Great Expectations: On the design of predictive motion cues to alleviate carsickness

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Abstract. Motion sickness has gained renewed interest in the context of the developments in vehicle automation in which we are witnessing a transition from a driver-centric to passenger-centric design philosophy. As a corollary, motion sickness can be expected to become considerably more prevalent which creates a considerable hurdle towards the successful introduction of vehicle automation and its ultimate socio-economic and environmental benefits. We here review early proof-of-concept studies into the beneficial effects of providing passenger with predictive motion cues as an elegant and effective method to reduce motion sickness in future vehicles. Future design parameters are discussed to finetune such cues not only for optimum effectiveness but, importantly, also for acceptance including sensory modality, timing, information detailing, and personalization.

Keywords: Motion sickness, automation, interface design.

1 Introduction

"It's Wednesday morning, 8am, 2035, Martin is walking his kids to school. After dropping them off at the school gate, he walks another 5 minutes to his local Mobility Hub where he hops on his pre-booked commuter pod. Martin greets his fellow passengers, settles in, and gets on with his work for the day. His travel time has become valuable office time and, given his 45 mins commute each way, he is now able to pick Rosa and Rudy up from afterschool club at 4.30pm, take them to the park before heading home for the evening."

While perhaps somewhat utopian, at the time of writing, the above scenario is increasingly starting to feel within the realms of possibility. Indeed, being able to use our travel time more enjoyable or productive is arguably one of the main benefits that vehicle automation may bring to our everyday lives. However, the ability to do so in comfort is far from trivial [1], not in the least due to the fact that a sizeable proportion of passengers may feel queasy and experience signs and symptoms of motion sickness while engaging in so-called Non-Driving Related Activities (NDRA) [2,3]. Thus, to realize the full potential of vehicle automation, we need to understand not only the causes of motion sickness, but also the effectiveness and acceptance of design solutions that may prevent or at least reduce the likelihood of motion sickness [4]. While no silver bullet, we argue here that predictive motion cues may go some way towards achieving this goal. Before discussing motion cueing in more detail, we will provide a brief introduction to the topic of motion sickness in general and anticipation in particular.

Motion sickness is a natural response to an unnatural motion environment and is commonly reported aboard ships, in space, virtual reality, simulators, and cars. Although the ultimate manifestation of motion sickness is vomiting, this is typically preceded initially by signs and symptoms such as (cold) sweating, pallor, flatulence, burping, salivation, apathy, and finally by nausea and retching [5, 6]. These symptoms may vary considerably between people regarding their (order of) occurrence, and degree.

A mismatch between sensed and expected motion is widely regarded as the root cause of motion sickness [5,7]. It occurs under conditions in which the actual sensory information following motion is sufficiently at odds with the expected bodily sensory state as based on prior experiences [8]. Motion sickness is experienced when we are exposed to motion that, from an evolutionary perspective, we are not used to, such as low frequency oscillating motion [9]. Whereas sea and airsickness are mainly caused by slowly oscillating vertical motion, carsickness, on the other hand, is mainly caused by horizontal accelerations due to accelerating, braking, and cornering [10,11,12]. Hence, an aggressive driving style involving plenty of these actions is therefore more likely to result in carsickness.

In addition to the motion of the vehicle per se, there are several modulating factors that have the potential to aggravate carsickness [13]. These modulating factors are becoming increasingly important in the design of automated vehicles in which we are witnessing a transition from a driver-centric to a passenger-centric design philosophy. Whereas automation creates a new set of design opportunities with respect to the vehicles' interiors, exteriors, and passenger experiences, there are a number of reasons why these may inadvertently lead to an increased prevalence of car sickness [2,3]. For the successful introduction and acceptability of vehicle automation, it is imperative that we understand not only the fundamental mechanisms and relevant parameters of these modulating factors, but also how they can be integrated within the design process and the design of the overall passenger experience.

