Knowing what's coming: anticipatory audio cues can mitigate motion sickness

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Abstract

Being able to anticipate upcoming motion is known to potentially mitigate sickness resulting from provocative motion. We investigated whether auditory cues could increase anticipation and subsequently reduce motion sickness. Participants (N = 20) were exposed on a sled on a rail track to two 15-minute conditions. Both were identical in motion, being composed of the same repeated 9 meter 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. Illness ratings were recorded at 1-minute intervals using a 11-point scale. After exposure, average illness ratings were significantly lower for the condition that contained informative auditory cues, as compared to the condition without informative cues. The knowledge that anticipation can be aided auditory can be of importance in domains such as that of autonomous vehicles to reduce carsickness.

Keywords: motion sickness, autonomous driving, multisensory integration, anticipation, carsickness, countermeasures, unpredictable motion

1. Introduction

Motion sickness is a state of discomfort that can affect all those with a functioning vestibular system exposed to sufficient provocative motion. Its root cause has been theorized to be a mismatch between sensed and expected motion (Money, 1970; Reason & Brand, 1975). If actual sensory information following motion is sufficiently at odds with the *expected* bodily sensory state, as based on prior experiences, motion sickness occurs (Reason, 1978; Bos & Bles, 1998; Bos et al., 2008; Oman, 1982; Oman, 1990; Bos & Bles, 2002). Furthermore, a plethora of modulating factors are established in the literature, the most well-known effect being the role of visual information. For instance, when below deck in a ship, motion sickness can be significantly worsened due to a visual-vestibular conflict (Bles et al., 1998). In addition, the effect of an individual's capacity to anticipate upcoming motion is known to influence motion sickness (Rolnick & Lubow, 1991). However, even though motion sickness is understood primarily as stemming from an incongruence between sensed and expected motion, the concept of anticipation has only preliminarily studied directly in the literature on motion sickness.

The potentially beneficial effects of the ability to anticipate upcoming motion on subsequent motion sickness have been mentioned in several studies, mainly in the context of carsickness (Griffin & Newman, 2004; Perrin et al., 2013; Wada et al., 2018). However, the number of studies focused primarily on the link between anticipation and motion sickness is limited. In an experiment utilizing a motion platform, Rolnick and Lubow (1991) found that even when two participants were simultaneously exposed to identical motion, the participant in control and thus able to anticipate the motion was significantly less motion sick. A comparable study with exclusively visual motion cues yielded comparable results (Stanney & Hash, 1998). Feenstra and colleagues (2011) found that by showing an artificial "roller coaster like" trajectory offering information on upcoming motion to passive subjects in a 6 DoF motion simulator, motion sickness was reduced by a factor of two. In a previous study (Kuiper et al., 2019) we found that motion composed of events that were presented either at semi-random moments or in semi-random direction were more provocative with respect to sickness as compared to the same events presented at fixed, and thus predictable, moments and directions. To our knowledge, however, it has not been studied whether cues anticipating otherwise unpredictable motion events can reduce sickness in a similar manner.

The latter question is relevant in particular in the domain of transport. In particular, self-driving cars are expected to become commonplace, shifting car occupants from drivers to passengers (Sivak & Schoettle, 2015; Diels & Bos, 2016; Diels et al., 2016), which makes them also more vulnerable to carsickness. Moreover, a benefit of automated vehicles, i.e., the freedom to engage in non-driving activities such as working on a display, can be expected to further exacerbate motion sickness (Cyganski et al., 2015; Probst et al., 1982; Griffin & Newman, 2004; Perrin et al., 2013; Kuiper et al., 2018). Consequently, presenting visual anticipatory cues to reduce sickness may be less practical, raising the question whether, e.g., auditory cues warning for upcoming motion events, such as accelerating or cornering, could be effective as well.

We therefore exposed participants to two conditions of equal motion, i.e. composed of repetitions of an 8-second motion forward-and-backward but at irregular intervals and with uncertainty in direction. In the anticipatory condition, participants received auditory cues one second in advance of the upcoming motion direction. In the control condition, they received similar but non-informative auditory cues. Our hypothesis was that the anticipatory condition with informative cues would lead to less motion sickness as compared to the control condition with non-informative cues.

