(Im)possibilities of studying carsickness in a driving simulator

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Abstract - *When studying (the effectiveness of countermeasures to) carsickness in a simulator, it currently remains a question whether results still hold true in a real car. This question not only concerns its practical consequences, but the scientific interest in the underlaying mechanisms as well.*

By reckoning previous observations and new insights focussing on the differences between simulator and car motion as well their Out-the-Window (OtW) visuals, this paper nuances the assumption that (moving base) simulators can be useful in research on driving comfort in autonomous vehicles. It elaborates on six specific issues: 1) the use of fixed base simulators, 2) motion cueing, 3) linear displacement limitations, 4) display limitations, 5) perceptual scaling of visual and vestibular cues, and 6) physical and visually induced self-tilt.

The overall conclusion is that only without OtW artificial visuals and when true car motion can be replicated, it is possible to elicit carsickness in a simulator. If motion is limited by displacement, sickness is most severe at 0.35 Hz. Whenever motion cueing and/or artificial OtW visuals are applied, sickness elicited is better described as simulator sickness, then defined as sickness only occurring during the simulated, but not during the real ride.

Keywords: *carsickness, simulator sickness, visual-vestibular conflict, moving base limitations, display limitations*

Introduction

Carsickness can be defined as a syndrome caused by car motion, characterised by symptoms varying from, e.g., drowsiness and stomach awareness, to nausea and ultimately vomiting [Rea75]. When studying carsickness, or the effectiveness of specific countermeasures to it, in a simulator, it currently remains the question whether results still hold true in a real car. This question not only concerns its practical consequences, but the scientific interest in the underlaying mechanism(s) as well.

By reckoning previous observations and new insights on differences between real and simulated physical motions and Out-the-Window (OtW) visuals, this paper will nuance the conclusion that (moving base) simulators can be a useful research tool to study driving comfort in (autonomous) vehicles, as suggested by, e.g., [Bel17]. As a consequence, it will discriminate possible from impossible studies on carsickness using driving simulators.

The origin of simulator sickness

Although multiple motion sickness theories have been proposed, the most cited and successful theory is the sensory or neural mismatch theory proposed by [Rea75] and [Rea87]. Its success is substantiated by the fact that it is the only theory that has been explicated in mathematical terms, allowing for (quantitative) predictions and explicit validation [Oma82, Ble98, Bos98, Bos08, Bos11, Wad10, Wad20, Wad21]. This theory basically takes the observer theoretical control of body motion as a starting point. Then, as a consequence, there is a conflict between sensed signals about self-motion and self-tilt on the one hand, and an expectation or prediction thereabout as generated by an internal model or neural store on the other hand. The importance of self-tilt has been put forward by [Ble98]. In simulators, this vestibular-expectation conflict is enhanced by visual-vestibular conflicts, the latter thus being a modulating rather than a causative factor [Bos18]. Vestibular cues as sensed by the organs of balance in particular, are ambiguous due Einstein's equivalence principle regarding inertial and gravitational accelerations. Visual cues can be ambiguous due to the projection of the 3D world onto a 2D screen (or two in case of stereoscopic views). The importance of this notion concerns the difference between perceived real and simulated cues that should be minimised, rather than the difference between the actual cues per se. Perception of these cues is furthermore affected by the limitations of the simulator. Some of these limita-

tions will be elaborated on below, both with respect to the physical and the visual cues and their effect on simulator sickness in particular.

Here, we refer to *perception* being the result of cues as *sensed* by our senses (sensors), their dynamics, and processing by the central nervous system.

Simulator limitations contributing to simulator sickness

Physical effects

Fixed base simulators

Fixed base simulators are inherently causing a conflict between visual and vestibular cues. The (artificial) imagery then typically shows an OtW view suggesting a vehicle motion relative to the world. Different from what may be thought of, the organs of balance, though not sensing inertial motion in a fixed base simulator (apart from minor readjustments of the body and head within the simulator cabin), still do sense the gravitational acceleration. As a result, both the sensed physical self-motion and self-tilt do remain constant, different from the visually sensed self-motion and self-tilt, thus causing a considerable conflict different from what happens in a real car.

The other way round, though maybe farfetched, still, when blindfolded, people getting sick in a real car will most likely not get sick in a fixed base simulator. The same holds for blind people, who have been shown to be susceptible to motion sickness [Gra70].

