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Abstract - *A limitation to the use of driving simulators is simulator sickness. Its discomforting symptoms frequently impact the quality of measurements and complicate interpretation of results obtained from simulator studies. With a yet unclear cause of motion sickness, ever-increasing technological advances in simulator development and the rising demand to study (automated) carsickness, there is a need to align on the definition of simulator sickness. As its exact representation is oftentimes unclear, we present a theoretical vision on the definition of motion sickness, visually induced motion sickness (cybersickness) and lastly simulator sickness and its possible causes.*

Keywords: *Motion Sickness, Simulator Sickness, Sensory Conflict Theory*

Introduction

Driving simulators are increasingly important tools for a broad variety of purposes (e.g. development of automated vehicle functionalities, human factors research, training), due to many advantages as compared to studies with real vehicles. Nevertheless, an often occurring complication is simulator discomfort, specifically simulator sickness. According to Kolasinski (1995), three factors are of influence on simulator sickness: The *individual* subject, the (driving) *task* and the *simulator* itself. The effect, however, appears to manifest similar to ordinary motion sickness.

Although the exact cause of motion sickness is still unknown, several theories on the origin exist (McNally and Stuart, 1942; Riccio and Stoffregen, 1991; Steele, 1970; Treisman, 1977). The most prominent theory explains its occurrence as resulting from a conflict between actual and expected neural inputs of self-motion and self-tilt, based on previous experience represented in a neural store (Reason and Brand, 1975). Continuous exposure to similar conditions updates the neural storage, reducing the neural mismatch, and consequently sickness symptoms. Changes in conditions result in a renewed mismatch, and thus reintroduce motion sickness.

Even though active drivers would rarely encounter motion sickness during actual driving, they do encounter sickness in simulators. A common approach is to select as participants individuals who are not susceptible to motion sickness, or to discard data when sickness is reported. Ideally, however, we would design simulators to minimize simulator sickness. New challenges emerge in studies where motion sickness is an actual study objective, such as sickness occurring when driven by automated vehicles. In that case, the goal is to reproduce aspects of motion (dis)comfort in driving simulators, as they would occur in actual vehicles.

Simulators may be divided into fixed based and motion based setups. Whereas motion based simulators feature a variety of actuators that allow reproduction of physical motion, both types can be equipped with various visualization modalities, such as multiple displays, projections or head-mounted displays. Upgrading the technology, or in other words increasing the simulator *fidelity* (Liu, Macchiarella, and Vincenzi, 2008), increases sense of presence in users, which generally results in a higher validity for many driving parameters. These technological advances also reveal two limitations of the use of simulators. Firstly, the challenge to compare the experimental outcomes of studies employing different simulator setups. Secondly, the potential for additional mismatches (sickness) arises, both with respect to the real world and between simulator modalities. In parallel, understanding of how to mitigate sickness in simulators focuses on multi-modal stimulation (e.g., field-of-view (FOV) modifiers or actuated seats), increasing technological and sensory complexity. In light of this complexity and the increasing interest, this paper aims to clarify what simulator sickness represents and how it relates to motion sickness in real vehicles.

Theory

Classical Motion Sickness

Motion Sickness (MS) is a syndrome that emerges from exposure to movements such as abrupt or unnatural accelerations in vehicles. It manifests with symptoms such as dizziness, nausea and vomiting. When experienced in a car, a plane or on a boat, the phenomenon can respectively be called carsickness, airsickness or seasickness.

The nature of the sensory conflict causing sickening symptoms can be either explained as the conflict between sensations of motion and expectations based on previous experience or as a mismatch between sensed motion generated by different sensory systems, as compared to patterns recognized from previous experiences. It is important to note that these conflicts often emerge between sensory modalities (visual-vestibular), but sometimes also within modalities (vestibular-vestibular).

Visually Induced Motion Sickness

Sickness occurring when inertial motion might be absent but (artificial) visual motion is present, is referred to as *Visually Induced Motion Sickness* (VIMS). VIMS is typical for fixed-based simulators, but can also occur for example when watching driving videos, in a wide-screen cinema or virtual reality (VR) environment. Therefore, both cybersickness and VR sickness are classified as VIMS.

Even in absence of inertial motion, the human vestibular system's detection of gravitational force and its inability to reconcile this with the visual environment, can lead to a sensory mismatch. The main nature of the conflict can thus be explained as a visual-vestibular mismatch, but visual-visual conflicts can also occur in situations of contradictory inputs within different parts of the visual field.