2. Methods

2.1. Participants

Approval of the TNO Human Factors institutional Review Board on Experiments with Human Subjects was obtained in accordance with the ethical standards stipulated in the 2013 Declaration of Helsinki. All participants indicated they had no vestibular disorders and were in overall good health. They were instructed to refrain from alcohol the 24 h before the experiment. In advance of the first condition the procedure was explained to participants and they signed an informed consent form. A total of 20 participants participated, 12 males and 8 females. The average age of participants was 39.47 years (*SD* = 12.68).

2.2. Motion apparatus and profile

To expose participants to motion we used a 40 m rail track on which a platform (with a cabin) could move forward and backward on a series of 48 wheels. The cabin offered an enclosed environment without visual and airflow cues. Participants sat on a rally car seat that was fixed to the base of the platform, which offered a 5-point safety belt and a headrest. The motion platform was moved forward- and backward by two motors at the far side of the track using synthetic cables. Fig. 1a and 1b respectively show the cabin on the track, and the inside of the cabin.

Fig. 1a: The 40 m track with the cabin. Only 9 meter peak-to-peak motion was used for the present purpose. Fig. 1b: The cabin interior. The cabin prevented visual and somatosensory (via airflow) information from giving participants information on the occurring motion.

The motion in this experiment was constructed in the exact same manner for the two conditions, 1) Control (C), and 2) Anticipatory (A). Both conditions lasted 15 minutes and consisted of repetitions of raised cosine fore- and backward displacements. Each displacement had a duration of 8 seconds, a total amplitude of 9.0 meters, and a peak acceleration of 2.5 m/s^2. The motion was reversed in direction randomly half of the time, going backwards first, then forwards. Between repetitions, there was a static interval with a duration that varied randomly between 4 and 12 seconds. See fig. 3 for a visual representation of the motion profiles over time.

This motion was based on a previous study in which the effects of unpredictable interval duration and motion direction were found to increase motion sickness as compared to a motion profile in which both the interval duration and motion direction were kept constant (Kuiper et al., 2019). We therefore assumed the motion used in this experiment would be sufficiently provocative, and could also potentially be made less so by reducing its unpredictability.

2.3. Auditory cues

To facilitate anticipation in the anticipatory condition (A) 1 s in advance of each displacement, a sound clip was played over headphones, veridically communicating “forward” or “backward” (in the native language of the participant). Participants were explained that in this condition always 1 s before a displacement initiated, the auditory cue associated with that direction would be presented. To ensure the control condition (C) was as similar as possible to the anticipatory condition, we also played the sound clips in that condition, but at 2 to 6 s after the actual motion onset, varied randomly. The directionality of the auditory cue was random as well in this condition. We did not explicitly state anything on the relation between the auditory cues and motion sickness to keep participants as naïve as possible.

