What we don't (yet) know about self-driving carsickness

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***Abstract**: Of all passengers, 2/3 does suffer from carsickness to some extent, while drivers suffer considerably less and comprise about 2/3 of all car occupants. Whilst this renders carsickness a minority concern today, in a future of automated vehicles in which all occupants are passengers, the majority of occupants will suffer, thereby making carsickness a game changer regarding the way vehicle motion should be controlled optimally. This paradigm hence requires knowledge about carsickness, explicated by means of numerical models that generate valid predictions for the syndrome as a whole.*

Although the ISO 2631-1:1997 is still the most widely acknowledged numerical model to predict motion sickness, in this paper we discuss a number of limitations why ISO may not be the appropriate model for predicting carsickness in particular. As a consequence, we define several outstanding questions that should be answered for an optimal prediction of carsickness. These questions concern temporal aspects such as accumulation, habituation, recovery and retention, the effects of angular motion, predictability of motion and visual effects. The latter not only concerns carsickness, but simulator sickness in particular. In addition, we address susceptibility to sickness, i.e., individual and demographic effects, as well as methodological issues regarding the quantification of sickness that currently hamper the progress of our understanding of carsickness.

To offer passengers of automated vehicles comfortable rides time after time, answers to these outstanding questions should be known not only regarding vehicle motion control, but regarding routing and driving simulation as well.

***Keywords:** carsickness, simulator sickness, outstanding questions, pre-competitive research*

Introduction

The promise of the self-driving car has considerably increased the interest in carsickness. This can be understood by the fact that about 2/3 of all car occupants are currently drivers, who, compared to passengers, are relatively insensitive to carsickness (Schmidt, et al., 2020). However, self-driving or automated vehicles will render all occupants passengers whilst we know that about 2/3 of all passengers do suffer from carsickness, at least to some extent. Subsequently, this turns carsickness from a minority into a majority problem. Carsickness is therefore a game changer regarding the way vehicle motion and routing should be controlled in automated vehicles. This paradigm hence requires knowledge about carsickness, preferably in the form of numerical models.

To date, the ISO 2631-1:1997 (ISO, 1997) is still the most widely acknowledged model to predict motion sickness. For historical reasons, this ISO model is limited to vertical motion as was found to be pivotal in explaining seasickness caused by motion of relatively large ships, mainly driven by swell. Moreover, this model only calculates the incidence of people reaching the limit of vomiting (emesis) in conditions without a view of the (real) outside world. It further assumes a peak in sickness incidence at about 0.2 Hz, with virtually no sickness predicted below 0.03 Hz and above 1 Hz (O'Hanlon and McCauley, 1974). Vehicle motion, however, also comprises considerable horizontal motion, which is generally assumed to be sickening too. At the same time, it remains to be seen whether vertical car motion, typically showing most power above 1 Hz, is not provocative as predicted by ISO. The latter likely relates to the fact that motion sickness concerns a syndrome characterized by a multitude of symptoms that typically precede vomiting (Reuten, et al., 2021). Hence, even when nobody is vomiting (yet), sickness may be a serious issue (Bos, 2004). Out-the-window views, lastly, are known to reduce sickness considerably (see below), which is not considered by ISO. This too adds to the conclusion that ISO 2631-1 in its current form is only of limited value to predict carsickness.

At the same time, several more recent studies have already clarified motion sickness characteristics due to horizontal motion, with some estimates about their frequency dependence (e.g., Donohew and Griffin, 2004; Golding, et al., 2001). Although these data do suggest a peak in sickness severity again about 0.2 Hz, the actual frequency weighting function over a

wide range of frequencies for horizontal motion remains to be determined. Moreover, lateral and fore-aft motion may even show different weightings.

