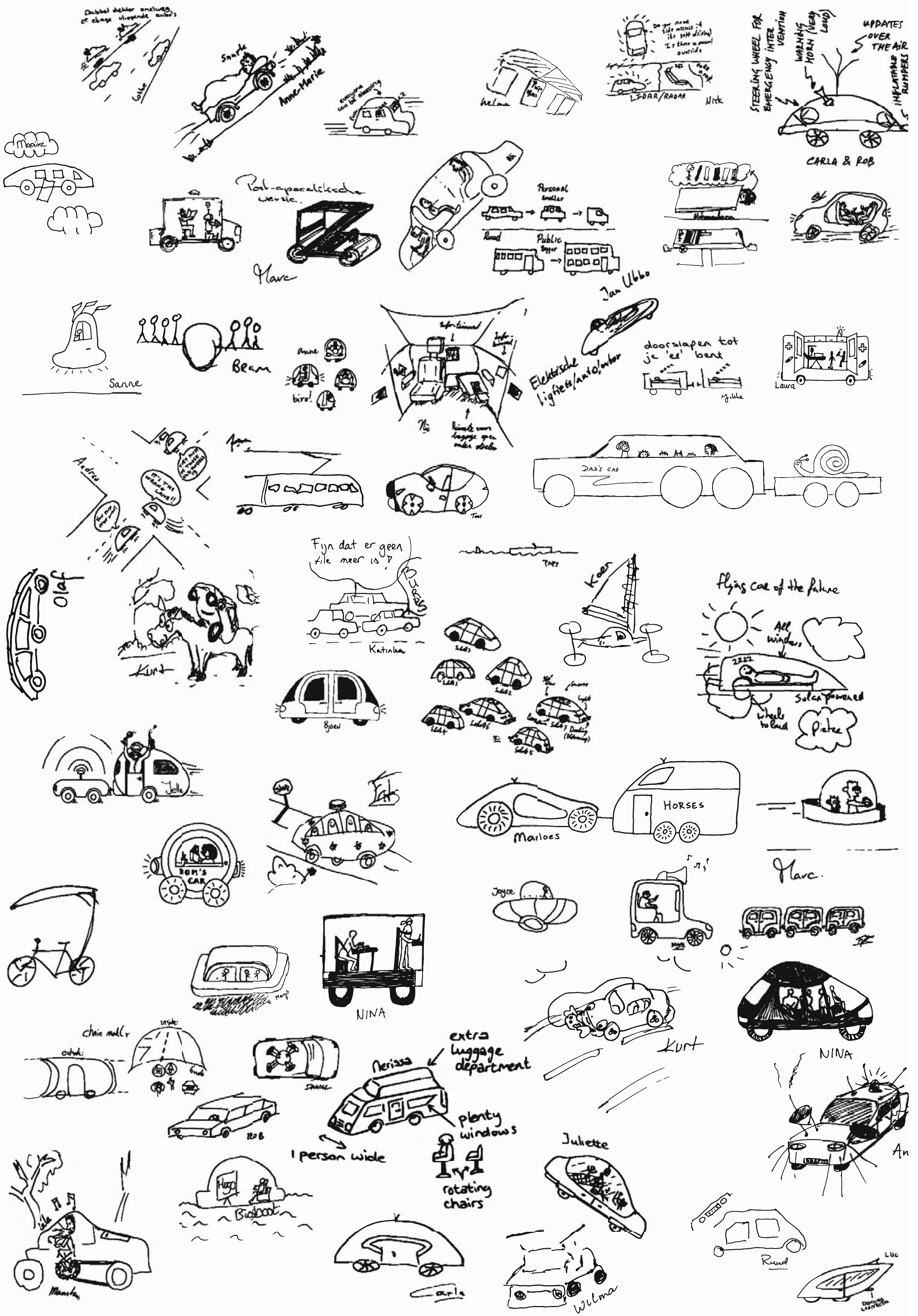
SICKNESS IN MOTION

ANNA REUTEN



Dubbel dekker snelweg, of etage vliegende auto's
Lotte
Snurk
Anne-Marie
everyone can be sleeping
Helma
Do you need side mirrors if its self driving?
Is there a manual override
LIDAR/RADAR
Nick
STEERING WHEEL FOR EMERGENCY INTERVENTION
WARNING HORN (VERY LOUD)
UPDATES OVER THE AIR
INFLATABLE BUMPERS
CARLA & ROB
Maaike
Post-apocalitische versie
Marc
Personal
Smaller
Public
Bigger
Ruud
Jan Ubbo
Elektrische ligfiets/auto/weber
doorslapen tot je er bent
Laura
Sanne
Bram
Anne
bird!
DAD'S CAR
Andres
IT'S THE WRONG LANE!!
Toos
Fijn dat er geen file meer is!
Katinka
Koen
flying car of the future
All windows
solar powered
wheels to land
Pieter
Olaf
Kurt
Bjoen
Jelle
HORSES
Marloes
MOM'S CAR
Marc.
Joyce
NINA
chain maker
outside:
inside:
extra luggage department
Nerissa
plenty windows
1 person wide
rotating chairs
ROB
Hugo
Bioboot
Juliette
Rund
Carla
Wilma
Luc
Kurt
NINA

Sickness in Motion

ANNA REUTEN

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Sickness in Motion

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door

Anna Johanna Carola Reuten

geboren te Weert

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PROLOGUE

There are several things I value most in life: spring, friends & family, health, iced coffee, cats. But one other thing may be most important of all: time. There is simply not enough of it. I am young, yet still fantasize about the possibility to stop time for a minute, to never need to sleep again, or to have the ability to clone myself. Unfortunately, none of these options seem realistic this moment in time. There is an alternative – admittedly a less exciting one – to save at least some time per day on a (for me) unpleasant activity. No longer needing to drive, but hopping aboard an automated vehicle. Family, friends, work, school, the supermarket, doctor, or flower shop. A fully automated vehicle could bring you wherever and whenever. Shared automated vehicle services could increase mobility, a valuable advantage for a population that is of increasing age. They may also reduce traffic accidents and congestion, and offer environmental benefits. But to return to my initial desire, would we actually feel to have more time when we live in a time where so much seems to be about time efficiency?

Well, envision that you would be a passenger in an automated vehicle. What would you do? Admit it, probably spend most of the additional free time on your phone scrolling through social media feeds. But for longer journeys you might actually pick up that book you started reading ages ago. Or perhaps you would rather watch the latest episode from your favorite show? How about playing some video games with friends? And.. probably also quickly answer those emails or finish that report now that you have the time for it. However, for many of you, you would probably not manage to perform the task you are doing for very long: nausea is starting to settle in.

This work aims to add a piece of knowledge to a big puzzle on an everyday problem: motion sickness. I hope you enjoy the journey of words, numbers, and figures that make up this book, hopefully they contribute to us driving comfortably in the future one day.

Denk, denk, denk – Winnie de Poeh

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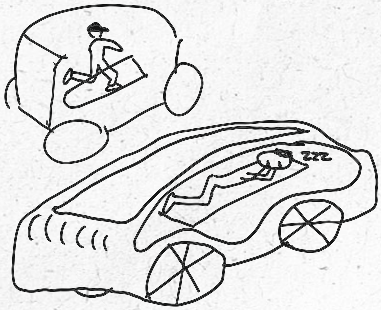
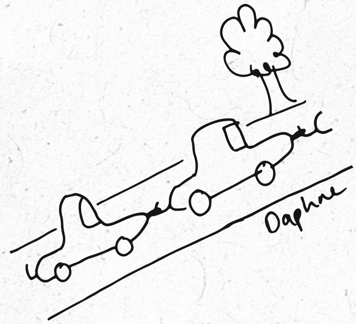


Nick

Guido



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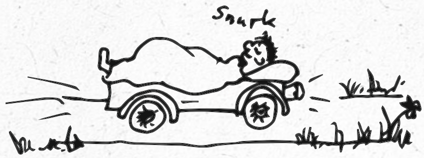
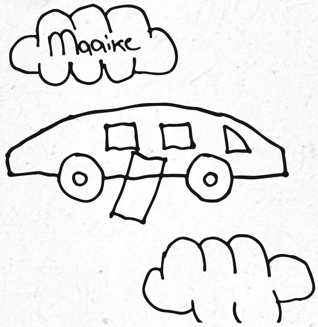
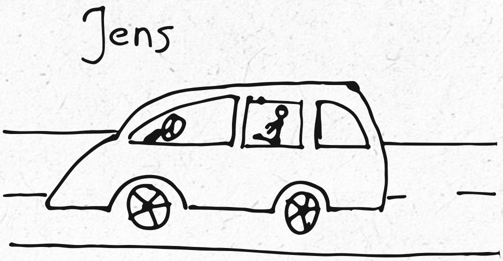


Anne-Marie

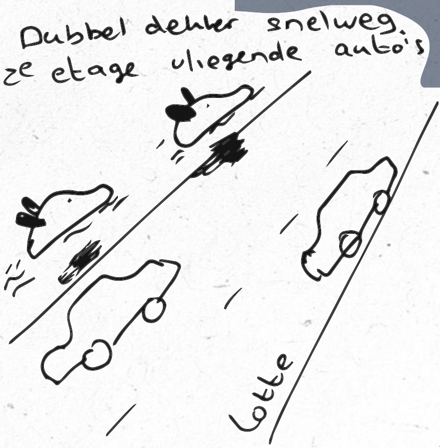
Georgios

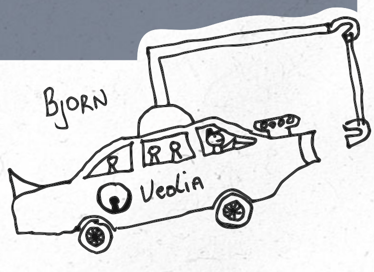


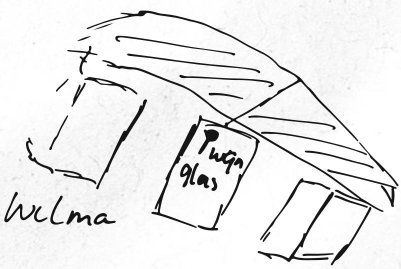


CHAPTER 1

A general introduction to motion sickness







In the summer of 2004, I travelled to England with my parents and older sister. We boarded the Stena Discovery ferry from Hoek van Holland to cross the North Sea. The high-speed catamaran could reach speeds up to 75 km/h, which was horrifying in combination with a storm of category 9-10 on Beaufort's scale. Despite the ship reducing its speed during the crossing, my mother and I felt dizzy, extremely nauseous, and miserable for what felt like forever. In contrast, my father and sister went to the stern to enjoy the ship's heave motions the best.