Simulator Sickness

Simulator Sickness (SS) refers to sickness symptoms experienced in a (driving) simulator. Literature addressing the total of sickness symptoms measured in any simulated environment as "simulator sickness", or "motion sickness", refers to what we designate *Absolute Simulator Sickness*. Theoretically, the possible cause of absolute SS is twofold. The first cause is sickness as a result of actual motion in a moving-base simulator, which would also be encountered during actual driving. This will be referred to as *Simulated Carsickness* (SCS). Absolute SS could also develop from the simulator-specific technological factors, such as from the limited motion envelope and the artificial visualization modality, i.e., false and missing cues. This second phenomenon is a result of ambiguities within (e.g., bad resolution of visuals) or between (e.g., lagging) the motion or visualization modality of the simulator, and can be called *Simulator Induced Sickness* (SIS). Compared to the theory of Kolasinski (1995), SCS can be seen as resulting from the simulated *task* and SIS as resulting from the *simulator*.

The nature of the conflict can again be described by means of the Sensory Conflict Theory. SCS could originate from a conflict between sensed and expected neural inputs, possibly modulated by a conflict between visual stimuli and the appropriate vestibular motion. Contrarily, SIS could, by definition, solely originate from the conflict between perception (the simulated drive) and expectation (real world driving).

Spectrum

By definition, SCS should be similar to MS in terms of symptoms, individual sensitivity and time course (Talsma, et al., 2022). SIS, however, is dependent on the specific simulator setup and fidelity (De Winkel, Talsma, and Happee, 2022). For the latter, the sickness caused by mismatches between or within specific simulator modalities, we can distinguish two main factors: The visual modality and the motion modality. Whereas SIS may occur as a result of visual-vestibular or visual-visual mismatches, a vestibular-vestibular mismatch (e.g., the conflict between what is expected from real vehicle motion versus a simulator motion cueing settings) is as far as our knowledge goes, unknown. Without vision, isolated motion-related settings (bad or decent) only, do not cause SIS. If it is possible to get sick from this (delta) motion, it will be SCS instead. Visual-visual SIS, ambiguities of the simulator such as a limited resolution or unnatural parallax, is by definition a variant of VIMS. Visual-vestibular SIS, such as lagging between the displayed and the mapped motion content, could contain aspects of both MS and VIMS.

To structure our interpretation of sickness constituents, we propose the spectrum in Fig. 1. Classical MS, with inertial motion as a prerequisite, is shown in blue. VIMS, in yellow, represents sickness occurring in the absence of inertial motion. The red ellipse covering both spheres, represents the elements of SS. On the left-hand side (in red), we can place SCS as a subset of classical MS; on the right-hand side we can place SIS as part of VIMS; produced by artificial imagery ambiguities, and in the middle, we place absolute SS as an (yet) indistinguishable blend of both.

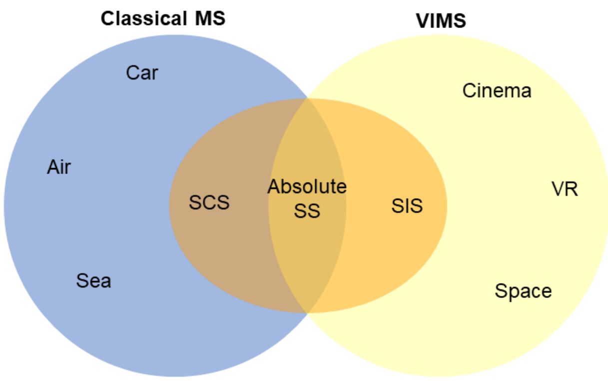

Figure 1: A vision on how different aspects of motion sicknesses are related. From left to right: Classical MS in blue, SS (SCS, Absolute SS, SIS) in red and VIMS in yellow.

We postulate that SCS and SIS jointly determine absolute SS, but also recognize that an interaction between both may exist. Himmels, et al. (2022) demonstrated an interaction effect between simulator and driving scenario, i.e. the choice of the simulator should be tailored to the driving task. We recall these as two of the influencing factors for SS (Kolasinski, 1995), hence, we think a similar relation holds for SCS and SIS. Although SCS by definition is conditional (and possibly proportional) to actual MS (Talsma, et al., 2022), less is known about the quantification of SIS. Individual simulator technologies causing SIS, can hardly be considered in isolation. Vice versa, without complete MS models yet existing, it is impossible to determine exactly from what specific components absolute SS originates.

The exact relative importance of the different senses involved is also unknown. Even though more sensory cues are said to have an effect on SS, such as anticipatory vibrations or auditory cues, these appear to be secondary contributors, compared to visual and vestibular systems (Britton and Arshad, 2019).