Though trivial, it can be concluded that it is impossible to study carsickness in fixed-based simulators. Sickness then elicited is better described as visually induced motion sickness, or cybersickness.

Motion cueing

The perception of motion is affected by several moving base limitations, both with respect to linear and angular displacement, velocity and acceleration (and possibly higher order time derivatives like jerk), and their interactions. Although current motion cueing algorithms are optimised based on a minimum difference between the perception of real and simulated motion, conflicts still existent can accumulate over time to cause sickness. Tilt coordination, for example, compensates for the (washout) high-pass characteristics of the (limited) linear displacement, of Stewart platforms in particular. In car driving this is of particular interest when accelerating, braking, or cornering. By tilting the platform simultaneously, part of the gravitational acceleration is projected onto the cabin's "horizontal" plane. Concurrently, the visual Earth-horizontal plane is kept parallel to that same plane. On the one hand, this tilt motion should be as fast as possible to keep the total acceleration as close as possible to the intended acceleration (see Figure 1). On the other hand it should be below the threshold for perception. As a trade-off, tilt motion is generally limited to 2-3 deg/s [Gro01]. Then, however, 1) there may remain a large discrepancy between intended and realised total acceleration (see Figure 1), 2) the angular motion may still be perceived, 3) the "vertical" total acceleration generally gets smaller, which may be perceived as well, and 4) negative acceleration, even enhanced by washout, is considered "bad" motion. These unnatural and hence unexpected effects can all accumulate to manifest sickness.

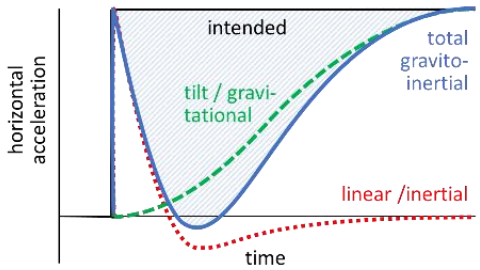

Figure 1. Horizontal accelerations due to linear platform displacement and tilt. The hatched area shows the discrepancy between intended and total acceleration (after [Gro01]). Note that with, e.g., "XY tables" the dashed area can be reduced.

From these considerations it can be concluded that it is doubtful whether sickness observed in a simulator will also occur in real driving, at least when considering a wide variety of driving conditions and using a Stewart platform in particular.

Moving base limitations

The most acknowledged predictive model for motion sickness is given by ISO2631-1:1997 [ISO97]. Figure 2 (left) shows some of its motion sickness incidence (MSI) curves when keeping the maximum acceleration fixed. These curves typically peak at 0.17 Hz. To accelerate and decelerate on a motion platform with a sinusoidal profile and using frequencies about the MSI peak frequency and amplitudes within the range for normal day driving [Hug03], would require displacements as listed in Table 1. The majority of these displacements cannot be realized by standard Stewart platforms. Even the largest simulators using a linear sled would not be capable of covering the entire range listed. Moreover, this range is only a subset of all conditions met in real life.

Table 1. Total displacements (m) required to realize a sinusoidal acceleration profile with peak acceleration *a* (m/s²) and frequency *f* (Hz).

f↓ *a*→	0.5	1	2	4
0.1	8	16	32	64
0,2	2	4	8	16
0.4	0.5	1	2	4

The most salient kinematic limitation of Stewart platforms in particular, is their limited linear displacement. These are typically less than 1 to 2 m peak-to-

peak in any direction. This limitation also poses serious limits to the accelerations that can be realised, the peak values of which increase with frequency squared for sinusoidal motion. When, then, keeping the total displacement fixed and assuming high accelerations can be achieved (a typical advantage of hydraulic systems), the ISO curves can be recalculated, resulting in some curves as shown in Figure 2 (right). As a result of the acceleration depending on the frequency squared, these curves then peak at 0.35 Hz [Kui19]. With a total displacement of 2 m, for example, [Kui19] experimentally confirmed that significant sickness in blindfolded subjects can be obtained. Whether tilt coordination can add to reduce sickness for low frequency motion in particular, remains to be seen.