Me and my mother's experience is a classic example of motion sickness: a syndrome of discomfort that may develop following exposure to a motion stimulus (McCauley et al. 1976, Reason 1978, Dobie 2019). Sufferers typically experience symptoms such as dizziness, drowsiness, headache, pallor, nausea, and vomiting, often accompanied by a general feeling of malaise (Money 1970, Lawson 2014b). The earliest reports of motion sickness can be found in ancient Greek, Roman, and Chinese literature, in which symptoms, causes, and treatments of motion sickness have been described (Brandt et al. 2016, Huppert et al. 2017). Most historical reports concern incidences of camel sickness, cart sickness, and predominantly, sea sickness. The word "nausea" is actually derived from the Greek word "ναῦς", meaning ship. Research into motion sickness gained popularity because of World War II, during which the transport of troops via sea and air negatively affected human performance (Tyler and Bard 1949, Shaw 1954, Reason and Brand 1975). In the last decade, the introduction of new technologies such as automated driving and virtual reality has generated a re-interest into motion sickness research (Bos et al. 2022, Keshavarz and Golding 2022). In this dissertation, I limit my scope to the domain of motion sickness in the context of automated driving.

Automated driving

Self-driving cars are no longer science fiction: they are driving on our streets. In several cities in North America and Asia, automated taxi services ("robotaxis") have been launched since 2020 (e.g., Cruise, Waymo One, Apollo, Pony.ai). An automated shuttle is also operational in The Netherlands, where it transports 1850 members of the public between Rotterdam and Capelle aan de IJssel on a daily basis (ParkShuttle). These are examples of "high driving automation" according to the proposed taxonomy of the Society of Automotive Engineers (SAE). The SAE (2021) classifies automated driving into six levels, starting from level 0 (no automation) to level 5 (full driving automation under all weather and road conditions). From level 3 and onwards, automated driving features can take over aspects of driving, thereby transforming drivers into (observant) passengers. Automated driving has various potential societal, environmental, and economic benefits, such as reduced congestion and increased mobility (Milakis et al. 2017, Faisal et al. 2019, Othman 2022). However, one presumed negative consequence is an increase in motion sickness (Diels and Bos 2016, Iskander et al. 2019). The primary reason for this expected increase is that motion sickness affects car passengers rather than car drivers (Schmidt et al. 2020). Four interrelated reasons that explain the increased motion sickness prevalence in (automated) car passengers are listed hereafter.

1. **Passive exposure to a motion stimulus**
   Self-initiated motion such as walking does not cause motion sickness. Motion sickness only occurs when exposed to an unnatural motion stimulus, especially when not being in control of the motion. Using a two-seat rotation device, Rolnick and Lubow (1991) demonstrated that individuals who controlled the motion of the device experienced less sickness than yoked participants passively exposed to the same stimulus.

2. **Head position during cornering**
   It has been observed that the head position of car passengers is different from drivers when navigating a curve. Car drivers tilt their head into the direction of the curve (i.e., centripetal force), whereas passengers do so in opposite direction (Zikovitz and Harris 1999). Actively tilting passenger's head into the direction of centripetal force has been demonstrated to mitigate motion sickness (Wada et al. 2012, Wada and Yoshida 2016).

3. **Opportunity to engage in non-driving related tasks**
   The time saved by not having to control the car is presumably used by passengers to perform other tasks. Besides listening to music and talking to co-passengers, other frequently mentioned tasks that individuals indicate they would perform are reading and using electronic devices (Sivak and Schoettle 2015; Pfleging et al. 2016; Detjen et al. 2020). As many readers will have experienced themselves, these latter tasks often provoke motion sickness during car travel (Jones et al. 2019, Schmidt et al. 2020).

4. **Possibility to redesign car interiors**
   If human control on driving is no longer required, car designers receive the freedom to drastically change the traditional car interior. Automated car concepts include large screen displays, small windows, and reversed seating orientations – features that benefit the non-driving related tasks mentioned above (Smyth et al. 2020). These features will however limit external view and anticipation of the road ahead, which are factors known to influence motion sickness (Griffin and Newman 2004; Kuiper et al. 2018; Salter et al. 2019).

Currently, the majority of car occupants are drivers (CBS 2022, TSGB 2022, BTS 2023). This implies that the number of car travelers who may experience motion sickness will multiply following a human-to-automated driving transition. This will render motion sickness an issue of societal concern. The overall aim of my dissertation is to contribute to research on the mitigation of motion sickness, particularly in the context of automated driving. Before describing the studies which I performed in collaboration with my supervisors and other colleagues, in this first chapter I start by providing a short overview of those aspects concerning motion sickness in general. First, I will discuss demographic factors that affect motion sickness susceptibility, followed by the approaches used to measure motion sickness in experimental settings. Then I describe the contributing role of the vestibular and visual systems in the development of motion sickness, and integrate it with the role of anticipation when discussing the theoretical background of motion sickness. Lastly, I will describe the research questions that outline my dissertation.

Motion sickness susceptibility

My personal anecdote at the beginning of this introduction illustrated that not everyone is susceptible to motion sickness. Three demographic variables that affect motion sickness susceptibility have been pointed out in the literature, which I will briefly describe in the following paragraphs.

The first variable is age, with motion sickness susceptibility following the pattern of a positively skewed (right-tailed) distribution across the life span (e.g., Turner 1999, Gahlinger 2006, Bos et al. 2007, Keshavarz and Golding 2022). Infants younger than one or two years of age usually do not suffer from motion sickness, after which susceptibility quickly rises until late childhood. After this peak incidence in childhood, motion sickness susceptibility shows a gradual decline across adolescence into adulthood. Older adults seem least affected by motion sickness. Even though children might benefit the most from a solution to mitigate motion sickness, experimentally exposing them to motion sickening stimuli raises some ethical concerns. For that reason, in my studies I only included adults between 18 and 65 years old.

Secondly, studies have repeatedly reported that women suffer more from motion sickness than men (e.g., Lentz 1977; Klosterhalfen et al. 2005; Bos et al. 2007; Schmidt et al. 2020; Keshavarz and Golding 2022). This difference may reflect biases in the recall of past motion sickness exposures and the scoring of symptoms (reviewed by Mittelstaedt 2020), though some studies do suggest higher vomiting incidences for women (Lawther and Griffin 1986, 1988, Turner and Griffin 1995, Dobie 2019). Because I did not aim to expose possible (biological) sex differences, none of the analyses in my studies were performed separately for men and women.

A third variable concerns ethnicity. Chinese individuals seem hypersusceptible to motion sickness compared to European, European American, and African American individuals (Stern et al. 1996, Klosterhalfen et al. 2005, Schmidt et al. 2020). Given that the children of Chinese parents who were raised in America also demonstrate a higher motion sickness susceptibility, a genetic component may contribute to explain the observed ethnical differences (Stern et al. 1996). In general, twin studies indicate that motion sickness susceptibility has a strong genetic component (Bakwin 1971, Sharma 1980, Reavley et al. 2006). Since many studies on motion sickness are performed in Europe and America, as are those in my dissertation, the extent of the problem may be underestimated for the Asian population.

My personal anecdote also illustrated another aspect: even individuals of the same age, sex, and (genetic) ethnicity differ in susceptibility. My sister and I responded very differently to the same ship motion. Suggested factors to explain such interindividual differences are differences in the time constant of velocity storage (e.g., Bos and Bles 2002; Bertolini and Straumann 2016) or perceptual style (Witkin and Asch 1948, Mittelstaedt 2020; which I investigated in studies not part of this dissertation). The large variability between participants makes it difficult to reliably measure and compare motion sickness, which indicates that experiments require large sample sizes or large manipulation effects to achieve high statistical power. Between-subjects designs are thus less suited to study motion sickness, wherefore I used within-subjects designs in my experiments. But how is motion sickness measured in experimental settings?

Measuring motion sickness

The Motion Sickness Incidence (MSI), defined as the percentage of individuals who reach the limit of vomiting during a certain timeframe, has been a popular index to objectively quantify motion sickness in the past (O'Hanlon and McCauley 1973, McCauley et al. 1976, ISO 2631-1 1997). However, this measure can be considered suboptimal for two reasons. First, it may be regarded unethical when considering that milder symptoms encompassing earlier stages of motions sickness are informative as well. Second, it requires long-lasting exposure durations which are costly in terms of resources.

In a search for alternative objective measures of motion sickness, a multitude of physiological responses has been investigated (see reviews by Money 1970; Harm 1990; Shupak and Gordon 2006; Koohestani et al. 2019). The observed changes within such responses during sickening exposures support a role for the autonomic nervous system in motion sickness. Common physiological measures include monitoring heart rate via electrocardiography, sweating of the skin via electrodermal activity, and myoelectrical stomach activity via electrogastrography. Several studies successfully differentiated motion sickness severity using one or multiple physiological measures (e.g., Cowings et al. 1986; Stout et al. 1993; Gianaros et al. 2003; Kim et al. 2005; Farmer et al. 2014). However, the direction of physiological responses within measures varies between studies, illustrating they lack specificity (reviewed by Money 1970; Harm 1990; Shupak and Gordon 2006; Koohestani et al. 2019). In my dissertation, I therefore decided to refrain from using physiological measures and focused on self-report rating scales instead.

Elaborate multi-value rating scales ask participants to report on the severity of a list of symptoms (e.g., Graybiel et al. 1968; Kennedy et al. 1993; Gianaros et al. 2001). This offers the advantage of a multidimensional view on symptomatology, but these scales can take up to several minutes to complete. Single value rating scales lack this disadvantage and can quickly and repeatedly be reported on during exposures by asking participants to provide only one rating. As stated earlier, motion sickness is described as a *syndrome* of *discomfort*, with these italicized aspects separately reflected in the spectrum of available single value rating scales. Some scales question how unpleasant someone is feeling (e.g., Reason and Graybiel 1970; Lawther and Griffin 1986; Draper et al. 2001; Keshavarz and Hecht 2011; Jones et al. 2018), whereas other scales focus on the symptoms that individuals may experience (e.g., McCauley et al. 1976; Golding and Kerguelen 1992; Golding et al. 2003; Donohew and Griffin 2004; Bos et al. 2005). The plethora of available rating scales indicates that a standard for measuring motion sickness is currently lacking. To measure motion sickness reliably, a scale should capture its progression unambiguously. Whether single value unpleasantness and symptomatology rating scales do so is yet unclear. Generally, one feels worse as symptoms progress (e.g., Keshavarz and Hecht 2011; Nooij et al. 2017), though there is anecdotal evidence suggesting a non-monotonic relationship between unpleasantness and symptomatology (e.g., Reason and Graybiel 1970; Leung and Hon 2019). If unpleasantness ratings decrease with ongoing motion stimulation, this would trouble an unambiguous measurement of motion sickness progression. To that end, I investigated the temporal development of ratings on an unpleasantness and symptomatology scale, as well as their mutual dependence, in **Chapter 2**.