Practice

Practical application

Fig. 1 shows a visualization of the described motion sickness spectrum. Together with the observations below, it is possible to determine which variant of SS (in red) you are facing in a particular experiment.

- SCS (Fig. 1 left red area) can be studied by means of a motion-base driving simulator without artificial visual stimuli, as was also concluded by Kuiper, et al. (2019). In their experiment, SIS as a result of ambiguities in the visualization modality is eliminated, but note that the level of SCS experienced does not necessarily equal its real-world drive equivalent, MS.
- Research in a fixed-base simulator will encounter SIS only (Fig. 1 right red area). We agree with Bos, Nooij, and Souman (2021) that classical MS by definition cannot be studied in such a static, unimodal environment as actual motion is absent: Instead, sickness in a static simulator is better addressed as VIMS.
- A complete motion-base simulator with visualization modality (Fig. 1 center red area), may provide both visual and inertial (i.e. acceleration) cues that might induce sickness, thus the total value of absolute SS measured here could include a (yet) inseparable combination of SCS and SIS.

Some general practical measures include a common set of scenarios to execute or a minimum duration of the exposed drive (Himmels, et al., 2022). This ensures the *task* (influential for SCS) is consistent between experiments.

Dependencies

With the classification made in Fig. 1, we will now elaborate on unimodal (fixed-base) and multimodal artificial environments (motion-base simulator) separately, to compare SS with MS in Fig. 2.

- Firstly, for very low fidelity fixed-base simulators (e.g., a display and a stationary seat) it is possible not to experience any sickness. Multisensory integration of visual and vestibular information in the brain may not occur when visual motion is not realistic enough to be interpreted as self-motion (De Winkel, Katliar, and Bülthoff, 2017). Secondly, Bos, Nooij, and Souman (2021) suggest that it is impossible to study actual carsickness in a fixed-base simulator. Consequently, we propose that research will encounter SIS only when conducting experiments in a fixed-base simulator. By definition, the contribution of SCS to the amount of absolute (measured) SS is non-existent here. Therefore, since occurrence of SS is possible in fixed-base simulators, just as it is not uncommon to experience sickness in a wide-screen cinema, reported SS in these studies must be SIS. Thirdly, studies (Chang, Kim, and Yoo, 2020; De Winkel, Talsma, and Happee, 2022) suggest that for unimodal virtual systems, SS (thus SIS) increases with simulator fidelity. These findings are in line with the Conflict Theory: if only the visual system is stimulated (unimodal), the user is more likely to experience (stronger) sensory conflicts, and thus sickness. This situation is represented by Fig. 2. a.
- Similarly, it is suggested that for multimodal virtual systems, absolute SS could decrease with simulator fidelity (Chang, Kim, and Yoo, 2020; De Winkel, Talsma, and Happee, 2022). Aforementioned studies (Bos, Nooij, and Souman, 2021; Talsma, et al., 2022) address also the second argument of the relation: Motion-base simulators, equipped with a limited motion envelope, are unable to simulate motion 1:1. Therefore, we suggest that SCS alone, will be lower than its actual MS equivalent (shown in Fig. 2. b). Motion-based simulators with higher fidelity, e.g. with a larger stroke, can approximate real road MS more closely, producing more realistic SCS than simulators with less extensive motion envelopes. This is visualized by an upward slope of SCS. Lastly, when these findings are combined, they result in a decrease of SIS with increasing simulator fidelity. A simulator at the right end of the horizontal axis, resembling real-world driving perfectly, creates, by definition, only the sickness that would also occur in real-road driving. SIS is then theoretically non-existent (there are no more latencies, visual errors, poor visual quality, etc.) and SCS will be equal to MS. Multimodal systems are able to provide more sensory cues than only visual ones and possible neural conflicts will therefore be reduced by increased simulator fidelity. These notions are visualized in Fig. 2 b.