Both ISO (1997) and the other studies published assume that any motion profile can be recalculated into a power spectrum to which a frequency dependent human sensitivity function can be applied to find the sickening effect of that motion. Although this seemed highly appropriate for ship motion, car motion is largely characterised by specific single events alternated with relatively long periods of more or less constant velocity, the latter only marginally contributing to motion sickness. These single events typically concern accelerating, braking, cornering and lane changes. Moreover, these single events can occur at unpredictable moments, with predictability playing a role in the genesis of motion sickness (Kuiper, et al., 2020a). The same predictability relates to anticipation (Kuiper et al., 2020b) which has also been suggested to explain the difference in sickness experienced by drivers and passengers (Rolnick and Lubow, 1991; Schmidt, et al., 2020; Diels and Bos, 2021).

As already referred to regarding the ISO (1997), vision is an important factor in motion sickness (see also, e.g., Griffin and Newman, 2004; Kuiper, et al., 2018). Although sometimes considered a causative factor, we here explicitly refer to the effect of vision as a modulating factor. We do so because 1) blind or blindfolded people do suffer from motion sickness (Graybiel, 1970), and 2) people without functioning organs of balance are insensitive to physically as well as visually induced motion sickness (Cheung, et al., 1991). Also Salter, et al. (2019) concluded on an increased likelihood of getting sick in a car when facing rearward. Moreover, the effect of vision is of particular interest in the case of simulator sickness (Bos, et al., 2021).

In the following sections we will therefore summarise a number of outstanding questions, focussing on temporal aspects such as accumulation, habituation, recovery and retention (of both habituation and accumulation), the effects of angular motion and predictability of motion, and visual factors as particularly relevant regarding simulator sickness. In addition, we will address susceptibility to sickness, i.e., individual and demographic effects, as well as methodological issues regarding the quantification of sickness. Some of these issues were also included in Diels and Bos (2016, 2021) and in Diels, et al. (2022).

Outstanding questions

Temporal aspects

Figure 1 shows the generic temporal behaviour of motion sickness severity due to two temporally separated provocative stimuli. Here, six characteristic phenomena can be distinguished: onset delay, accumulation, habituation, recovery and retention.

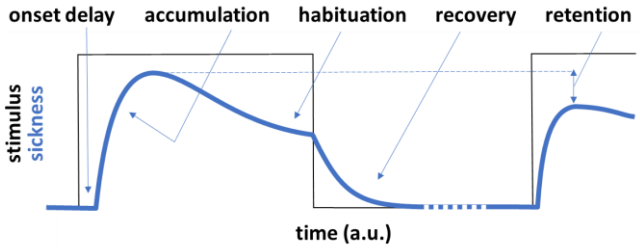

Figure 1: Temporal sickness behaviour due to two temporally separated provocative stimuli

Accumulation is the only temporal factor for which a numerical estimation is given. ISO (1997) assumes this accumulation to behave according to the square root of time. This, however, implies a theoretically unlimited accumulation of sickness. When assuming vomiting as an endpoint of sickness severity (Reuten, et al., 2021), according to ISO the validity of this square root dependency is therefore limited to 6 hours. Moreover, asymptotic behaviour does occur (Van Emmerik, et al., 2011), which further indicates a need for further scrutiny. Accumulation may in addition only start after a certain onset delay and literature on this issue is rather scarce (but see again Van Emmerik, et al., 2011).

After a certain, but yet undocumented time, sickness may decrease due to what is generally called habituation. Although the term adaptation is used too, in perception research adaptation typically refers to the sensory receptors, while habituation refers to a central process, i.e., controlled by the central nervous system. Because the latter most likely applies to motion sickness (see Bos and Bles, 2002), habituation seems to be the appropriate term here. Literature on habituation is rather limited too (but see McCauley, et al., 1976; Howarth, et al., 2008), making this a topic of further study as well.

If a stimulus stops, sickness severity typically does not stop immediately (see, e.g., Bos, et al., 2002). The temporal behaviour of this recovery is, however, largely unknown, hence being another issue worth being studied.