The role of the vestibular system

Evidently, self-motion plays a fundamental role in motion sickness. The vestibular system processes sensory information underlying self-motion perception, supporting functions such as motor responses, spatial orientation and navigation, and stabilization of gaze and posture. The peripheral part of the system contains the organs of balance, which are five structures located within the labyrinth of the inner ears (Khan and Chang 2013, Purves et al. 2018). These structures are critical to the development of motion sickness given the observation that individuals with complete loss of labyrinthine function do not, or to a much lesser extent, suffer from motion sickness (Irwin 1881, James 1883, Kellogg et al. 1964, Kennedy et al. 1968, Money 1970, Johnson et al. 1999). Whereas labyrinthine defective individuals are essentially immune to motion sickness, individuals with deficits in vestibular function demonstrate a drastically elevated susceptibility to motion sickness (Boldingh et al. 2011, Paillard et al. 2013, Mittelstaedt 2020). For these reasons, in my studies I only included participants without self-known vestibular disorders.

The two otolith organs, the utricle and saccule, respond to head tilt and translational motion. They register the sum of gravity and inertial linear acceleration, or in other words the total gravito-inertial acceleration. Both structures contain a sensory epithelium called the macula, which consists of hair cells and other supporting cells. A gelatinous layer covers the macula and is embedded with calcium carbonite crystals called otoconia ("otolith" is Greek for "ear-stones"). Because the otolithic membrane has a larger specific mass than the surrounding parts, head tilts relative to gravity and inertial linear accelerations cause a shearing motion with respect to the macula that results in the deflection of hair bundles. Deflection of these hair bundles does not differentiate between head tilts and translational motions; otolith afferents only convey information about the total gravito-inertial acceleration. Neural processing is required to make the distinction. In addition to neural processing, visual information contributes to discriminating tilts from translations, as well as information from three semicircular canals. The semicircular canals register angular accelerations along three axes: yaw (cephalocaudal axis), roll (naso-occipital axis), and pitch (interaural axis). Each canal has a dilated part which includes a gelatinous mass called the cupula, with at their base the crista ampullaris, a sensory epithelium containing hair (and other) cells. Self-rotation causes endolymph, a fluid running through the canals, to lag head motion due to inertia. This lag results in deflection of the cupula and the hair bundles within, yielding a percept of angular self-motion opposite to the direction of endolymphatic flow. From this simplified explanation, it becomes apparent that the organs of balance provide information about head orientation with respect to gravity, and inertial linear and angular head motion. Their vestibular afferents project onto various brain areas, including the brainstem, cerebellum, thalamus, and cortex, subserving a variety of functions as mentioned above.

Since the organs of balance only respond to accelerations, translating or rotating at constant velocity without external view (and other somatosensory and auditory cues on self-motion) equals the perception of being stationary. As an example, we do not perceive to move with 900 km/h as we do when travelling via airplane. Rather than the speed of motion, its variation (characterized by the frequency and duration of acceleration) is determining motion sickness. Several studies have demonstrated a peak sickness incidence at around 0.2 Hz for vertical motion (e.g., McCauley et al. 1976; Lawther and Griffin 1987; ISO 1997), which might also apply to horizontal (Golding and Markey 1996, Golding et al. 2001, Donohew and Griffin 2004) and visual motion (Golding et al. 2009, Diels and Howarth 2013). Larger exposure durations and accelerations are generally more provocative (O'Hanlon and McCauley 1973, McCauley et al. 1976, Lawther and Griffin 1987, Guignard and McCauley 1990). Individuals can however habituate to a sickening stimulus after prolonged (several hours) or repeated exposure (Reason and Brand 1975, Howarth and Hodder 2008, Mittelstaedt 2020).

Tilt-translation ambiguity and the inability to detect self-motion at constant velocity indicates that our brain integrates information from multiple sensory systems for self-motion perception. This suggests a role for the visual system in motion sickness, which is discussed in the following section.

The role of the visual system

In contrast to individuals with complete loss of labyrinthine function, individuals with congenital as well as late-acquired blindness are susceptible to motion sickness (Graybiel 1970). Motion sickness can thus develop in the absence of visual input, wherein it is noteworthy to mention that humans perform poorly at judging acceleration visually (Brouwer et al. 2002, Brenner et al. 2016). Several observations illustrate that visual information does modulate motion sickness severity. For example, a well-known remedy for motion sickness during sea travel is to look at the horizon, an effect observed for artificial horizons as well (Rolnick and Bles 1989, Stevens and Parsons 2002, Tal et al. 2012). Furthermore, clear external view on the motion trajectory reduces motion sickness (Griffin and Newman 2004; Wada and Yoshida 2016; Kuiper et al. 2018), presumably as this helps individuals to anticipate self-motion. The unobstructed forward view of passengers sitting in the front seat of a vehicle might accordingly explain why they usually report less sickness compared to passengers sitting in the back seat (Turner and Griffin 1999, Schmidt et al. 2020). These two examples demonstrate that visual information can mitigate motion sickness, but it may aggravate sickness when it conflicts with vestibular cues on self-motion. Many readers will recognize experiencing motion sickness when reading a book during car travel, which evokes a conflict between stationary visual input and self-motion registered by the organs of balance. For my dissertation, I performed several studies in which I utilized the modulating effect of visual information to aggravate motion sickness in short exposure durations by blocking external view. Instead of looking outside, participants observed a stationary interior, which reduced anticipation of self-motion and created a visual-vestibular conflict on self-motion perception. The assumed causative role of sensory conflicts in motion sickness is elaborated on in the next section.

Theoretical background of motion sickness: the role of anticipation

Many theories on the root cause of motion sickness have been proposed over the past decades (see Reason and Brand 1975; Keshavarz et al. 2014; Lackner 2014; Dobie 2019 for overviews). Of those theories, the sensory conflict theory may be considered the one most widely acknowledged today.

As mentioned in the previous section, reading a book during car travel is provocative for many individuals. Sitting still whilst viewing a moving environment in virtual reality is so too. Performing head nods when spinning steadily on an office chair also leads to motion sickness (i.e., cross-coupled stimulation). These examples describe inter- and intrasensory conflicts on self-motion perception that have been pointed out by various authors to play a causative role in motion sickness (e.g., Claremont 1930; Steele 1961; Guedry 1970). To account for the observation that individuals can habituate to provocative stimuli despite persisting sensory conflicts, Reason and Brand (1975) suggested that the origin of the conflict is a neural mismatch between sensed and expected sensory signals on self-motion. They hypothesized that expectations of sensory information, based on previous motion exposures, are retained in a neural store (see also Reason 1978). Oman (1982, 1990, 1991) laid the groundwork for a mathematical model of the sensory conflict theory in which he replaced the concept of a neural store by internal models assumed relevant for sensorimotor control. Multiple authors later adapted his model, for example Bles et al. (1998) and Bos et al. (2008), who limited the conflict to a mismatch between the sensed and expected gravitational verticals, defined as vectors with a direction and a magnitude. I present a simplified version of the sensory conflict model in Figure 1.1 and elaborate on it in the text below.

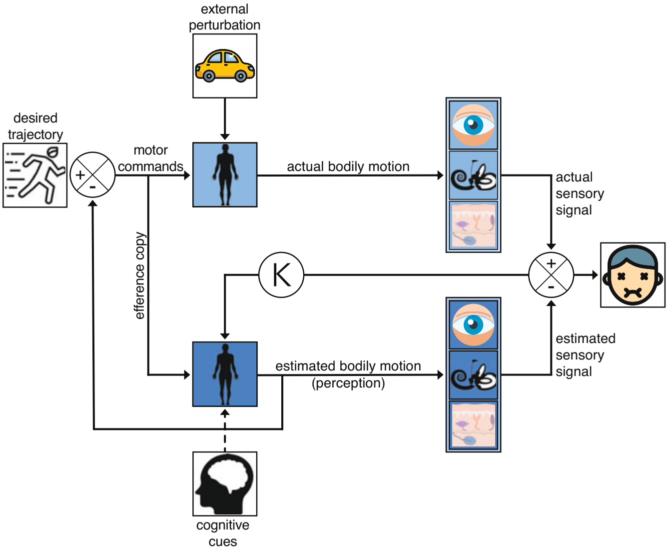


Figure 1.1 Simplified model of sensorimotor control, including the origin of motion sickness (based on Reason 1978; Oman 1982; Bos et al. 2008). Light blue boxes represent the actual motor and sensory systems; the dark blue boxes represent internal models of these systems. A conflict between the integrated sensed and estimated sensory signal is hypothesized to cause motion sickness.

1

To achieve a desired motor trajectory, motor commands are sent from the central nervous system to control the body (light blue). External perturbations, for example car motion, influence the body as well. The resulting bodily motion is registered by the senses, in particular the visual, vestibular, and somatosensory systems (light blue). In a simple servo control loop, the resulting integrated sensory signal would be compared to the desired motor trajectory to determine whether additional motor input is required. This can however not satisfactorily explain sensorimotor control. First, the sensory systems are noisy (Faisal et al. 2008), resulting in imperfect sensory estimates. Second, neural processing of sensory signals is rather slow. For example, visuomotor delays to respond to changes in target position can take 110 ms (Brenner and Smeets 1997, 2023). Third, as described above, accelerations due to gravity and inertia are physically indistinguishable (the equivalence principle, Einstein 1907). To resolve these issues, the existence of internal models (dark blue boxes) containing a priori sensorimotor estimations is assumed (von Holst 1954, Wolpert et al. 1998, Popa and Ebner 2019). Neural evidence for the existence of internal models is accumulating (Angelaki et al. 2004, Laurens et al. 2013, Oman and Cullen 2014, Laurens and Angelaki 2017).

