In conclusion, ambient visual displays show great potential to reduce carsickness, elevate the rear-seat passenger experience and facilitate in-vehicle activities. Possible positive interactions with vehicle dynamics-related design strategies, including vehicle accelerations and pitch movements, suggest that carsickness management might benefit from a multipronged approach combining different design strategies collectively before disregarding what may appear to be unsuccessful individual strategies.

References

[1] A. Rolnick and R. E. Lubow, "Why is the driver rarely motion sick? The role of controllability in motion sickness," Ergonomics, vol. 34, no. 7, pp. 867–879, 1991, doi: 10.1080/00140139108964831.

[2] O. X. Kuiper, J. E. Bos, and C. Diels, "Looking forward: In-vehicle auxiliary display positioning affects carsickness," Appl. Ergon., vol. 68, pp. 169–175, Apr. 2018, doi: 10.1016/j.apergo.2017.11.002.

[3] C. Diels, J. E. Bos, K. Hottelart, and P. Reilhac, "Motion Sickness in Automated Vehicles: The Elephant in the Room," pp. 121–129, 2016, doi: 10.1007/978-3-319-40503-2_10. Diels, C., & Bos, J. E. (2016). Self-driving carsickness. Applied Ergonomics, 53,374–382.

[4] J. C. Guignard, M. E. McCauley, "The Accelerative Stimulus for Motion Sickness," in: Crampton, G.H. (Ed.), Motion and Space Sickness. (Boca Raton, FL: CRC Press, 1990).

[5] M. Turner, M. J. Griffin, "Motion Sickness in Public Road Transport: The Relative Importance of Motion, Vision and Individual Differences," British Journal of Psychology 90, no. 4, 1999: 519-530.

[6] M. Turner, M. J. Griffin, "Motion Sickness in Public Road Transport: Passenger Behaviour and Susceptibility," Ergonomics 42, 1999: 444-461.

[7] J. F. Golding, W. Bles, J. E. Bos, T. Haynes, and M. A. Gresty GOLDING JF, "Motion Sickness and Tilts of the Inertial Force Environment: Active Suspension Systems vs. Active Passengers," Aviat. Space. Environ. Med., vol. 74, no. 3, 2003.

[8] J. T. Reason, J. J. Brand, Motion Sickness (London, New York, San Francisco: Academic Press, 1975).

[9] C. Diels, J. E. Bos., "Great Expectations: On the Design of Predictive Motion Cues to Alleviate Carsickness," in: Krömker, H. (Ed.), HCI in Mobility, Transport, and Automotive Systems. HCII 2021, Lecture Notes in Computer Science, vol 12791 (Cham: Springer, 2021).

[10] J. F. Golding, "Predicting individual differences in motion sickness susceptibility by questionnaire". Personality and Individual Differences 41:237-248, 2003.

[11] A. Brietzke, R. Pham Xuan, A. Dettmann, & A. C. Bullinger, Influence of dynamic stimulation, visual perception and individual susceptibility to car sickness during controlled stop-and-go driving. FORSCHUNG IM INGENIEURWESEN-ENGINEERING RESEARCH, 85(2), 517-526, 2001.

[12] J. E. Bos, S. N. MacKinnon, and A. J. Patterson BOS, "Motion Sickness Symptoms in a Ship Motion Simulator: Effects of Inside, Outside, and No View," 2005.

[13] C. Diels, M. Cieslak, E. Schmidt, R. Chadowitz, "The effect of auditory anticipatory motion cues on motion sickness," Client project report, Coventry University, 2018.

[14] E. A. Schmidt, J. Josupeit, "Do Turn Warning Cues and Postural Stabilization Mitigate Reading- Reading - Induced Carsickness?" Workshop Motion Comfort of Automated Driving Carsickness, TU Delft, 2019.

[15] O. X. Kuiper, J. E. Bos, C. Diels, and E. A. Schmidt, "Knowing what's coming: Anticipatory audio cues can mitigate motion sickness," Appl. Ergon., vol. 85, p. 103068, 2020, doi: https://doi.org/10.1016/j.apergo.2020.103068.

[16] D. Bohrmann, A. Bruder and K. Bengler, "Effects of Dynamic Visual Stimuli on the Development of Carsickness in Real Driving," in IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 5, pp. 4833-4842, May 2022.

[17] J. Karjanto, N. M. Yusof, C. Wang, J. Terken, F. Delbressine and M. Rauterberg, "The effect of peripheral visual feedforward system in enhancing situation awareness and mitigating motion sickness in fully automated driving", Transp. Res. F Traffic Psychol. Behav., vol. 58, pp 678-692, Oct. 2018.

[18] O. X. Kuiper, J. E. Bos, C. Diels, and E. A. Schmidt, "Knowing what's coming: Anticipatory audio cues can mitigate motion sickness," Appl. Ergon., vol. 85, no. March, p. 103068, 2020, doi: 10.1016/j.apergo.2020.103068.