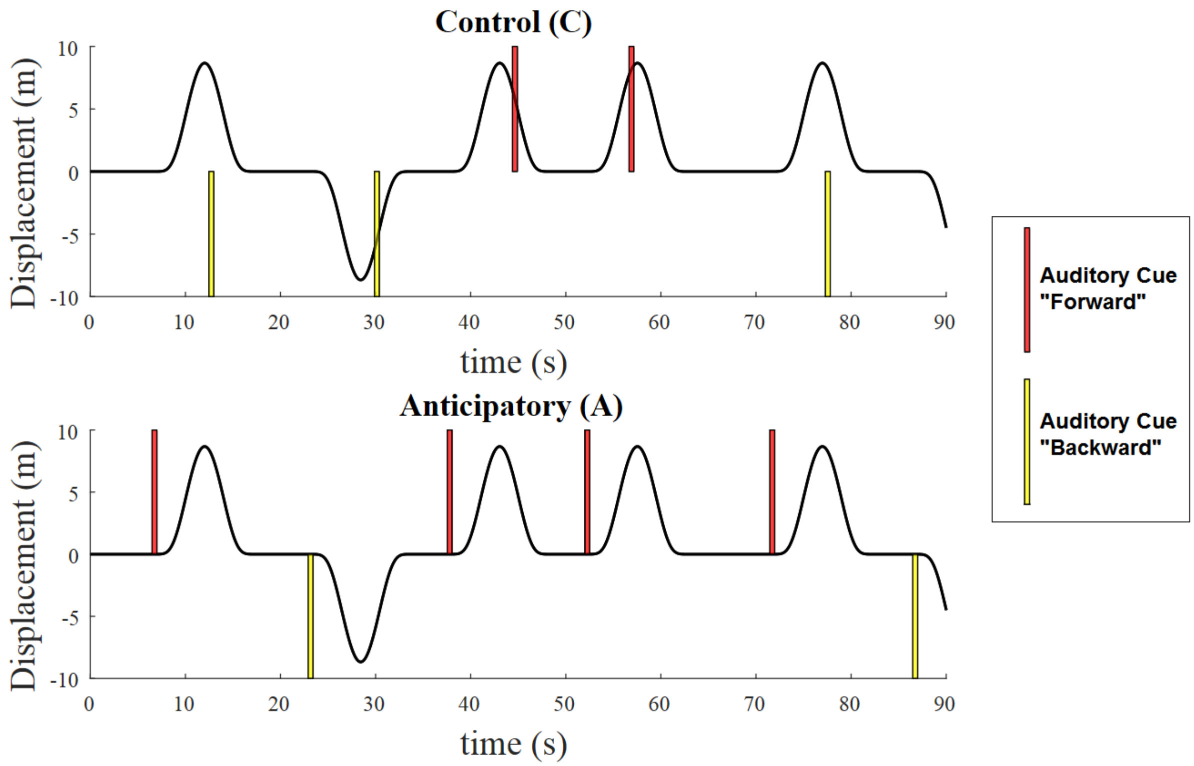

Fig. 3. First 90 seconds of the 15 minutes motion profile also showing the timing and directionality of the auditory cues. The motion profile was semi-random in direction and in timing: each condition exposed participant to the same number of displacements in each direction. The auditory cues in the control condition (C) were presented at semi-random timings, 4 to 6 seconds after a motion was already initiated. 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.

2.4. MISC

We used an 11-point scale, the *Misery Scale* (MISC) to assess participant motion sickness (Table 1, taken from Bos et al., 2005). This scale utilizes the knowledge that motion sickness manifests initially in symptoms such as sweating, yawning, apathy, stomach awareness, and dizziness, which may be followed by nausea, retching and vomiting. Given the single rating, this scale could easily be applied at 1-minute intervals over the course of the experiment. If at any point during a condition nausea occurred (corresponding with a MISC of 6 or higher), the current condition was halted, and that final score was conservatively assumed to stay constant for the remaining minutes.

Table 1.
11-point MIsery SCale (MISC) (Bos et al., 2005)

Symptoms		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness, sweating, blurred vision, yawning, burping, tiredness, salivation, . . . but no nausea	vague	2
	little	3
	rather	4
	severe	5
Nausea	slight	6
	fairly	7
	severe	8
	(near) retching	9
Vomiting		10

2.5. Procedure

Before the experiment, participants filled out the motion sickness susceptibility questionnaire (MSSQ; Golding, 2006), to assess whether our participants were representative of the general population in terms of motion sickness susceptibility. Before the first condition, the procedure was explained and participants signed an informed consent form. Participants were then seated inside the cabin in a comfortable position and were instructed to keep their eyes open and their head in a upright position. Between conditions, participants had a pause of at least one hour to recover from ill effects. Conditions were counterbalanced across subjects.

During the experiment, participants were continuously in contact with the experimenter via headphones. In addition, the experimenter could see the participant at all times via a video feed to ensure the participant was safe and remained in a stationary position. The headphone reduced outside noise by 23dB, and we added additional pink noise to mask remaining sound of motors at the far ends of the track, which could have otherwise acted as cues on the motion.

3. Results

The MSSQ scores of participants indicated they were among the 70th percentile, with scores of 18.49 ± 10.55 (Golding, 2006).

A repeated measures ANOVA on all MISC values obtained showed a significant effect of condition ($F(1, 19) = 5.933$, $p = .025$, partial $\eta 2 = 0.238$), and of time ($F(15,285) = 38.317$, $p < .001$, partial $\eta 2 = 0.669$) on motion sickness scores.