We can identify the following four major future scenarios that will impact the occurrence of carsickness: First, unlike drivers, passengers are not in control of the vehicle and are less able to predict the future motion trajectory with sufficient accuracy and more likely to suffer from motion sickness [14]. Secondly, vehicle automation opens up the opportunity to engage in leisurely or economically-productive so-called Non-Driving Related Activities (NDRA). Where NDRA preclude a view of the outside world, such as using in-vehicle displays or reading a book, this may lead to conflicting motion information provided by the visual and vestibular system and a reduced ability to predict future motion [15]. Thirdly, future vehicles may involve flexible seating arrangements including rearward facing seats. Depending on the design of the vehicle, this may preclude an out of the window view but invariably prevent the ability to anticipate future motion and lead to increases motion sickness levels [16]. Fourthly, automation also offers the possibility to optimize the control of vehicle motion for comfort, provided the sensitivity of humans to specific motion characteristics and personal factors would be known.

1.1 The role of anticipation in motion sickness

A common denominator in all the above scenarios is the passengers' difficulty or inability to anticipate future motion. Anticipation plays a key role in the development of motion sickness. This can be understood by considering that our Central Nervous System (CNS) not only reckons sensed motion, but also makes a prediction about self-motion based on previous experiences [8,17]. The necessity of such a feedforward system can be understood by the sensory imperfections, neural delays, and the fact that our organs of balance cannot make a distinction between inertial and gravitational accelerations that would prevent our CNS to adequately control body motion and attitude [18, 19, 20]. Here, attitude refers to our orientation with respect to gravity, which seems of particular interest with respect to motion sickness [17].

A discrepancy or conflict between integrated sensory afferents indicative for specifically attitude, and a prediction thereof by a so-called internal model or neural store, is assumed responsible for generating motion sickness [5,8,17]. A mathematical model of this concept has been able to explain the origin of the peak in sickness incidence about 0.16 Hz [17, 18]. This suggests that our CNS does apply a kind of feedforward mechanism.

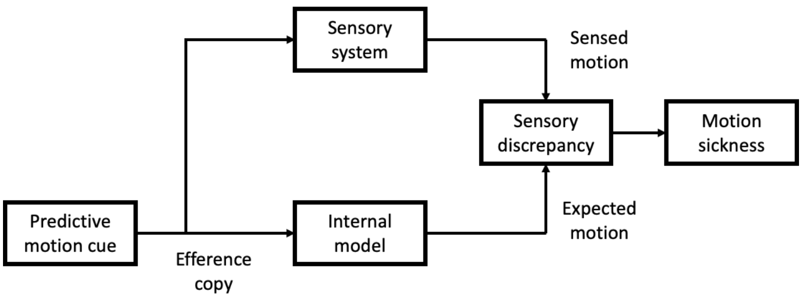

Fig. 1. Simplified motion sickness model illustrating the principle of the impact of predictive motion cues, activation of an internal model and subsequent impact on sensory discrepancies and associated motion sickness

In the context of carsickness, it becomes apparent that unlike passengers, drivers are able to anticipate the future motion due to the tight coupling between the control of pedals and steering wheel and subsequent known (learnt) vehicle motion, and thus minimising the likelihood of motion sickness (see figure 1 for a simplified representation of the proposed underlying principle). Further, whereas a forward-looking passenger will be able to see a curve ahead, only the driver knows when the vehicle will decelerate and whether this curve will be taken wide or sharp, thus having optimal information about upcoming self-motion, resulting in the smallest possible conflict. Likewise, braking and accelerating will cause a difference in conflict and hence a difference in sickness between drivers and passengers.

Importantly, this anticipatory mechanism concerns two major factors. First the motion itself can be more or less predictable. Kuiper et al. [21], for example showed that a series of equal motions following each other repeatedly in exactly the same way, does lead to less sickness as compared to the same motions following each other in a more random way, the two series yet showing the same RMS acceleration and peak frequency. Secondly, a view on the visual environment may also provide the passenger with cues about upcoming events, such as signs indicative for accelerating and braking (e.g., traffic lights), and curves. Note that this factor differs from the fact that instantaneous visual cues may result in a sense of self-motion, also referred to as vection [22].