Finally, retention can refer to accumulation and to habituation. When, for example, a motion challenge starts before recovery is complete due to a previous challenge, the new accumulation may not only start from an offset, but it may also show a faster accumulation. This is also referred to as sensitisation or sensibilisation. Retention of habituation refers to the observation that a following motion challenge results in less sickness as compared to a previous one. This generally only occurs after recovery to the previous challenge has been complete. We have not been able to trace any literature on either form of retention.

Angular motions

With the exception of four-wheel steering vehicles, nearly all angular motions go along and are (highly)

correlated with tangential and/or centripetal accelerations (Figure 2). Linear accelerations can therefore be assumed to predict motion sickness to a high level of accuracy in practice.

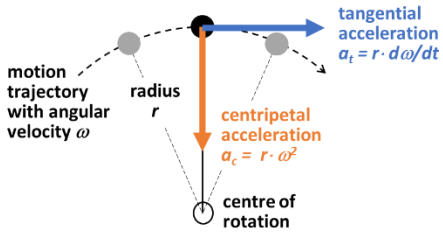

Figure 2: Tangential and centripetal acceleration due to angular motion

Moreover, angular motion per se is generally not that sickening. This holds true in particular for yaw motion about an Earth-vertical axis through the centre of the head, i.e., without any additional head movements (see, e.g., Bos and Bles, 2002). Only when the axis of rotation is tilted away from the Earth-vertical, people start getting sick from angular motion. But even then, as has been shown by oscillating subjects about an Earth-horizontal axis through the centre of the head, the angular motion is hardly, if not at all, provocative (Wertheim, et al., 1998). Only when the head is moved away from the rotation axis, people start getting sick. By moving the head away from the rotation axis, a centripetal acceleration will be at issue and/or the free fall acceleration will vary with respect to the head. The effect of angular motion will therefore be highly correlated with the accompanying effect of linear acceleration.

Yet, angular motion has been shown to interact with linear motion, possibly leading to (additional) sickness (Wertheim, 1998). Also, when considering four-wheel steering vehicles, linear accelerations may not correlate with angular motions and could be worth being elaborated on experimentally.

Predictability and anticipation

Cyclic motion generally has a high degree of predictability, which has been shown to be less sickening than unpredictable motion (Kuiper, et al., 2020a). In that respect it would make sense to find a predictability parameter that correlates best with the difference in the sickening effect of a motion relative to a comparable single sinusoidal motion.

This problem relates to the fact that ISO (1997) assumes that motion sickness due to a complex motion can be described by the linear addition of the separate responses to each of the single frequency sines of which the complex motion is composed of. Interestingly, Guignard and McCauley (1982) already observed that subjects exposed to several combinations of sinusoidal (vertical) motion showed “unexpectedly high” motion sickness in certain combinations. This problem too may be solved by introducing such a predictability parameter.

One way to affect the predictability of motion, in particular when this considers a series of single events rather than oscillatory motion, is the introduction of anticipatory cues preceding these events. Using an auditory cue, Kuiper, et al. (2020b) already gave a proof of concept. The question here still concerns the type of cue that would give the best result while at the same time giving the least interactions with in-car activities (Diels and Bos, 2021).

Here, it should be noted that looking out-the-window not only allows for anticipation, but will also give instantaneous visual information about self-motion (i.e., “vection”), as well as self-orientation or -tilt (see also below).

Visual factors

In Bos, et al. (2021) it has already been argued that several visual factors impede the application of simulators for use in carsickness research. These factors concerned the following.

Display limitations typically concern a limited Field of View (FoV; including differences between display and camera FoV; Van Emmerik, et al., 2011), limitations in spatial, colour and temporal resolution (including delays) and factors like lighting, shading, blur, and in most cases a lack of motion parallax, with fixed focus projection causing an accommodation-convergence conflict and aberrations in depth perception. Although in recent years several solutions have been proposed for these issues, they typically involve trade-offs with other aspects of image quality and usability, rendering commercial use still a thing of the future (see e.g., Zhou, et al., 2021).