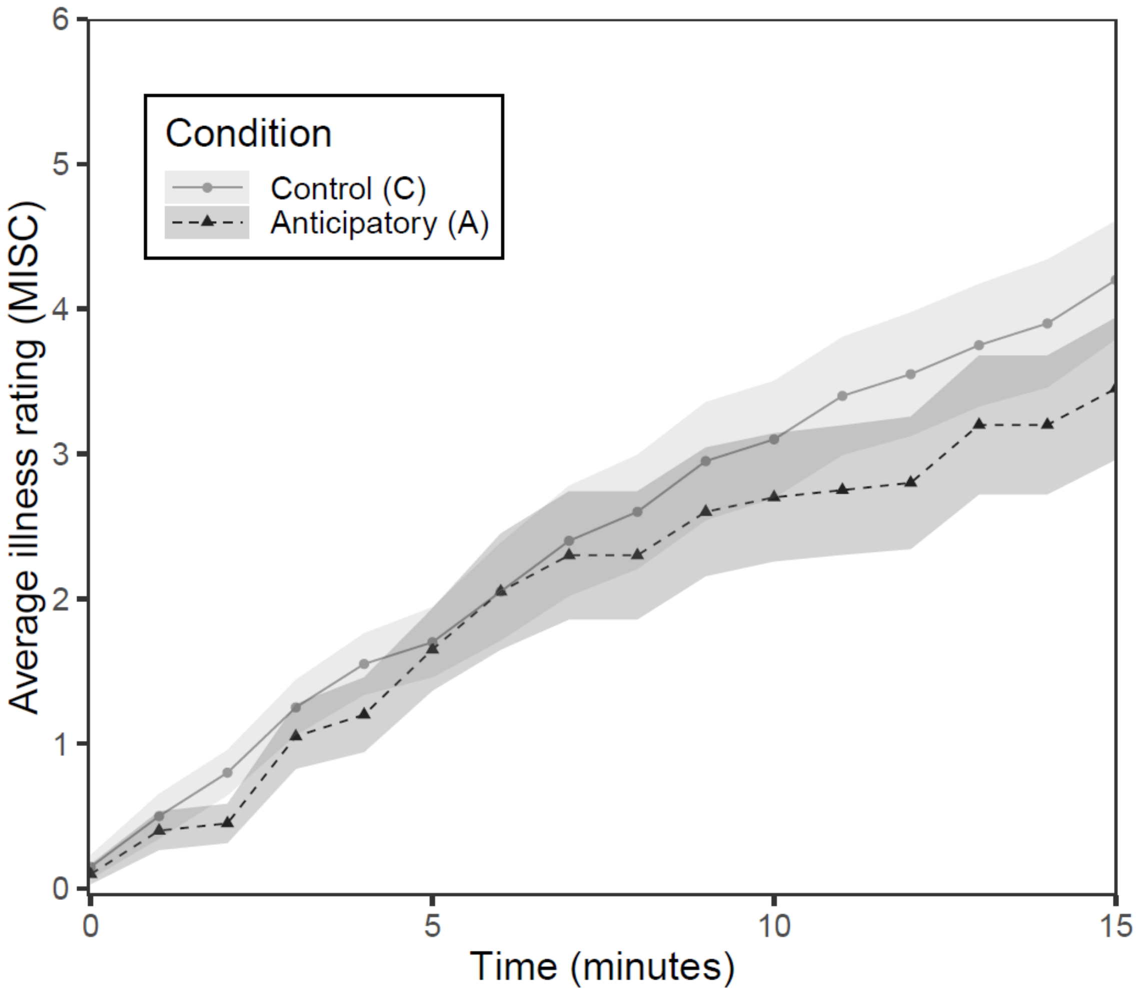

Fig. 4. Illness ratings over time for the two conditions. Grey bands depict SEM.

Fig. 4. shows the average participants' illness ratings over the two 15 minute conditions. For the control condition (C) the average illness rating after 15 minutes was 4.15 (SD = 1.82) while for the anticipatory condition (A) this was 3.45 (SD = 2.19); the effect of the anticipatory cues thus averaged to a difference of 17%.

When only considering illness ratings reported after 15 minutes of exposure to motion, a non-parametric Wilcoxon signed ranked test indicated the baseline condition (Mdn = 5.0) differed from the anticipatory condition (Mdn = 3.0), which was significant ($Z = -2.24$, $p = .02494$).

4. Discussion

Although the effect of anticipation in relation to motion sickness has been discussed in the literature before (Griffin & Newman, 2004; Rolnick & Lubow, 1991; Feenstra et al., 2011; Perrin et al., 2013), to our knowledge, this study concerned the first within-subjects experiment with an explicit focus on predictability using auditory warnings. After only 15 minutes of exposure to motion that was unpredictable in direction and timing, participants reported significantly lower sickness scores when correct anticipatory auditory information about upcoming events was added (A), as compared to a control condition in which the auditory information was added semi-randomly (C). This finding is of interest from a scientific as well as an applied point of view, which will be discussed further below.