The importance of visual information per se is demonstrated by the fact that rear seat passengers are particularly prone to carsickness under conditions where external visual views are limited [11,12,13]. The importance of anticipatory visual information is also suggested by the findings that backward looking passengers suffer more from carsickness than forward looking passengers, the former only seeing the trajectory that has been followed, the latter seeing the trajectory that will be followed [23]. The beneficial effect of anticipation on the basis of visual information was furthermore clearly demonstrated by [24], who showed a fourfold reduction in motion sickness when a visual track to be travelled was presented in a motion simulator. Assuming cognition to play a role in anticipation, even if that would be unconsciously, this would also imply that cues of a different modality could be helpful. Using an audio cue preceding certain events, Kuiper et al. [25], indeed did find a beneficial effect. Another observation on the role of cognition comes from Perrin et al. [26], who assessed motion sickness in rally co-drivers during the actual rally and "reconnaissance" drives. The reconnaissance drive allows the co-driver to write down shorthand notes (the pacenotes) on how to best drive the stage. Perhaps surprisingly given the differences in motion input, sickness was lower during the actual rally. The authors hypothesised this effect, at least in part, to be related to co-driver's ability to cognitively process and anticipate upcoming motion via the pacenotes.

From the above it follows that anticipation may be achieved in various ways. By extension, the method of delivery may be secondary to its effectiveness, which means that the information related to upcoming information may be provided via a range of sensory channels. This opens up the potential to use predictive motion cues as motion sickness countermeasures in automated vehicles. Whereas control cues are by definition not available since the passenger is not in control of the vehicle, the reported benefits of alternative predictive cues may prove promising. Importantly though, effectiveness in itself is not sufficient and the design and interaction of such cues with NDRAs need to provide an enjoyable, or at the very minimum, acceptable passenger experience. As suggested previously [27], the use of peripheral ambient displays may be particularly suitable in this context, providing effective yet unobtrusive and intuitive passenger information. In the following section we review recent studies that investigated the potential of such cues.

2 Effectiveness and acceptance of predictive motion cues

Several studies have recently explored the potential of predictive cueing to reduce motion sickness in passengers and, by extension, riders in future automated or shared vehicles. In the absence or limited availability of automated vehicles, these studies have adopted either Wizard of Oz approaches [28], passenger positions in conventional vehicles [29], or motion simulators [25].

2.1 Karjanto et al. (2018)

Karjanto et al. [28] developed a "peripheral visual feedforward system (PVFS)" installed in an instrumented vehicle (Renault Espace) modified to provide an automated driving experience. Participants were asked to watch videos on a television display placed on a wall partition separating the driver of the vehicle from the participants which were seated in the rear of the vehicle. The windows of the vehicle were made opaque to prevent passengers from being able to see any upcoming corners and junctions.

Predictive motion cues were provided via the peripheral visual feedforward system consisting of vertical arrays of 32 blue LED lights placed on the left and right of the television display. To indicate the upcoming motion, i.e. a left or right turn or righthand corner, the lights would start to move 3 seconds ahead of the actual manoeuvre from the bottom to the top on the left or right side, respectively.

The vehicle was driven on a pre-defined route on the University campus for a period of 9 minutes. The driving speed was set at 30kph with lateral accelerations being generated during turning and cornering to about 0.29 g (2.84 ms^2), while longitudinal accelerations were kept to the minimum. Using a within-subjects design, 20 participants experienced the same drive with and without the predictive cues. In addition to motion sickness as assessed by the MSAQ and heart rate measurements (BPM), acceptance and mental workload was measured by a User Experience Questionnaire (UEQ) and the Rating Scale Mental Effort (RSME), respectively.

The study results showed a significant beneficial effect of the predictive cues as measured by the Motion Sickness Assessment Questionnaire (MSAQ) [30]. The median MSAQ difference score (post minus pre MSAQ score) was reduced by 90% (Factor 7.4) in the test condition with predictive cues present. The heart rate data, on the other hand, failed to show any significant difference between the conditions. In terms of mental workload, there was no indication that the predictive cues resulted in elevated workload levels. Finally, system acceptance was relatively good as indicated by positive scores on the UEQ.

In conclusion, the study suggests that the presentation of predictive visual cues can have a sizeable and beneficial effect while also enjoying relatively high levels of acceptability. On the one hand, this is despite the fact that the exposure duration was relatively short and larger effects may have been observed over time. Also, the cues were relatively non-specific in that they only indicated the direction of the corner or junction but not its intensity, radius or position relative to corners [28]. On the other hand, however, it cannot be ruled out that some of the beneficial effects observed could, at least partly, be explained by the fact that participants were asked to press a button as soon as the cue was perceived. It has previously been shown that engagement in such mentally engaging tasks can divert the attention away from the stomach and lead to lower levels of reported sickness [31]. Lastly, the question remains to what extent such cues may be effective when applied to longitudinal vehicle motions, i.e. braking and accelerations in stop-start traffic or urban driving.