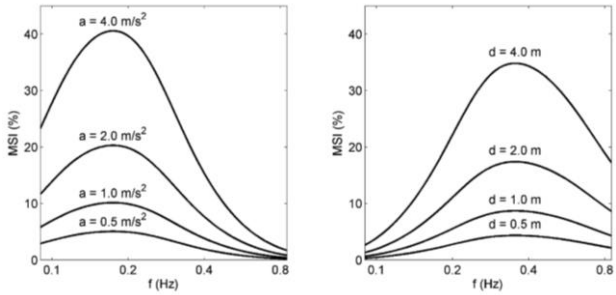

Figure 2. MSI curves versus frequency calculated for fixed accelerations (left) and displacements (right), taken from [Kui19].

Based on these considerations, it can be concluded that without OtW visuals it is possible to elicit relevant levels of carsickness using a moving base simulator, however for a limited range of car motions. If motion platform is limited by displacement, sickness is most severe at a frequency of 0.35 Hz.

Visual effects

Display limitations

Although the visualisation of a realistic environment using artificial imageries may seem straightforward, this is not the case. While the geometrical transformation of a 3D OtW environment onto a 2D projection plane is trivial, the projection itself and the motions involved can be ambiguous. Hard- and software limitations then add to the fact that the perception of the imagery does not necessarily equal that of the perception of the real imagery simulated. This also holds for stereoscopic images.

Several factors do contribute to this discrepancy, and may thus also explain part of the occurrence of simulator sickness, different from carsickness. Without going into detail, examples are a limited field of view (FoV; including possible differences between viewpoint and differences between display and camera FoV [Emm11]), limitations on spatial, colour and temporal resolution (including delays), and factors like lighting, shading, blur, and in most cases a lack of motion parallax [Led15]. Another, often neglected, factor concerns that all display systems do project the imagery on a fixed distance. In case of monoscopic systems, this prevents lens accommodation and vergence eye movements used by our brains for depth perception. In the case of stereoscopic systems, such as VR goggles, even today there are no systems allowing for true variable focus. Perception of depth is therefore inadequate in all current display systems as also used in driving simulators. It goes without saying that depth perception is an essential factor in motion perception, which already explains (part of) the difference between true carsickness and simulator sickness.

As a result, it can be concluded that with OtW artificial imageries it is doubtful whether sickness observed in a simulator will also occur in real driving.

Perceptual scaling of visual and vestibular cues

Although never done, subjects may be asked whether the physical and visual motion perceived in a real vehicle with ample OtW vision are equal. Likely this will result in a unanimous positive response, suggesting that the optimal ratio between visual and physical motion equals one. When using an artificial imagery, this has been shown to be different. [Cor14], for example, exposed subjects to periodic real motion with a fixed amplitude, while showing congruent visual motion, except for the amplitude thereof. Subjects were asked to adjust that visual amplitude such that it was perceived as coherent with the physical motion. For linear motion they found that the visual motion was required to be considerably larger than the physical motion. As assumed, the discrepancy became less with a larger FoV and more objects being placed in the virtual environment. Also, they found that the subjects who did get sick, did so in the conditions with the largest discrepancies.

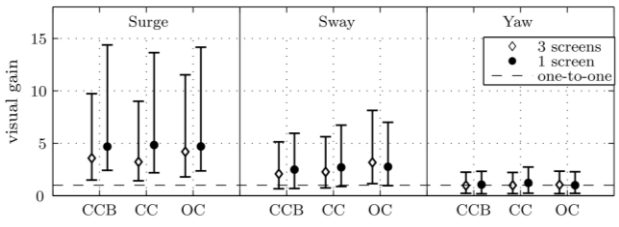

Figure 3. Visual/vestibular ratios (gains) for different degrees of freedom (Surge, Sway and Yaw motion), FoVs (#screens:1 = 41°, 3 = 120°) and visual scenes (CCB: a city center with a 3D matrix of balloons, CC: a plain city center, and OC: a scene outside a city). Taken from [Cor14].

On the one hand, the underestimation of physical motion relative to visual or true motion is a benefit, in that it reduces the requirements for motion platforms. On the other hand, the same underestimation further questions whether sickness observed in the simulator will also occur in real driving.