As compared to the effects observed by Feenstra et al. (2011), the effect reported on in the present study was rather small. These authors, however, utilized visual cues in their experiment that were likely to have a bigger effect than auditory cues for two main reasons. First, their visual imagery consisted of continuously moving objects, offering continuous and low level sensory information, therefore potentially having a more pronounced effect as compared to the effect of a single momentary auditory cue, which also might require higher order cognitive processing. The former low level process has previously been referred to as "percipation" (Bos et al., 2008), a process taking place in the order of a second. In this definition, it is distinguished from "anticipation", a process requiring higher order cognitive function, and typically taking place in the order of several (tens of) seconds. Please note that generally the literature, predictive neural processes, i.e. forms of anticipation, are not subdivided in this manner, nor does exploring this division lie in the scope of the present study. Secondly, anticipation was brought about by Feenstra and colleagues using a "roller coaster like" trajectory showing upcoming motion. Moreover, this anticipatory information was continuously updated in their experiment. It seems reasonable to assume that in particular the continuous updating entails a more forceful anticipation than the brief auditory cue as used in our current experiment. Feenstra and colleagues furthermore used motion that varied randomly in all six degrees of motion. The motion studied currently, however, only varied along one axis, in which a single motion event was presented repeatedly. It therefore arguably makes sense to assume that the effect of a countermeasure can be more comprehensive if more degrees of freedom are involved. A third, subordinate point, relates to the knowledge that visual and vestibular cues can interact with respect to postural stability, the latter also being related to motion sickness (Grace et al., 2012; Bos, 2011; Bos et al., 2013). Auditory information is generally unrelated to the process of orientation to gravity, as opposed to visual cues, while orientation has been assumed to be particular interest to motion sickness (Bles et al., 1998). These relationships likely add to the effectiveness of visual cues in mitigating motion sickness.

A further detail concerning the highly diverse 6-dof motion pattern as studied by Feenstra and colleagues (2011), analogous to turbulent aircraft motion, is that it is not representative for car motion and thus carsickness. Vehicle motions generally consist of many lateral accelerations, and are composed to discrete acceleration, braking and cornering events, rather than a continuously provocative motion pattern. With respect to the interest in self-driving carsickness, in the present study we deliberately opted for distinct motion events, i.e. the periodic 8 s displacement, both because of its similarity to certain car motion events, and also because it could be distinctly preceded by an auditory cue.

Furthermore, two temporal issues can be pointed out that might translate to a potentially even greater effect of anticipation on motion sickness. One issue concerns the limited time of exposure used in the present study, as sickness is known to increase for longer exposure durations (O'Hanlon & McCauley, 1974; Bos et al., 2005; Feenstra et al., 2011). It can therefore be expected that a longer period of time would also further increase the difference between conditions observed here. The other issue concerns the 1 second interval between the auditory cue and the actual motion onset, which was chosen somewhat arbitrarily and might not be optimal. 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 (Fraisse, 1984). Related to these temporal issues, it may be of interest to consider the approximately equal levels of sickness in the two conditions (C and A) during the first ten minutes of motion exposure, only after which a difference becomes evident. A similar pattern can, interestingly, also be seen in two other studies comparing conditions with and without additional information on upcoming motion, one by Griffin & Newman (2004, Figure 3) and, the other, again by Feenstra et al., (2011, Figure 5a). A possible explanation is that novel types of information, such as the auditory cue as used in our experiment, require some time to be effectively internalized. Due to the study designs, this can however not be concluded, but might be a fruitful topic of further research.

From a theoretical point of view, the current data, though not proving, are in favour of assuming an internal model or neural store allowing the central nervous system (CNS) to predict self-motion based on an "efference copy" of motor commands (Reason & Brand, 1975; Oman, 1982, 1990; Bles et al., 1998; Bos & Bles, 1998, 2002; Bos et al., 2008). Because it is the primary aim of the internal model to make a prediction about self-motion to compensate for neuronal delays, sensor imperfections, and the physically inherent ambiguity between inertial and gravitational accelerations (Bos & Bles, 2002), it naturally follows that this mechanism also accounts for the effect of anticipation. First, and different from the low level process of "percipation" as referred to above, it can be assumed to take time for a novel cue to be internalized within the internal model (or neural store), thus not being effective instantly. Within this internalization period, the CNS will have to reckon the coherence between the novel cue and the actual sickening motion, coherence that typically cannot be concluded on within a second. Only once this coherence is internalized, it can be helpful to make a better prediction about self-motion, thus minimizing the difference between expected and sensed self-motion, and subsequent motion sickness. It is this conflict that has been assumed to be the main cause of motion sickness (Reason & Brand, 1975; Oman, 1982, 1990; Bles et al., 1998). This reasoning can thus well explain the difference observed not only in the experiment discussed here and those by Griffin & Newman (2004) and Feenstra et al. (2011) as mentioned before already. Moreover, all these data suggest an equal time required for this internalization in the order of 10 minutes, which further favours the explanation assuming an internal model.