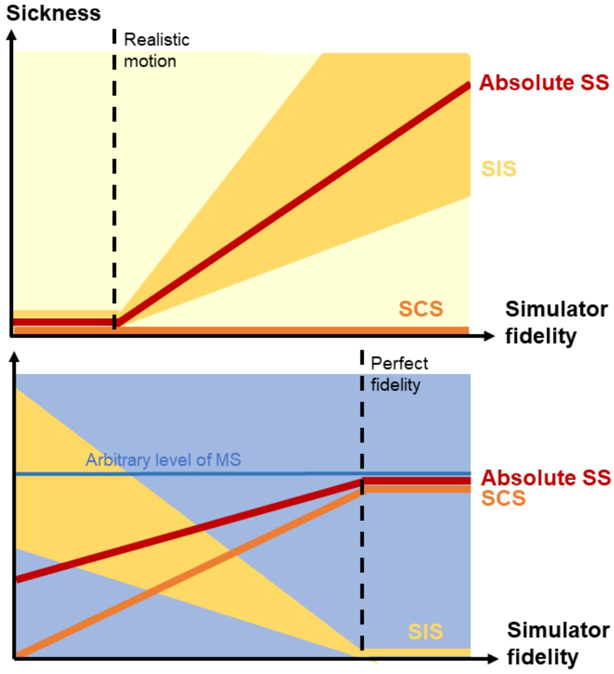

Figure 2: Visualization of SS components and MS versus simulator fidelity, for unimodal fixed-base simulators (2.a) and for multimodal motion-base simulators (2.b)

Discussion

Oftentimes in simulator studies, motion sickness is neither the study objective, nor an expected or desirable by-product of simulated motion. Hence, it is desirable to minimize SS in general. Other than filtering out susceptible participants (manipulating or ignoring the *individual* contribution), the importance lies here in designing *simulator* and *task* to minimize absolute sickness. In line with our theory, it is both possible to minimize SCS and to minimize SIS. Generally, to minimize SS, numerous studies mention countermeasures such as repeated exposure or training (De Winter, et al., 2007; Dużmańska, Strojny, and Strojny, 2018), avoidance of excessive curve negotiation (Mourant, et al., 2007), and addition of sickness-mitigating devices (Weech and Lamontagne, 2023). In a unimodal environment, we postulate that SIS is more prevalent than SCS (Fig. 2 a), thus minimizing SS could focus on minimizing factors causing SIS. In a higher fidelity multimodal environment, SS is much more dependent on SCS than SIS. Implying that the *task*, rather than the specific *simulator*, should be optimized.

In the cases where MS is the study objective (e.g. self-driving carsickness), we aim to have SCS approximate MS, and to minimize SIS (Fig. 2 b). In other words, allowing SCS and minimizing SIS by optimizing the simulator fidelity. The former could be executed through e.g., the usage of a simulator with a large stroke, able to simulate accelerations of similar size to those experienced in the real world. In a fixed base simulator, it is discouraged (if not impossible) to study MS. Nevertheless, SIS could here be minimized by the use of for example screens rather than projections or head-mounted displays, or decreasing the FOV. Contrarily, in a multimodal environment, we need to focus on presenting the visualizations as realistically as possible. This means that higher fidelity displays and large FOV could decrease SIS. Even though low fidelity simulators have demonstrated sufficient validity to several driving and training experiments, to study MS we would recommend the use of a motion-base simulator with the highest possible fidelity. Additionally, repeated exposure is beneficial. Subjects with previous simulator experience or even gaming experience, show a lower occurrence of MS (Kourtesis, et al., 2023). This is possibly a result of familiarity with the factors (intensity, brightness, refresh rate) attributed to artificial imagery.

A few remarks to this vision have to be taken into account:

- This paper is focused on the two main human senses and simulator modalities: vision and motion. A question remains whether these dependencies (Fig. 2) can be extended to other (sensory) modalities and how sickness-mitigating devices and other anticipatory cues reduce sickness for unimodal and multimodal simulators.
- We used the Sensory Conflict Theory as the most likely explanation of the cause of MS. An interesting approach could be to analyze these causes from the perspective of other non-excluded theories, such as the Postural Instability Theory.
- The exact cause of MS is not yet known, and no comprehensive model exists. It is also yet impossible to scale the contribution of different sensory modalities. A complete understanding of MS could help to further specify SIS. Similarly, isolating parts of the simulator and understanding all scenarios of SS, can potentially help unravel a model for MS.
- With the (practical) suggestions to reduce SS (absolute, SIS or SCS) proposed in this paper and by others, the question of ecological validity arises. Ecological validity refers to the extent to which results obtained in a simulator environment generalize to the real world. When measures are taken to reduce SIS, these could inadvertently produce a simulation setting that is too different from the real world situation for the study results to reflect human responses to the real world situation, in a similar vein as stimuli may require a certain threshold fidelity to be interpreted as indicative of self-motion (De Winkel, Katliar, and Bülthoff, 2017).

Clearly, we do not yet fully understand how the brain merges information from sensory modalities and how it learns which patterns of stimulation are normal or how it is decided that these are conflicting. Despite this, study objective or not, we believe that the theoretical vision proposed in this paper provides guidelines that may help to achieve a better understanding of simulator design and simulator study results, in a world where simulators are already indispensable.

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