Perceptual scaling of visual and vestibular cues refers to the observation that in simulators vestibular motion cues should generally be weakened against the visual motion in order to be perceived as congruent. Moreover, it has been shown that this scaling depends on the degree of motion freedom, FoV, and image content, and that subjects who did get sick, did so in the conditions with the largest scaling differences (Correia Gracio, et al., 2014).

Physical and visually induced self-tilt are fundamentally different. When, for example, sitting or standing on a tilted platform, the body tilts with the platform, which requires an action in the opposite direction to prevent tipping over or falling. When such a condition is simulated using a virtual visual environment, the virtual world tilts about an equal angle, however, in the opposite direction as in the real case. Comparable to the rod-and-frame effect, the body will then tilt with the virtual world, which hence is in the opposite direction as compared to the real tilt, also requiring an active control opposite to what is required in reality (Figure 3). Given the fact that moving base simulators typically apply motion gains of less than one (see also above), this problem will likely only be solved partly when using moving base simulators.

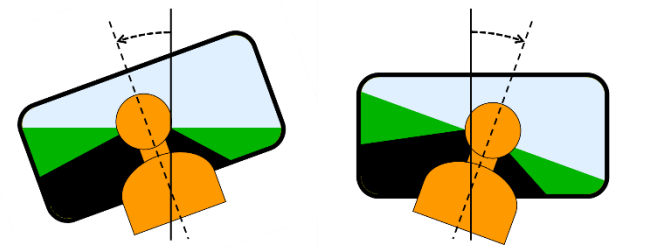

Figure 3: Self-tilt induced by physical platform tilt (left) and mere visual scene tilt (right)

As already stated by Bos, et al. (2021), these factors altogether contribute to a fundamental difference between simulator sickness and (true) carsickness, the former possibly occurring in cases where sickness in a real car on the road would not occur. The fact that these factors are often neglected and, likely as a consequence, have only been studied scarcely while yet possibly being of great importance, points to the need for further research. This not only holds for sickness, but most likely for effects on transfer of training as well.

Individual susceptibility

If the literature on motion sickness is consistent about one thing, it is about the high variability of levels of sickness observed between individuals in otherwise equal conditions. Part of this variability has been ascribed to age, gender and sickness history (see, e.g., Bos, et al., 2007), and ethnic effects (e.g., Hromatka, et al., 2015). These factors contribute to what is referred to as susceptibility, i.e., the a priori sensitivity of an individual based on biological and psychological factors. Currently, the most often used susceptibility rating scale is given by Golding's Motion Sickness Susceptibility Questionnaire (2006). Based on how often nine motion environments have led to sickness in the first 12 and in the most recent 12 years of life, a total score is given, which can be recalculated into percentile scores of a normal population. Although quite some literature relates sickness scores observed in particular experiments to these MSSQ ratings, showing some, but definitely no perfect correlation, surprisingly few efforts have been published on the dependence of the MSSQ on age, gender, sickness history and/or ethnicity. This implies that still no unique rating exists covering all factors determining an individual's a priori susceptibility, a challenge thus worth pursuing.

The actual value of knowing an individual's susceptibility can be twofold. When conducting motion sickness experiments, the susceptibility is likely the most important factor explaining the variability between subjects, apart from the desired variability induced by the experimental conditions. Hence, if a valid susceptibility rating would be available, that would be a big step forward in explaining and predicting motion sickness based on any experimental variable. The other reason is the possibility to adapt a vehicle's motion and routing to match an individual's optimum for comfort. Obviously, this is more difficult in the case of multiple vehicle occupants, where the most susceptible occupant might be taken as a reference.

Another unresolved issue concerns the question of how susceptibility relates to sickness. As highlighted under the temporal aspects, susceptibility may affect sickness onset, accumulation, habituation, recovery and retention all differently. It therefore still remains a question too whether a simple assumption such as a single "gain", like the parameter K_m as used by ISO (1997), suffices to mathematically account for susceptibility.