2.2 Diels et al. (2018)

Adopting a similar approach to Karjanto et al. [28] study, Diels et al. [29] explored the impact of auditory as opposed to visual predictive cues. In this this study, a total of 24 participants sat in the front passenger seat of a conventional vehicle (Ford Mondeo) and were driven around a city circuit (test track) at speeds up to 64kph. The route was representative of urban driving, navigating roundabouts, junctions, corners, and including several stop-and-start manoeuvres and took approximately 18 mins in total.

During each of the two drives, participants were engaged in a visual search task, the Surrogate Reference Task (SuRT). The SURT was presented on a 10-inch tablet placed in a head down position at the glove compartment. This head down location has previously been shown to lead to considerably more motion sickness than a head up display allowing for more peripheral vision and assumingly less sensory conflict [15].

Each participant was driven around on two occasions. In the "no cueing" condition, participants performed the visual task only whereas in the "cueing" condition, participants received auditory cues informing them of upcoming vehicle manoeuvres (e.g. *left hand corner ahead*, *slowing down to a stop*, *turning right*). The driver pressed the "next" button located on the steering wheel to trigger the pre-recorded motion cue for each upcoming manoeuvre which were provided approximately 1 seconds ahead of the actual manoeuvre.

Motion sickness was assessed using both subjective responses using the MISery sCale (MISC) [32] and the MSAQ and objective physiological measures (heart rate variability and electrodermal activity) while vehicle and occupant head accelerations were measured to ensure inter drive consistency and to explore potential effects of cueing on participant head movements.

The study findings vividly demonstrated the provocative nature of engaging in NDRA whereby all but one (96%) participant reported motion sickness, 50% had to terminate trials prematurely due to sickness levels MISC score of 6, while two incidences of emesis were reported, during a drive and following a drive. Several participants commented that they did not did not anticipate to suffer so much given the apparent innocuous nature of the task. It further shows that motion sickness is not a luxury problem and requires to be a fundamental consideration in the design of future automated vehicles and user interactions.

Returning to the main objective of the study, the results also showed that auditory predictive cues led to a significant 17% reduction in motion sickness as measured by the MISC. Similar to Karjanto et al. [28], none of the physiological measures were able to detect a difference between the conditions. In contrast, however, unlike the ambient visual cues, the auditory cues used in this study were perceived to be mentally demanding. Some participants experienced the cues as distracting and annoying with some reporting that they stopped paying attention to the cues and "tuned out". In turn, this may have suppressed the effectiveness of the motion cues and to some extent led to a conservative estimate of their effectiveness.

In conclusion, as for visual cues, auditory predictive cues can significantly reduce motion sickness levels. They can however also be perceived as rather annoying and distracting which points towards a design challenge and develop not only effective but also acceptable predictive motion cues.

2.3 Kuiper et al. (2019)

Whereas anticipation appears to have an effect on motion sickness as implied by the motion sickness literature as well as the studies explicitly addressing the role of anticipation, the effect size of anticipation as such is difficult to gauge due to the presence of potentially confounding factors such as mental engagement or the effectiveness of predictive cues in conveying anticipatory information, as discussed above.

In an attempt to avoid some of these pitfalls and to get a better grip on the exact importance of anticipation, Kuiper et al. [21] assessed motion sickness by exposing people to repeated fore-aft motion on a sled on a 40-m rail. 17 participants were asked to sit in an enclosed cabin positioned on top of the sled which did not allow for an external view.

In each of the three 15-min conditions, each participant was exposed to the repeated fore-aft motion at 1) constant intervals and consistent motion direction (i.e. predictable: condition P); 2) at constant intervals but varied motion direction (i.e. directionally unpredictable: condition dU); and 3) varied intervals but consistent motion direction (i.e. temporally unpredictable: condition tU).