Efference copies of motor commands and previous motion exposures are the main inputs for the internal model of the body (dark blue), which estimates the resulting bodily motion. To ensure that this estimate is indeed accurate, this signal is fed to the internal model predicting the sensory signals (dark blue boxes). If there is a difference between the resulting integrated estimated and actual sensory signal, their discrepancy will be used to update the internal model and hence the estimated bodily motion. The discrepancy itself is assumed to cause motion sickness, with the size of the conflict determining the severity of the motion sickness response. The updating of the internal model is weighted relative to the noise of the actual sensory systems by a gain K (Oman

1982; Bos and Bles 2002; Tanaka et al. 2020, see the 'Kalman' gain K in Figure 1.1). A high uncertainty about those signals is accounted for by a low gain and, vice versa, a low uncertainty by a high gain. This updating allows the internal model to take account of external perturbations, which provides an explanation for habituation to motion sickening stimuli.

The internal model is a function of the central nervous system. This raises the question whether not only efference copies and previous motion exposures, but also cognition influences self-motion perception (dashed arrow in Figure 1.1). In **Chapter 3**, I explored whether cognitive (non-sensory) cues suggesting self-motion can induce a systematic percept of self-motion in the absence of corresponding sensory stimulation. If possible, cues which announce upcoming car motion may be used to improve passenger's predictions of passive self-motion. This would minimize a possible sensory conflict and subsequently reduce motion sickness. Several studies investigated the effectiveness of *anticipatory cues* using auditory (Kuiper et al. 2020a, Diels and Bos 2021, Maculewicz et al. 2021) and visual (Feenstra et al. 2011; Karjanto et al. 2018, 2021; de Winkel et al. 2021; Hainich et al. 2021) stimuli. A disadvantage of providing cues via the auditory and visual modality is that these may already be occupied by non-driving related tasks that passengers may perform (Sivak and Schoettle 2015, Pfleging et al. 2016, Detjen et al. 2020, Schmidt et al. 2020). Moreover, visual cues sometimes aggravate, rather than mitigate motion sickness (Stauffert et al. 2020, Karjanto et al. 2021). As an alternative, anticipatory cues could be presented via a third channel unaffected by these disadvantages: the tactile modality. I investigated the effectiveness of anticipatory vibrotactile cues in **Chapters 4 to 6**.

Outline of this dissertation

The overall aim of my dissertation is to contribute to research on the mitigation of motion sickness, particularly in the context of automated driving. To that end, in Chapters 2 to 6 I describe five experiments which I performed together with my co-authors to answer several related sub-questions.

The plethora of available rating scales indicates that a standard for measuring motion sickness is currently lacking. To measure motion sickness reliably, a scale should capture its progression unambiguously. In **Chapter 2**, I therefore explored how the progression of motion sickness can be unambiguously quantified using single value rating scales: via measuring unpleasantness or symptomatology? To that end, I analyzed the temporal development of ratings collected from multiple studies using an unpleasantness or symptomatology scale, as well as their mutual dependence using psychophysical rating techniques. The results from this study indicate that the MIsery SCale, which I renamed the Motion Illness Symptoms Classification (MISC), provides an unambiguous quantification of motion sickness progression. This motivated my decision to use the MISC throughout the remaining studies within my dissertation.

In **Chapter 3**, I explored the influence of cognitive cues on the perception of self-motion. Prior studies demonstrated that mental imagery (Mertz et al. 2000, Nigmatullina et al. 2015), task instructions (Ellis et al. 2017), and contextual information (Wertheim et al. 2001, Riecke 2009, D'Amour et al. 2021) modulate self-motion perception of a physical or visual motion stimulus. These studies all concerned experiments with a motion stimulus and thus reflect modulations of a percept of self-motion that is elicited by sensory stimulation. Can cognitive cues that suggest self-motion also elicit a percept of self-motion in the absence of sensory motion? To answer this question, I seated blindfolded participants on a parallel swing that remained stationary during two sessions, apart from a deliberate perturbation at the start of each session. Using a different task instruction, discrimination task, and demonstration of swing motion, I manipulated participants' expectations regarding the motion of the swing: ceasing or continuing swing oscillations. The results indicated a profound impact of cognitive cues on self-motion perception, providing some support for a motion sickness mitigation method which I investigated next.

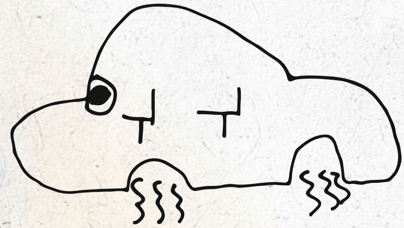
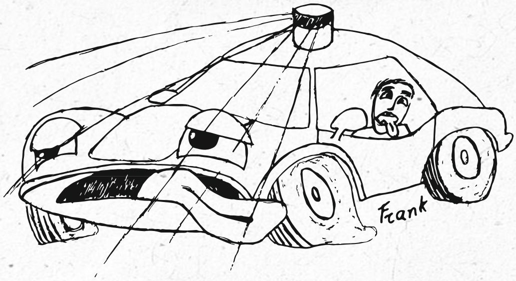
In Chapters 4 to 6, I investigated the effectiveness of a possible approach to mitigate motion sickness: anticipatory cueing. Alerting passengers of changes in upcoming car motion via anticipatory auditory (Kuiper et al. 2020a, Diels and Bos 2021, Maculewicz et al. 2021) or visual (Feenstra et al. 2011, Karjanto et al. 2018, 2021, de Winkel et al. 2021, Hainich et al. 2021) cues has been demonstrated to mitigate motion sickness. In automated vehicles, vibrotactile cues may be more desirable – are they effective as well?

In **Chapter 4**, I investigated whether anticipatory vibrotactile cues that announced the onset of a forward displacement mitigated motion sickness, and if the timing of the cue was of influence. To determine their effectiveness, I developed a new measure that quantified the reduction in motion sickness symptomatology between a session with anticipatory cues and a control session in a single value: R. Put briefly, R is defined as a weighted average of normalized differences in MISC scores between an anticipatory and control session across all time points and participants. I used a weighting approach that accounted for the low resolution of the MISC by assigning more weight to R values calculated on higher MISC scores, which are more reliable estimates of the generated reduction. As a consequence, more weight is assigned to reductions in later manifesting symptoms. R has a symmetrical distribution with fixed endpoints, thereby facilitating a comparison of the effectiveness of interventions between experimental sessions and studies. The results of a pre-registered analysis using the measure R did not show a significant mitigation by the vibrotactile cues in this study, irrespective of their timing.

Kuiper et al. (2020a) reported that anticipatory auditory cues significantly mitigated motion sickness whilst having used similar experimental conditions as those in Chapter 4. This might suggest superiority of the auditory modality for anticipatory cueing. However, the studies differed in the unpredictability of the used motion stimulus. In Chapter 4, only the onset of motion was unknown to the participants, whilst in Kuiper et al. (2020a) also the direction of motion (forward or backward) was unknown. The additional unpredictability of the motion stimulus in Kuiper et al. (2020a) might explain the increased effectiveness of their auditory cue. In **Chapter 5**, I therefore performed a replication study of Kuiper et al. (2020a) to compare the effectiveness of anticipatory auditory and vibrotactile cues. The same analysis using the measure R indicated that both cues mitigated motion sickness, but the reduction did not reach significance. Several aspects of our data suggested that the lack of a significant reduction might be explained by limited statistical power. To increase power, I performed an internal meta-analysis in which I combined the data of Chapters 4 and 5, and Kuiper et al. (2020a). Based on this analysis, I concluded that anticipatory cues are overall effective in mitigating motion sickness.

The studies in Chapters 4 and 5 were performed on a linear sled with displacements limited to one-dimensional motion. In **Chapter 6**, I compared the effectiveness of anticipatory auditory and vibrotactile cues to mitigate motion sickness in car passengers during a real car ride. This created the possibility to use motions consisting of multiple degrees of freedom. A trained driver performed driving maneuvers resembling those of everyday car driving: lane changes, accelerations, and decelerations. Using the same analysis approach, the measure R demonstrated the effectiveness of anticipatory vibrotactile cues as a solution to mitigate motion sickness in car passengers.

Answers to the questions I posed in Chapters 2 to 6 are summarized in **Chapter 7**. Here I additionally provide an exploratory analysis on the relationship between motion sickness susceptibility and the effectiveness of anticipatory cues. In this last chapter, I also describe the implications of my work as well as suggestions to guide future research.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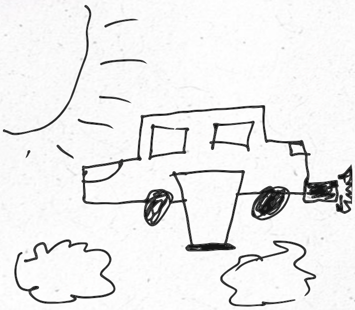

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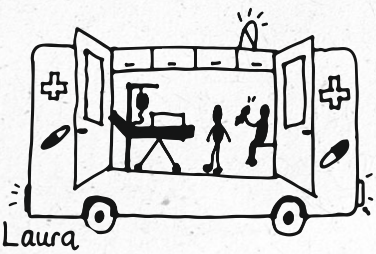
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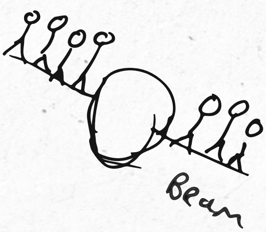
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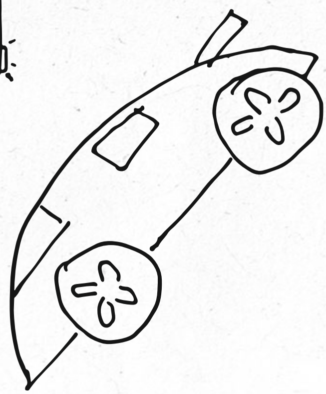
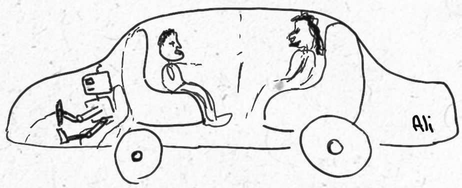
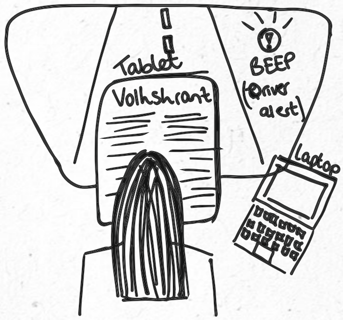
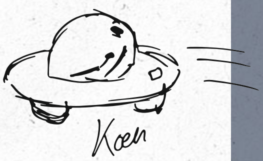