Measuring motion sickness

A multitude of rating scales are currently in use to quantify motion sickness in experimental studies. One group of these rating scales can roughly be described as multi factor rating scales, resulting in multiple ratings based on questionnaires rating different aspects of motion sickness. Examples are the Simulator Sickness Questionnaire (SSQ, Kennedy, et al., 1993) and the Motion Sickness Assessment Questionnaire (MSAQ, Gianaros, et al., 2001). These assessment methods, however, require a questionnaire to be filled out, and are of little use for being applied at regular intervals during an exposure. This holds in particular when performing other tasks, possibly with eyes closed. Alternative methods therefore ask for a single number indicative for sickness severity. These scales can be separated into scales asking for unpleasantness, such as the Fast Motion sickness Scale (e.g., FMS, Keshavarz and Hecht, 2011), or symptomatology (e.g., Griffin and Mills, 2002; Golding, et al., 1995; Bos, et al., 2005). The latter scales take advantage of the general observation that sickness symptoms typically develop in a fixed order and these symptoms hence offer anchor points, decreasing interindividual variability due to the process of rating by itself. Moreover, Reuten, et al., (2021) showed that, despite an overall positive correlation between unpleasantness as rated by the FMS and the progress of symptoms as rated by the MISC (Bos, et al., 2005), unpleasantness typically shows a decrease at the onset of nausea. As a result, unpleasantness can therefore be predicted based on symptom progression, while the progression of symptoms cannot be predicted based on unpleasantness (Figure 4). The latter can be considered a second reason speaking in favour of rating symptoms progression.

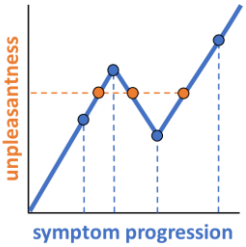

Figure 4: Idealized sketch of unpleasantness versus symptom progression (after Reuten et al., 2021). Each level of symptom progression is associated with a single level of unpleasantness only, while a level of unpleasantness can be associated with multiple levels of symptom progression

Despite some progression that has been made in comparing different rating scales, the large variety in rating scales used in the literature still impedes comparing motion sickness data described in that literature and hampers progress in our understanding of motion sickness.

While rating scales can only measure motion sickness subjectively, it would be tremendously beneficial to both science and application if objective and unobtrusive measures could be found that allow for continuous measurement of motion sickness. However, although several physiological measures of autonomous arousal have been found to correlate to some extent with subjective motion sickness ratings, to the best of our knowledge an objective measure that is both sensitive to and specific for motion sickness is still not available (see Shupak and Gordon, 2006).

Discussion

In this paper we discussed issues regarding motion sickness where our current knowledge falls short. With respect to carsickness and simulator sickness in particular, this concerns temporal aspects, angular motions, predictability and anticipation, visual factors, individual susceptibility, and the measurement of motion sickness. This knowledge, preferably explicated by means of numerical models that predict motion sickness, is essential for optimising ride comfort by means of vehicle motion control (controlling accelerating, braking, cornering and making lane changes), higher level routing or navigation systems, as well as the design of future vehicles, in-vehicle experiences and the use of driving simulators.

Given the fact that research on motion sickness requires relatively large numbers of subjects to find statistically significant effects and the succeeding mathematical predictive description thereof, the research required to answer the questions posed here do generally require considerable funds. However, as these questions can be considered pre-competitive or having a low TRL, these studies could well be performed by consortia in Joint Industry Projects. Considering the possible application of VR in automated vehicles, advantage may be taken as well of past and future research in VR, including the use of AI. This may, altogether, fill the knowledge gaps referred to in this paper, increasing our knowledge on carsickness and facilitating countermeasures that accordingly make sense, i.e., are based on a solid scientific foundation.

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