Each single displacement lasted for 8 s and had an amplitude of 9.0 m, corresponding to a peak acceleration of 2.49 m/s^2. In conditions P and dU, there was a fixed 8-s pause between each displacement, resulting in a regular 16-s cyclic motion. In condition dU, half of the displacements had their sign inverted semi-randomly, that is, motion was backward-then-forward instead of forward- then-backward. In condition tU, the pauses in between the displacements were varied semi- randomly between 4 and 12 s, still averaging 8 s over the 15-min experiment. The conditions were otherwise identical in motion intensity and displacement, as they were composed of the same repetitions of identical blocks of motion. Illness ratings were recorded at 1-min intervals using the MISC scale.

As expected, the average illness ratings after exposure were significantly lower for the predictable condition, compared to both the directionally and temporally unpredictable condition. With regard to the relative size of the effect of anticipation, the unpredictable conditions led to 52% higher illness ratings compared to the predictable condition.

2.4 Kuiper et al. (2020)

Following on from the previous study, Kuiper et al. [25] explored the use of auditory predictive cues. Using the same experimental setup and metrics, 20 participants were exposed on a sled on a rail track to two 15-min conditions. In terms of motion, the two conditions were identical being composed of the same repeated 9 m fore-aft displacements, with a semi- random timing of pauses and direction.

The auditory cues were either 1) informative on the timing and direction of the upcoming motion, or 2) non-informative. In the anticipatory condition (A), the auditory cues informed both of timing and of direction, by occurring consistently 1 s before the motion started and with the actual direction of upcoming motion. A sound clip was played over headphones communicating either "forward" or "backward". In the control condition (C), the auditory cues were presented at semi-random timings, 2–6 s after a motion was already initiated and were therefore non-informative, not aiding in the participants ability to anticipate the upcoming motion. The auditory cues in the control condition were included to ensure that the level of stimulation (i.e. hearing an auditory cue) was identical in both conditions.

The results showed that the average illness ratings were significantly lower for the condition that contained informative auditory cues, as compared to the condition without informative cues. The effect of the anticipatory cues averaged to a difference of 17%, similar to the effects observed by [29]. The fact that no such reduction in motion sickness was observed when presenting false cues with no predictive value suggests that the alleviating effects were not the result of "stimulation" per se.

3 Design considerations

Together, the above findings indicate that anticipatory information provided by predictive motion cues might be an elegant and effective method to reduce motion sickness in future vehicles in particular when engaging in Non-Driving Related Activities (NDRA), and able to reduce sickness levels by 17% or more. In fact, this estimate may be considered conservative in the light of the limited time of exposure used in these studies. It is widely known that sickness increases for longer exposure durations and as such the differences between conditions can be expected to become more pronounced over longer periods of time. At the same time, it is apparent that the cues were not sufficiently effective to *eliminate* sickness altogether, at least under the conditions studied. Also in real car driving, even with a perfect view on the road ahead, passengers still can get sick.

This means that motion cueing by itself may not be sufficient and able to provide a single solution and raises the question as to the relative effectiveness of motion cueing which may be a function of the nature of the provocative environment. For example, are cues more effective in less provocative environments such as the use of displays that allow for more peripheral vision and motion profiles involving fewer accelerations (highway driving)? These questions would benefit from future studies.

Furthermore, their real potential is yet to be determined as the above proof-of-concept studies did not consider the exact nature of the predictive cues. We here discuss several design parameters (see table 1) that should be considered to finetune the cues to enhance both their effectiveness and acceptance.

Table 1. Overview of parameters for the design of predictive motion cues

Parameter	Description
Sensory modality	Motor, visual, auditor, tactile, vestibular, multisensory cues
Timing	Time at which the cue is presented relative to the upcoming vehicle maneuver (e.g. 1 vs. 3 secs)
Discrete vs continuous	Presented at discrete moments (i.e. upcoming change in velocity) vs. available at all times
Information sensitivity	True positive rate, should be high
Information specificity	True negative rate, should be high
Information detailing	Level of detail to describe the upcoming motion (e.g. announcing "change in velocity" vs. "degree and direction of change in velocity")
Attentional demand	Centrally (intrusive) vs. peripherally (ambient) presented information (i.e. low vs. high level cognitive processing)
Customisation	Design for all vs. personalised and adaptive approach