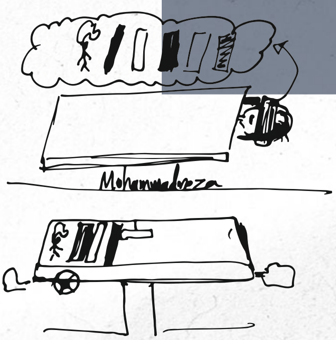
CHAPTER 2

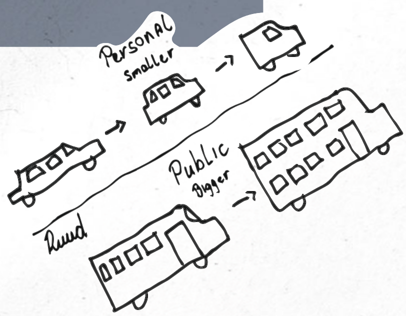
How feelings of unpleasantness develop during the progression of motion sickness symptoms



Adapted from
Anna JC Reuten, Suzanne AE Nooij,
Jelte E Bos & Jeroen BJ Smeets (2021)

Experimental Brain Research 239(12): 3615-3624





Abstract

To mitigate motion sickness in self-driving cars and virtual reality, one should be able to quantify its progression unambiguously. Self-report rating scales either focus on general feelings of unpleasantness or specific symptomatology. Although one generally feels worse as symptoms progress, there is anecdotal evidence suggesting a non-monotonic relationship between unpleasantness and symptomatology. This implies that individuals could (temporarily) feel better as symptoms progress, which could trouble an unambiguous measurement of motion sickness progression. Here we explicitly investigated the temporal development of both unpleasantness and symptomatology using subjective reports, as well as their mutual dependence using psychophysical scaling techniques. We found symptoms to manifest in a fixed order, while unpleasantness increased non-monotonically. Later manifesting symptoms were generally judged as more unpleasant, except for a reduction at the onset of nausea, which corresponded to feeling better. Although we cannot explicate the origin of this reduction, its existence is of importance to the quantification of motion sickness. Specifically, the reduction at nausea onset implies that rating how bad someone feels does not give you an answer to the question of how close someone is to the point of vomiting. We conclude that unpleasantness can unambiguously be inferred from symptomatology, but an ambiguity exists when inferring symptomatology from unpleasantness. These results speak in favor of rating symptomatology when prioritizing an unambiguous quantification of motion sickness progression.

Introduction

Motion sickness is a syndrome of discomfort that may be induced by exposure to a physical or virtual motion stimulus (Cha et al. 2021). Research on the mitigation of motion sickness is gaining interest in particular with respect to automated driving (Diels and Bos 2016, Jones et al. 2018, Iskander et al. 2019, Kuiper et al. 2020a, Yusof et al. 2020) and virtual reality (Rebenitsch and Owen 2016, Nooij et al. 2017b, Kim et al. 2018, Saredakis et al. 2020). However, to find solutions for mitigating motion sickness, one should be able to quantify it unambiguously.

The Motion Sickness Incidence (MSI), defined as the percentage of people who reach the limit of vomiting during a certain timeframe, has been a popular index to quantify motion sickness in the past (O'Hanlon and McCauley 1973, McCauley et al. 1976, ISO 2631-1 1997). Although the MSI may be considered the most objective measure, it entirely neglects the wide range of unpleasantness and symptoms encompassing the earlier stages of motion sickness. Therefore, self-report scales that also cover these earlier stages are nowadays an often-used alternative to measure motion sickness. As an alternative to elaborate multi-value questionnaires (Kennedy et al. 1993, Gianaros et al. 2001), single value rating scales (Lawson 2014a) have become particularly popular. For such a report, participants assign one value on a given scale to indicate their feelings and/or symptoms. After participants have familiarized themselves with such a scale, they can easily report on it within a second, with minimal interference on any task performed, and allowing repeated application within experimental sessions, even with eyes closed. This paper limits its scope to this specific type of numerical scales. These scales can largely be grouped into two categories: scales questioning how bad someone feels, here termed unpleasantness, or scales based on the symptomatology one experiences. In this paper we address the relationship between these two types of scales.

Scales rating unpleasantness use a severity grading to report on a general feeling of malaise (Reason and Graybiel 1970, Lawther and Griffin 1986, Turner and Griffin 1999, Draper et al. 2001, Keshavarz and Hecht 2011, Jones et al. 2018). They often use magnitude estimation, anchored with endpoints ranging from feeling fine to feeling absolutely dreadful. One example, that will be analyzed in the current context, is the Fast Motion sickness Scale (FMS), in which observers give verbal ratings of experienced motion sickness on a 21-point scale ranging from 0 (no sickness) to 20 (frank sickness) (Keshavarz and Hecht 2011). On the other hand, scales rating symptomatology often include a numerical characterization which is based on the observation that different classes of symptoms generally progress in a fixed order over time. Although bodily symptoms like flushing, stomach awareness, and dizziness often vary between people, this class of symptoms is typically followed by nausea, retching, and ultimately vomiting (Reason and Graybiel 1970, Reason and Brand 1975, Bos et al. 2005, Lawson 2014b). This allows these classes to be given incremental values, possibly with a grading for the experienced severity within a symptom class (Bos et al., 2005; Donohew & Griffin, 2004; Golding et al., 2001, 2003; Golding & Kerguelen, 1992; Hemingway, 1975; McCauley et al., 1976). The largest refinement is provided by the MISC (Bos et al. 2005) as given in Table 2.1. Different from its original naming will we refer to this scale as the Motion Illness Symptoms Classification.

Class description		**MISC**
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, yawning, headache, tiredness, sweating, stomach awareness, burping, blurred vision, salivation, … but no nausea	vague	2
	little	3
	rather	4
	severe	5
Nausea	little	6
	rather	7
	severe	8
	retching	9
Vomiting		10

Table 2.1 The Motion Illness Symptoms Classification (MISC) used to assess motion sickness symptomatology (Bos et al. 2005).

With both types of scales often being used in research on motion sickness, there is a surprising lack of knowledge on how feelings of unpleasantness develop during the progression of motion sickness symptoms. Intuitively, one feels worse as symptoms progress, which is supported by the high positive correlations observed between measures of unpleasantness and symptomatology (Bos et al. 2005, D'Amour et al. 2017, Keshavarz and Hecht 2011, Nooij et al. 2017b, Reason and Graybiel 1970). Yet, such correlations hide possible local deviations of a monotonic relationship. If unpleasantness ratings were found to decrease with ongoing motion stimulation, this would trouble an unambiguous measurement of motion sickness progression. Anecdotal evidence indeed suggests unpleasantness to increase non-monotonically with symptom progression. To illustrate, vomiting is generally considered the final manifesting symptom, yet also reported to offer relief of misery (Lackner 2014, Dobie 2019, Leung and Hon 2019). Additionally, one study reported specific decreases in unpleasantness ratings during ongoing motion stimulation, also suggesting the presence of a non-monotonic relationship (Reason and Graybiel 1970). These two examples provide reason to assume that rating how bad someone feels may not be equivalent to rating how close someone is to the point of vomiting.

In the present study we therefore systematically explored the relationship between unpleasantness and symptomatology during the progression of motion sickness. First, we focus on how unpleasantness and symptomatology develop for up to 30 minutes of motion stimulation. We there explicitly investigate if they increase monotonically with the progression of motion sickness over time. Second, we focus on the relationship between unpleasantness and symptomatology, answering the question: do we consistently feel worse as symptoms progress?

Methods

Temporal development of unpleasantness and symptomatology

Data collection

In this first part, we investigate how unpleasantness and symptomatology develop with the progression of motion sickness. To do so, we (re-)analyzed motion sickness ratings collected during five previously published experiments (Exp 1 = Nooij et al., 2017b; Exp 2 = Nooij et al., 2017a; Exp 3 = Nooij et al., 2021; Exp 4 = Bos et al., 2005; Exp 5 = Bos, 2015) and two additional experiments to be published later (Exp 6–7). In all experiments, participants were exposed to either physical or virtual motion for a maximum duration of 30 minutes and indicated their level of unpleasantness or symptomatology at regular intervals (two to five minutes). Unpleasantness was assessed in Exp 1–3 using the FMS, whilst symptomatology was assessed in Exp 4–7 using the MISC. The provocative stimulation was aborted when a participant reported an FMS class of ≥ 15 or a MISC class of ≥ 7, except for Exp 4 that used no stop-criterion. All experiments (except for Exp 3) consisted of multiple provocative sessions, which were presented on separate days. Additional experimental details are summarized in Supplementary Table S2.1.

Data analysis

We analyzed the FMS ratings from 58 participants performing a total of 132 sessions with at least two ratings within each session, and MISC ratings from 148 participants performing a total of 528 sessions with at least two ratings within each session. For all scale ratings, we analyzed the difference in rated class between two consecutive ratings, which we will further refer to as a rating transition. We first determined the number of observed transitions between two classes, and subsequently calculated the proportion of cases in which the rating after a certain class remained constant, increased, or decreased. Our null hypothesis is a monotonic increase of unpleasantness and symptomatology with the progression of motion sickness over time, implying that their respective ratings should increase or remain constant. Decreases in ratings might occur due to random fluctuations in rating, and thus should be infrequent and evenly distributed over the whole range of the scale.

To promote a comparison with the normalized results for unpleasantness on the psychophysical scaling tasks (see next section), we rescaled the FMS to describe the temporal development of unpleasantness to range from 0 “no sickness” to 1 “frank sickness”, which we refer to as FMS’.

Relationship between unpleasantness and symptomatology

Data collection

In the second part, we assessed the relationship between unpleasantness and symptomatology. This part was performed in Exp 6 and 7, in which participants performed a psychophysical scaling task before and/or after the last provocative session of the experiment.