A possible point of improvement in our study would be to measure to what extent participants in fact attend to the cues. As participants were fairly naïve as how to utilize the cues, potentially some participants ‘tuned out’, and were forgoing consciously attending to the cues. In addition, an order effect might exist, even though conditions were counterbalanced. Participants either experience, and lean, in their first condition that the cues are either informative, or of no use in anticipation motion. This effect might carry over to the second condition that is experienced.

A separate issue that might be of interest is to compare the findings in the present study to those found in a previous study which employed the same 8 s motion events and the same method of rating motion sickness (Kuiper et al., 2019). In this previous study, three conditions were realized, either unpredictable in direction of the motion events, unpredictable in the pauses between motion events, or unpredictable in neither. The two unpredictable conditions were found to lead to more motion sickness, respectively 3.58 (*SD* = 1.59) for directionally unpredictable, 3.58 (*SD* = 1.65) for the temporally unpredictable, and 2.36 (*SD* = 1.95) for the predictable condition. Notably, the stimulus used in the present study experiment, a combination of the manipulations of the two unpredictable conditions of the previous study, is found to lead to potentially more sickness, namely 4.15 (SD = 1.82). However, as the two studies are based on different populations, a comparison would be underpowered, thus not suitable for further statistical comparison. Nevertheless, an additive effect of detrimental factors might be expected, as based on the literature (Guignard & McCauley, 1982; Feenstra et al., 2011). How such effects interact is not fully known, and necessitates future research.

From an applied point of view, the current results are also of value, in particular for automated driving. As mentioned in the introduction, carsickness has been predicted to become a serious issue in automated vehicles, more so than it currently is in conventional human-driven vehicles. While medicine is effective against carsickness (Lucot, 1998; Zhang et al., 2016), this may not be the preferred option to reduce self-driving carsickness, as they are sedative, affect performance, and have to be taken well in advance. Other approaches, however, are more promising. As we found in the present study, information about upcoming motion events is beneficial, and could be a main reason why currently, in conventional vehicles, drivers are rarely motion sick (Perrin at al., 2013). Employing anticipatory information to warn passengers about upcoming provocative motion in autonomous vehicles might be an elegant but effective way to reduce carsickness. In terms of implementation using warning cues is especially well-suited to autonomous vehicles, since upcoming motion events are generally planned seconds before they occur by the vehicle computer. Auditory or haptic cues may be preferred to visual cues, as in automated driving the use of displays seems to be primarily reserved for entertainment or work related tasks (Steck et al., 2018). Although incorporating visual cues about self-motion to these displays might be considered, this could lead to issues with vection and cybersickness (Rebenitsch & Owen, 2016), worsening rather than alleviating the situation. An alternative, parallel, approach to reducing carsickness would be to allow for ample vision outside, which is found to be beneficial even when this vision is peripheral (Griffin & Newman, 2004; Kuiper at al., 2018)

In future vehicles, auditory or haptic methods of warming passenger about provocative motion events could provide, relatively non-intrusively, a potential means against carsickness. In aviation, for example, the use of haptic, i.e. vibro-tactile, cues has already show to be of value in aiding spatial orientation, closely related to motion sickness (Van Erp et al., 2006). As autonomous vehicles take shape in our society, many novel human factors questions are bound to arise, such as the impact of rearward facing car seats on passenger well-being (Salter et al., 2019). These novel problems might require novel solutions, combining fundamental theoretical knowledge with human-centered design. While transportation of people by its very nature will always expose individuals to non-natural and potentially provocative physical motion, keeping forms of motion sickness to an acceptable minimum might be essential in the coming decades to gain the public's acceptance and facilitate a successful shift to automated vehicles.

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