Sensory modality is one of the key design parameters under consideration. Are visual cues more effective than auditory or tactile cues, or should we consider multisensory cues? The above review shows that both visual and auditory cues can be effective. However, perhaps the single most disadvantage of visual motion cues is the fact that occupants have to direct their attention and / or gaze towards these visual cues in order for these to be effective. This may be appropriate for passive occupants looking out the window or at a display showing such visual motion cues. However, once passengers engage in non-driving tasks that involve redirecting their attention away from such visual cues, their effectiveness loses its potential. In conditions in which occupants are using in-vehicle displays, these visual cues may be presented co-located with the media content of interest. Where this may prove to be effective, additional concerns here would relate to interference with the task at hand and ultimately user acceptance. Perhaps even more importantly, when artificial visual cues are used, these should be (near) perfect, bad cues likely causing more sickness. Also, when based on predictive mechanisms, both sensitivity (positive response rate for sickening events) and specificity (negative response rate for non-sickening events) should be high. Even if 1 out of 100 events would give a false alarm, it could jeopardize the passengers' system trust, while false alarms are known to be annoying irrespectively.

Alternatively, visual cues in the form of ambient displays may be considered to avoid to some extent this issue. In the context of automated vehicles and the ability to engage in NDRA, there would be significant benefit in using anticipatory motion cues that are less contingent on the occupants' direction of gaze and attention. Such ambient displays may provide a valuable direction for automated vehicles if they prove to be not only effective in reducing motion sickness by also enjoy a high level of user acceptance and, for example, result in limited interference with other tasks. The results from Karjanto et al [28] do indeed indicate that ambient visual cues are not only effective in reducing motion sickness but also enjoy a high level of user acceptance.

As mentioned in the previous section, auditory cues are equally able to provide beneficial effects. However, an important consideration in this context is that such auditory cues may become more distracting and demanding for occupants to process. In the study by Diels et al. [29] some participants found it difficult to perform the visual search task while also attending to the motion cues at the same time. This then raises the question whether motion cues of reduced complexity may be less demanding but possibly similarly effective in reducing motion sickness.

Furthermore, the auditory cues reviewed here were language based. Alternatively, the use of auditory cues may be based on sounds. As for ambient visual displays, these auditory sounds could be more abstract and could involve increasing / decreasing pitches to indicate vehicle acceleration / deceleration, while direction (left, right) may be indicated using 3D audio signals. More specific cues may require changes to the auditory signal including pitch, loudness, and 3D location. Yet, and apart from an undesired learning process, it seems to make sense that the more intuitive the cue would be the more effective it is.

Of particular interest in the context of alternative cueing mechanisms is the demanding nature of the cues. Some participants in the study of Diels et al. [29] experienced the cues as distracting and annoying with some reporting that they stopped paying attention to the cues. This may have suppressed the effectiveness of the motion cues and to some extent led to a conservative estimate of its effectiveness and highlights the need to consider attentional demands of anticipatory motion cues.

The actual information detailing is a further variable. The studies reviewed here, the level of detail was low and future research would benefit from exploring motion cues with an increased or decreased level of detail. An increase in detail may allow the occupant to predict with a higher level of accuracy the upcoming motion and thereby reducing the discrepancy between the sensed motion.

Timing, the temporal characteristics of the predictive cues, is a further parameter to consider in future. In the studies by Diels et al. [29] and Kuiper et al. [25] cues were presented at approximately 1 second ahead of the motion manoeuvres where as a time window of 3 seconds was used by Karjanto et al. [28]. A longer period could allow for more time to cognitively process the cue, while, conversely, a shorter time could enable participants to estimate more accurately the time when the motion will occur. Future research would benefit from exploring if and to what extend different timings affect the level of motion sickness.

Finally, one of the most consistent findings in the field of motion sickness is that individuals show immense variability in their susceptibility to motion sickness. This provides a real design challenge in that a solution for all may not be desirable from an acceptance point of view. Personalised solutions may be desirable in particular in the context of future shared mobility.

4 Conclusions

The experience of motion sickness in automated vehicles, no matter how slight, is one of the main barriers to the successful introduction of this technology. This is particularly relevant under conditions in which passengers engage in Non-Driving Related Activities such as reading and thus jeopardizes the perceived benefit of future automated or shared mobility. The provision of predictive motion cues has the potential to considerably alleviate the severity of motion sickness in such circumstances. However, our understanding of the design of such predictive cues is still immature and their real potential is yet to be determined.

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