In Exp 6, participants judged the level of unpleasantness associated with each MISC class using magnitude estimations (MAG) as originally used for the ratio scaling of psychophysical stimuli, such as the brightness of light (Stevens 1956) or social phenomena (Kuennapas and Wikstroem 1963, Lodge 1981, Venrooij et al. 2015). We here asked participants to draw lines whose lengths represented the level of unpleasantness they associated with each MISC class description (1 to 10). We only provided the descriptions, without referring to the numerical values corresponding to the classes. We provided two A4 papers in landscape orientation, with a horizontal 10.5 cm reference line at the top of each page. This line represented the unpleasantness for MISC 6, whose description was printed below the line. In addition, four or five other descriptions were printed below, which we asked participants to judge by drawing a line. We explained participants that drawing a line twice the length of the reference line, would imply twice the amount of unpleasantness as compared to the reference symptom (i.e., feeling a little nauseated). Lines could be of any length, if needed consisting of multiple line segments. The class descriptions were randomized in four different orders. We let participants perform this task both before the first session and after the last, to investigate whether exposure to a provocative motion affected the judgements.

In Exp 7, we investigated whether the choice of reference class affected the judgements. We therefore repeated the MAG task of Exp 6 using class description MISC 4 instead of MISC 6 as the reference. In addition, we investigated whether the type of psychophysical task affected the judgements by letting participants perform a two-alternative forced choice (2AFC) task (Thurstone 1927). In this 2AFC task, we presented participants two MISC class descriptions and asked them "which of these two symptoms do you consider most unpleasant?". Ignoring the order of the two descriptions within each comparison, this resulted in 45 comparisons that were presented in a random order using a computer. Both the MAG and the 2AFC task were performed once, either before the first session, or after the last. The order of tasks was counterbalanced between participants.

In Exp 6—7, we asked participants to rate their experienced unpleasantness directly after a session on a visual analogue scale (VAS). Whilst the MAG and 2AFC tasks asked participants to imagine how they would feel when experiencing the symptoms described, and were thus made independent of a motion stimulus, the VAS rating allowed for a direct comparison of the experienced unpleasantness and the highest MISC rating given during that session. The VAS consisted of a 12 cm line segment with endpoints "very unpleasant" and "very pleasant". Participants marked their judgement on this line and also indicated the main reason of their experienced unpleasantness, by choosing one of the following categories: motion sickness, physical stress, temperature, smell, sound, boredom, other, and not applicable.

Data analysis

To equalize the scale range between participants and allow for an optimally balanced comparison of the three tasks, we normalized all psychophysical ratings. For the MAG task, we first measured the drawn line length (L) for each question with a ruler. We then determined the normalized MAG ratings for each participant using their shortest and longest drawn line, giving MAG = $(L - L_{min})$ / $(L_{max} - L_{min})$. We add subscripts 6 and 4 to refer to the reference used: MAG6 for the task using MISC 6 (n = 30) and MAG4 for the task using MISC 4 (n = 79). For the 2AFC task (n = 83), we first counted the number of times (C) a participant chose a MISC class as the most unpleasant. We then determined the normalized 2AFC ratings for each participant using the counts of the classes they had rated least and most unpleasant, giving 2AFC = $(C - C_{min})$ / $(C_{max} - C_{min})$. For the VAS task (n = 107), we first measured the distance up to the mark that each participant had drawn (V). We then determined the normalized VAS rating for each participant by dividing this distance by the total line length, giving VAS = $V/12$.

Five participants in Exp 6 and six participants in Exp 7 did not perform all rating tasks. There were two participants who misinterpreted the MAG4 task and reversed the sign for their line drawings (i.e., MISC 1 or 2 receiving 1 and MISC 9 or 10 receiving 0). They performed as expected in their 2AFC ratings. For these participants, we replaced the MAG4 ratings by 1 − MAG4. Due to an administrative error, two participants performed the 2AFC task twice. We averaged their responses in the data analysis.

Our null hypothesis is a monotonic increase in unpleasantness with increasing symptom progression. To test for possible reductions in unpleasantness with increasing symptom progression, we compared the MAG and 2AFC ratings for all pairs of successive MISC classes using one-sided Wilcoxon Signed Rank tests with Bonferroni correction (α = 0.0056). For the VAS ratings, we followed the same procedure but with one-sided Mann Whitney U tests instead (α = 0.0063). For significant effects, we used r to express the effect size (Tomczak and Tomczak 2014).

Regarding the visual presentation of data, error bars are generally plotted in the direction of the axes. Because some data allowed for a within-participant comparison of ratings (Figures 2.2a and 2.4a below), we used the opportunity to determine the interquartile ranges in directions that take the within-participant characteristics into account: along the identity line and perpendicular to that. The rotation applied to this data resulted in the displacement of some medians due to an asymmetric distribution of data points (see Supplementary Figure S2.1).

Results

Temporal development of unpleasantness and symptomatology

To investigate the temporal development of unpleasantness and symptomatology, we analyzed consecutive ratings collected on respectively the FMS’ and MISC scale during ongoing motion stimulation in Exp 1–7. Note that the number and distribution of decreasing rating transitions tells whether unpleasantness and symptomatology increase monotonically with the progression of motion sickness over time. Figure 2.1 shows the distribution of transitions for the FMS’ and MISC.

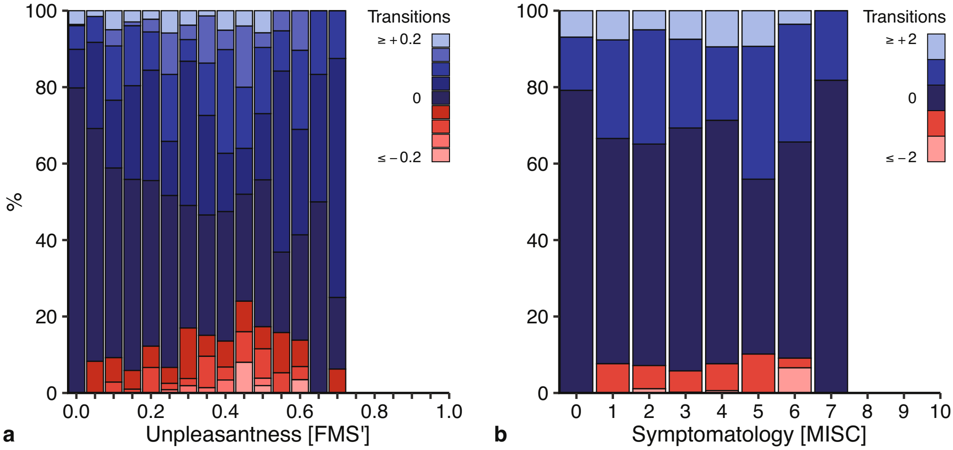


Figure 2.1 Overview of the transitions in consecutive ratings during ongoing motion stimulation. Colors indicate whether the transitions are consistent with a monotonic increase (blueish) or not (reddish). Sessions were generally terminated once participants reached an FMS′ of 0.75 or MISC 7. **a.** Unpleasantness ratings using the FMS′. **b.** Symptomatology ratings using the MISC. Contrary to the FMS′ is there no clear peak indicating non-monotonic behavior.

Whereas decreases accounted for only 4% of all transitions for the MISC, this proportion was doubled (8%) for the FMS′. In addition, where the decreases were distributed evenly over all classes of the MISC (for MISC 1 to 6 between 6-10%), the FMS′ decreases peaked (24%) in the central area of the unpleasantness scale. Moreover, in 45% of all sessions rated using the FMS′, one or multiple decreases occurred, which only applied to 25% of all sessions rated using the MISC. The number of transitions in consecutive ratings for both types of scales is presented in Supplementary Figure S2.2.

These results show that decreases in unpleasantness ratings occur more frequently, and are moreover linked to the center of the scale, compared to the decreases in symptomatology ratings. This suggests that participants temporarily feel better during motion sickness progression, which is an indication of a non-monotonic dependence of unpleasantness on symptom progression.

Relationship between unpleasantness and symptomatology

We collected information on how unpleasantness corresponds with each of the MISC classes using three psychophysical scaling tasks. In Exp 6, participants performed the MAG task using MISC 6 as a reference (MAG6) both before and after a provocative session. The results show that the experience of motion sickness did not affect the judgements (Figure 2.2a). The ratings for most classes are well reproducible, with MISC 4, 5, and 8 showing the largest variability between measurements. Given that all perpendicular error bars overlap the identity line, we pooled the pre-test and post-test ratings in further analyses. Our main observation is that unpleasantness generally increased with symptom progression, with a noticeable exception for the rating on MISC 6, at the onset of nausea (Figure 2.2b). The only comparison where the

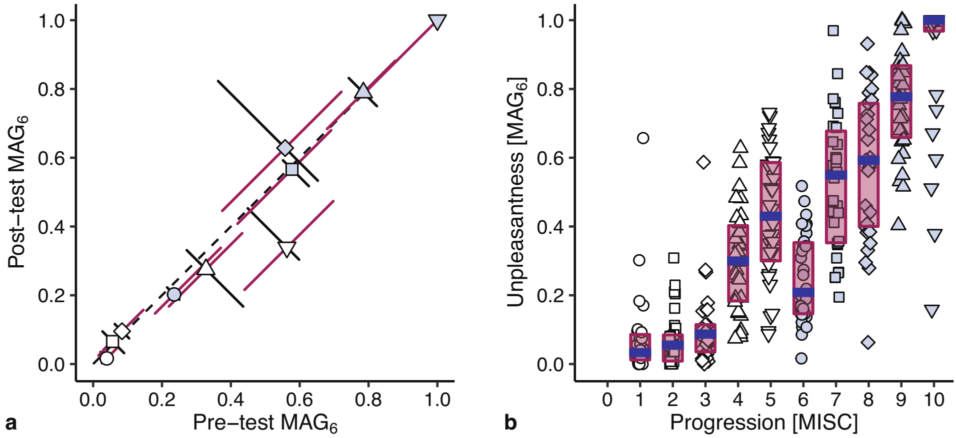


Figure 2.2 The unpleasantness of the various MISC classes rated using magnitude estimation with MISC 6 as a reference (MAG6). **a.** Comparison of median ratings given before and after the last exposure to a provocative motion. The symbols correspond to MISC classes (see panel b). The error bars indicate interquartile ranges. They express the between- participant variability in pre-test/post-test difference (black error bars) and in overall ratings (magenta error bars). **b.** Individual MAG6 ratings (symbols), medians (in blue), and interquartile ranges (magenta bars) of the corresponding unpleasantness of 10 MISC class descriptions. Horizontal jitter is added to the individual ratings for distinguishability.

unpleasantness was lower on a successive MISC class, was for MISC 6 compared to MISC 5 ($\alpha = 0.0056$, $p < .001$; $r = -0.61$).