Physical and visually induced self-tilt

Real and fixed-based vehicle tilt differ with respect to linear accelerations and anticipatory behaviour (see above). In real driving, postural behaviour of drivers and passengers differ in addition [Zik99]. Despite these complicating factors, the following focuses on the effect of mere tilt. With physical tilt, the body is then forced to tilt with the vehicle. At the same time, the Earth-fixed OtW visual scene tilts in the opposite direction relative to an observer in the vehicle. In a fixed-based simulator, this tilt is simulated accordingly. This visual scene tilt, however, generally causes the body to tilt with the scene, a phenomenon also known from the rod-and-frame effect [Gib38, Asc48]. As shown in Figure 4, these effects are opposite.

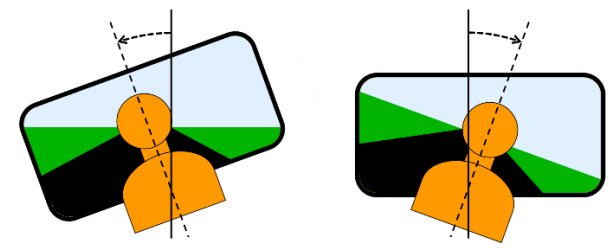

Figure 4 Self-tilt induced by physical platform tilt (left) and mere visual scene tilt (right).

The other way round, by viewing a subject-fixed frame of reference, as when reading a book in a car, perceived self-tilt will be underestimated, increasing the visual-vestibular conflict, why sickness with an interior view only is typically larger than with eyes closed [Bos05].

Though not proven (yet), it does make sense to assume that the discrepancy between physically and visually induced self-tilt may cause a negative transfer of training in case of skill based training, such as when fast postural and manual action is required. Moreover, for the same reasons as mentioned before, and reckoning [Ble98], the discrepancy shown adds to the doubts on using a simulator to study carsickness.

Conclusions

In the above we focussed on six differences between the effects of both physical motion and OtW visuals in simulated and real driving. The conclusions drawn regarding physical effects were:

1) Though trivial, it is impossible to study carsickness in fixed-based simulators. Sickness elicited is rather described as visually induced motion sickness.

2) It is doubtful whether sickness observed in a simulator will also occur in real driving when using a wide variety of driving conditions and a Stewart platform in particular.

3) Without OtW visuals it is possible to elicit relevant levels of carsickness using a moving base simulator, This holds for a limited range of conditions. If limited by simulator displacement, sickness is most severe at a frequency of 0.35 Hz.

With respect to visual effects these were:

4) With OtW artificial imageries it is doubtful whether sickness observed in a simulator will also occur in real driving.

5) This doubt is enhanced by an underestimation of perceived physical relative to visual motion.

6) Which doubt is further enhanced by differences in physical and visual induced self-tilt.

These conclusions can be condensed into the final conclusion that *only without OtW artificial visuals, and when true car motion can be replicated, it is possible to elicit carsickness in a simulator.* If the motion is limited by displacement, sickness is most severe at 0.35 Hz.

This conclusion also implies that there are conditions, typically when using artificial OtW imageries, carsickness cannot be studied in a simulator.

The latter also implies that, taxonomically, simulator sickness should be differentiated from true carsickness when sickness only occurs during the simulated, but not during the real ride, as previously suggested already by [Kui19].

Even without OtW visuals, the value of using a simulator to study carsickness is given by, e.g., the evaluation of motion predictability [Kui20b] and specific countermeasures providing anticipatory cues by visual displays [DeW21, Fee11, Kar18, WinYus20], or auditory cues [Kui20a]. Likewise, the effect of air quality, seating configurations and body posture may be studied without OtW visuals.

A detail concerns the observation that drivers of real cars suffer considerably less from carsickness than passengers do [Rol91, Sch20]. This difference, however, should (not proven yet) be smaller in a simulator. This can be explained by assuming that the driver's internal model (initially) only reckons the dynamics of a true vehicle, and not that of the simulator. The latter is affected by, e.g. tilt coordination as elaborated on above. Habituation to simulator sickness with repeated and/or prolonged exposures can be explained likewise [Bos18].

Another interesting detail concerns that motion cueing algorithms are mainly optimised for a perception that comes closest to the motions as visualised or as memorised from previous experiences [Col08]. Whether or not an optimisation with respect to simulator sickness would differ from an optimisation based on perception has never been addressed yet, and remains an intriguing topic for future scrutiny.

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