To investigate whether the reduction at MISC 6 was not just a reflection of the choice of reference, we let participants perform the MAG task with MISC 4 (MAG4) as the reference in Exp 7. The results show that the ratings do not depend strongly on the reference used (Figure 2.3a). Although MAG4 ratings were slightly larger than MAG6 ratings, the error bars for all MISC classes overlap the identity line. Most importantly, Figure 2.3b shows the same exception of the increase in unpleasantness at MISC 6. The tests indeed showed that the unpleasantness at MISC 6 was significantly reduced compared to that on MISC 5 ($\alpha = 0.0056$, $p < .001$; $r = -0.38$).

We then wanted to confirm that the obtained results were not restricted to the used rating technique, for which participants performed the 2AFC task in Exp 7 as well. The normalized 2AFC ratings were slightly larger in unpleasantness than the MAG4 ratings (Figure 2.4a), but as all perpendicular error bars overlap the identity line, we consider the ratings of these two tasks equivalents. This is substantiated in Figure 2.4b, which again demonstrates an exception of the increase in unpleasantness at MISC 6. This reduction in unpleasantness at the transition from MISC 5 to MISC 6 tested significant ($\alpha = 0.0056$, $p < .001$; $r = -0.56$). In contrast to the data in Figures 2.2b and 2.3b, the statistical analysis of the data in Figure 2.4b showed a second decrease: although the median of MISC 9 is higher than MISC 8, there was a significant reduction in unpleasantness from MISC 8 to MISC 9 ($\alpha = 0.0056$, $p = 0.0053$; $r = -0.22$).

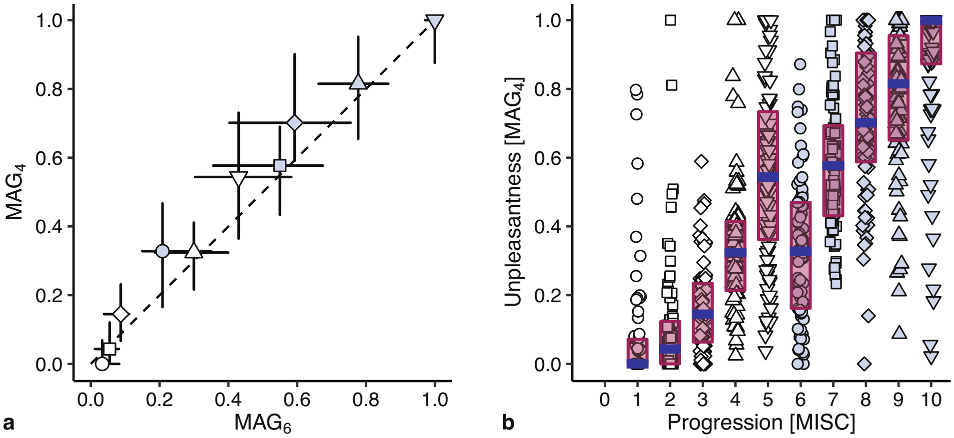


Figure 2.3 The unpleasantness of the various MISC classes rated using magnitude estimation with MISC 4 as a reference (MAG4). **a.** Comparison of median ratings across participants with those rating MAG6 in the first experiment. Horizontal error bars represent interquartile ranges for MAG6 and vertical error bars interquartile ranges for MAG4. **b.** Individual MAG4 ratings, medians, and interquartile ranges. Further details as in Figure 2.2.

In contrast with the MAG and 2AFC tasks, our last comparison with the VAS ratings in Exp 6–7 on the experienced unpleasantness during a session allowed for a direct comparison with the symptomatology rated during that session. When all normalized VAS ratings obtained after sessions are plotted against their highest reported MISC ratings within sessions (Figure 2.5), we observe a pattern of results that is very similar to those in Figures 2.2b–2.4b. However, this apparent reduction of unpleasantness at MISC 6 was not significant ($\alpha = 0.0063$, $p = 0.0514$). We established that motion sickness was generally causing the experienced unpleasantness (Supplementary Figure S2.3).

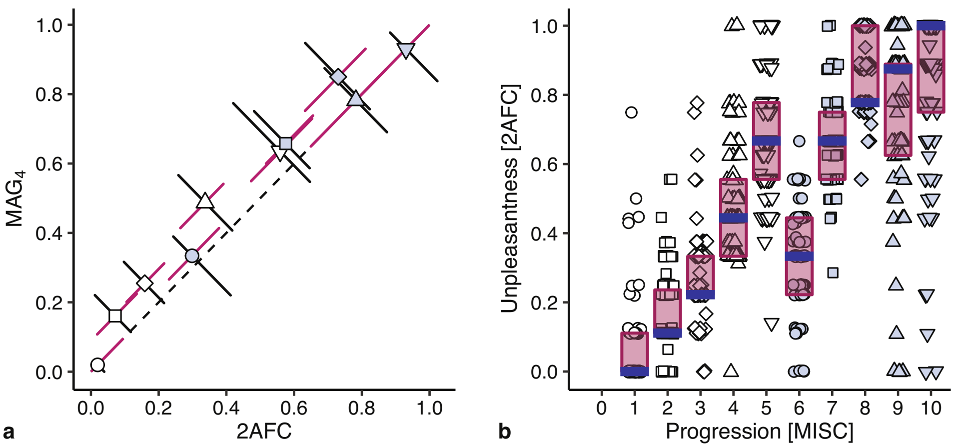


Figure 2.4 The unpleasantness of the various MISC classes rated using a 2-alternative forced choice task (2AFC). **a.** Comparison of median within-participant MAG4 and 2AFC ratings. **b.** Individual 2AFC ratings, medians, and interquartile ranges. Further details as in Figure 2.2.

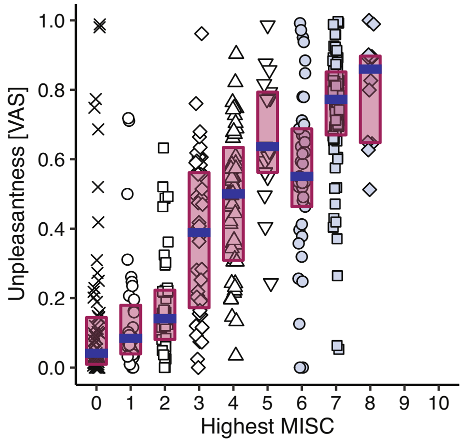


Figure 2.5 The relationship between the reported unpleasantness experienced during a provocative session and the highest rated MISC class during that session. Further details as in Figure 2.2b.

Discussion

To facilitate research on mitigating motion sickness, we here compared two major categories of rating scales: those measuring either general unpleasantness or specific symptomatology. We found that during ongoing stimulation, symptoms manifested in a fixed order, while unpleasantness appeared to increase non-monotonically (Figure 2.1). Using psychophysical scaling techniques, we then showed that although symptoms manifesting later were generally judged as more unpleasant, there was an exception at the onset of nausea. At this point, participants systematically indicated that little nausea corresponded to feeling better compared to any severe pre-nausea symptom. We found that this reduction in unpleasantness was independent of a recent episode of motion sickness (Figure 2.2), the choice of reference in magnitude estimations (Figure 2.3), the type of rating task (Figure 2.4), and was present on visual inspection when considering the experienced unpleasantness within a provocative session (Figure 2.5).

A limitation of our data is that the unpleasantness ratings shown in Figures 2.2–2.4 were not obtained during exposure to a provocative motion, and thus reflect estimates of unpleasantness based on personal histories. Given that the formulation of the symptoms in the MISC scale at MISC 5 (various severe symptoms) might sound less pleasant than the 'little nausea' of MISC 6, such predictions might be biased. Two aspects of our data invalidate this reasoning. Firstly, the ratings obtained after a provocative motion did not differ from those obtained before: MISC 6 was judged less unpleasant than MISC 5 (grey disc to the left and below the downward pointing triangle in Figure 2.2a). Secondly, we observed a similar reduction of unpleasantness at MISC 6 in an experiment where we directly compared motion induced unpleasantness and symptomatology (Figure 2.5). The reduction in this comparison is slightly smaller than that in Figures 2.2–2.4, which is presumably due to the fact that participants judged the unpleasantness of the whole session in Figure 2.5, rather than that of the highest MISC value they rated (which we used as the independent variable). Therefore, those reaching MISC 6 likely having suffered from the symptoms associated with MISC 5 too.

The anomaly in the otherwise monotonic relationship between unpleasantness and symptom progression concerns MISC classes 5 and 6. Looking at Figure 2.1b, these classes also show the largest relative number of decreases, which might raise the question whether the order of MISC classes is appropriate. We believe it is, as over 80% of the rating transitions for these classes were still those of no change or an increment of 1 class. Furthermore, the number of decreases is in the same order of magnitude as those of other MISC classes, suggesting that these decreases are due to inaccuracies in the reports. Hence, it makes most sense to conclude that we do not consistently feel worse as symptoms progress, which answers the main question we explored in this paper. Our study located this specific decrease in unpleasantness at the onset of nausea. Yet, we would like to stress that we replicated the general increase of unpleasantness with symptom progression (Bos et al. 2005, D'Amour et al. 2017, Keshavarz and Hecht 2011, Nooij et al. 2017b, Reason and Graybiel 1970). Our findings fit well in the context of an earlier study reporting a general increase in unpleasantness during ongoing stimulation, but with temporary decreases in those ratings (Reason and Graybiel 1970). Those decreases mainly occurred in the central range of the unpleasantness scale, in alignment with our own observations in which unpleasantness decreased midway the progression of motion sickness symptoms. Also our observation that several participants judged the unpleasantness of MISC 10 as less than other classes, is in line with the reports of decreasing unpleasantness after vomiting (Lackner 2014, Dobie 2019, Leung and Hon 2019). Further validation of this latter issue is impeded by the fact that our experimental sessions generally stopped at MISC 7 (i.e., before vomiting) or FMS 15.

Despite our observation that unpleasantness and symptomatology ratings go hand in hand, the anomaly at the onset of nausea shows that they are two different constructs in the quantification of motion sickness. The question now remains how to explain the observed unpleasantness reduction at nausea onset. We believe that the simplest explanation concerns a cessation of previous symptoms with the introduction of a new class of symptoms. From personal histories, it then makes sense that feeling a little nauseated is less bad than suffering from severe headaches or dizziness, as these latter symptoms more severely impact daily functioning. However, we cannot substantiate this idea because the MISC is not informative on the cessation of individual classes of symptoms nor has such information been reported in the literature.

Our results indicate that there is a risk associated with a rating of unpleasantness when wanting to prevent from vomiting during a provocative exposure. Participants will report to suddenly feel better when progressing from MISC 5 to 6, suggesting that their distance to the point of vomiting increases, whereas they are actually getting closer to that point. We therefore consider a rating of symptomatology more relevant when it is important to prevent individuals from reaching the point of vomiting. For example, in fully automated car driving, automated processes could for instance adjust the driving style of the self-driving car from sporty to relaxed when an occupant indicates to feel slightly nauseated. On the other hand, a rating of unpleasantness is still more useful when testing the attractiveness of a commercial device, for example of a game played in virtual reality. In any case, we want to caution for a comparison of studies that have employed the two different types of rating scales, as we believe that they cannot one-to-one be compared in terms of motion sickness progression level. After all, we here demonstrated that rating how bad someone feels is not the equivalent of rating how close someone is to the point of vomiting.

To conclude, the non-monotonic dependence of unpleasantness on symptom progression implies that each class of symptoms can be associated with a single unpleasantness rating, while unpleasantness ratings in the center of the scale are associated with multiple classes of symptoms. This effectively means one can predict unpleasantness from symptomatology, while one cannot unambiguously determine symptomatology from measurements of unpleasantness. In Table 2.2, we present the predicted feelings of unpleasantness corresponding with each class of MISC symptoms, which we have determined by averaging the obtained within-participant MAG and 2AFC data. To come to our overall conclusion, we believe that our results favor a rating of symptomatology when prioritizing an unambiguous quantification of motion sickness progression.

MISC	**Unpleasantness (median)**	**95% CI**
1	0.02	0.00, 0.04
2	0.11	0.08, 0.11
3	0.19	0.16, 0.21
4	0.39	0.36, 0.42
5	0.58	0.54, 0.61
6	0.31	0.29, 0.33
7	0.60	0.58, 0.63
8	0.76	0.72, 0.80
9	0.77	0.75, 0.82
10	0.94	0.89, 0.98

Table 2.2 Conversion table of the predicted median unpleasantness scores from MISC classes denoting symptom progression (n = 109). 95% confidence intervals (CI) are calculated using bias-corrected and accelerated bootstrapping (N = 2500).

SUPPLEMENTARY INFORMATION

Experimental details

Table S2.1 Details of the seven experiments which data was (re-)analyzed in this paper.

Exp	Reference	Motion stimulus	n	# sessions	Duration (min)
1	Nooij et al., 2017b	Visual yaw rotation	18	4	20
2	Nooij et al., 2017a	Visual yaw rotation	21	2	20
3	Nooij et al., 2021	Visual yaw rotation	19	1	20
4	Bos et al., 2005	Physical simulated ship motion	24	3	30
5	Bos, 2015	Physical off-vertical axis rotation	18	4	20
6	–	Physical vertical oscillations	30	3	20
7	–	Physical horizontal oscillations	84	3	20

The effect of coordinate system on location of the median

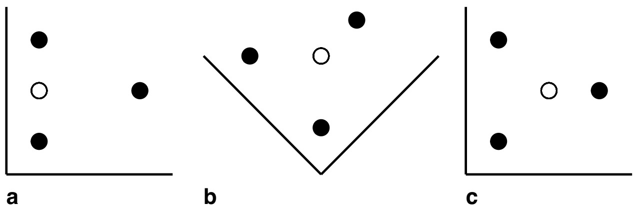


Figure S2.1 Example of the displacement of medians after rotation of data points. **a.** Three data points (filled) with their median (open). **b.** The same three data points after 45° degree rotation with their median. **c.** Panel b after −45° rotation: the data points are at the same position as in panel a, but the median is at a different position.

Overview of all observed transitions between consecutive ratings

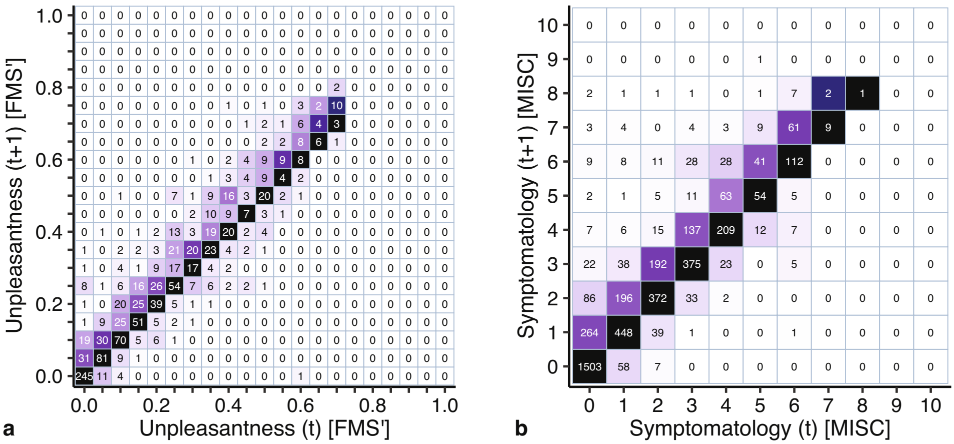


Figure S2.2 Data underlying Figure 2.1 of the main text. Overview of transitions between ratings taken at consecutive (t versus t+1) time points during ongoing stimulation. **a.** FMS' ratings on unpleasantness. **b.** MISC ratings on symptomatology. Diagonal cells contain the number of unchanging ratings. The shading of other cells represents the fraction of the off-diagonal transitions in that column.

Reported causes of unpleasantness

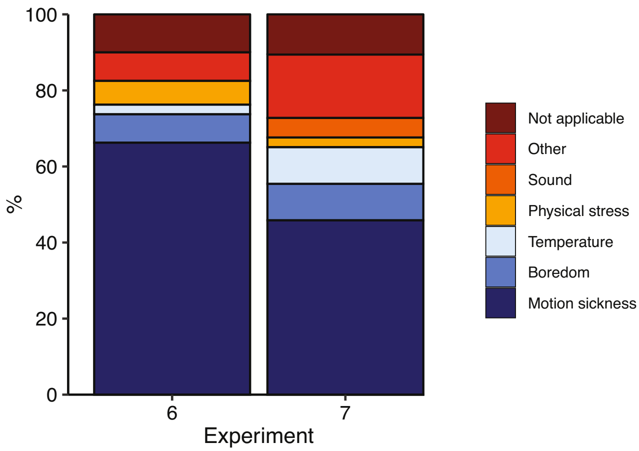
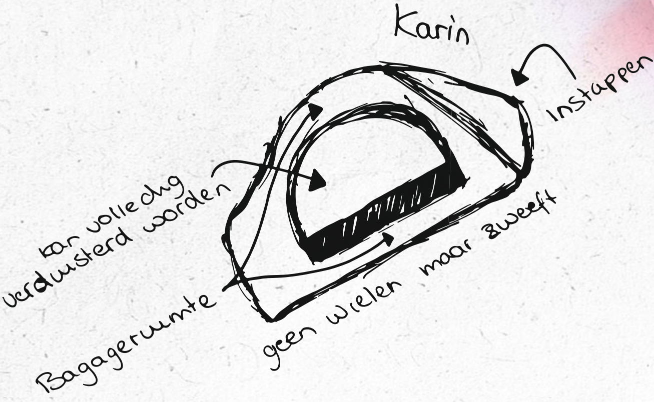


Figure S2.3 Main factor contributing to the experienced unpleasantness in response to a provocative motion.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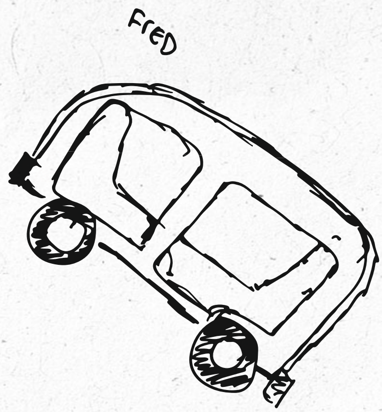
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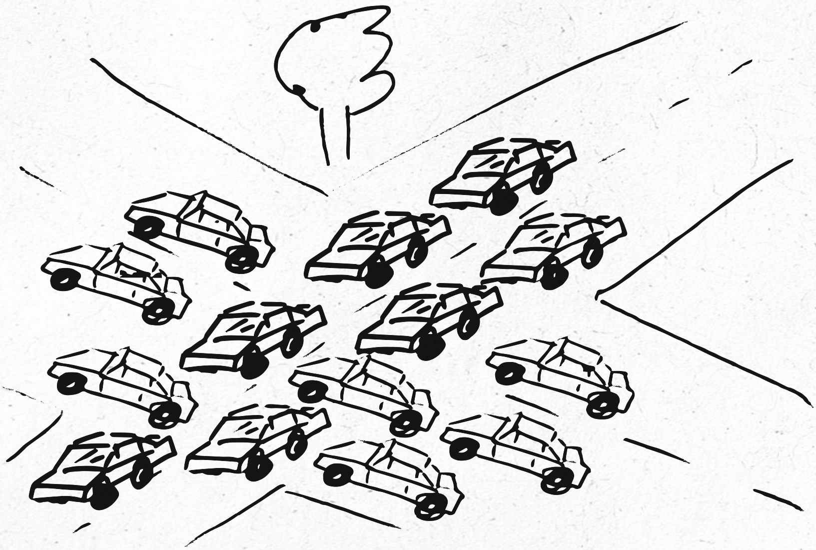

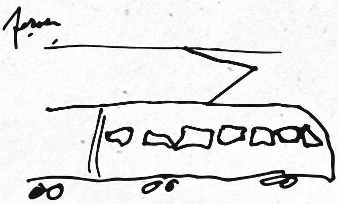

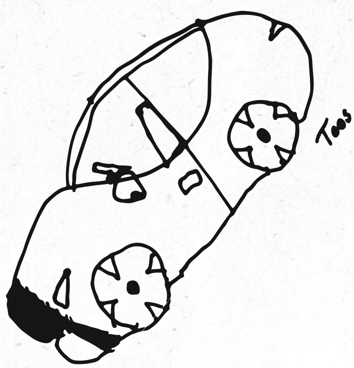
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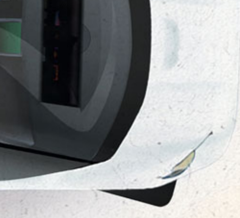
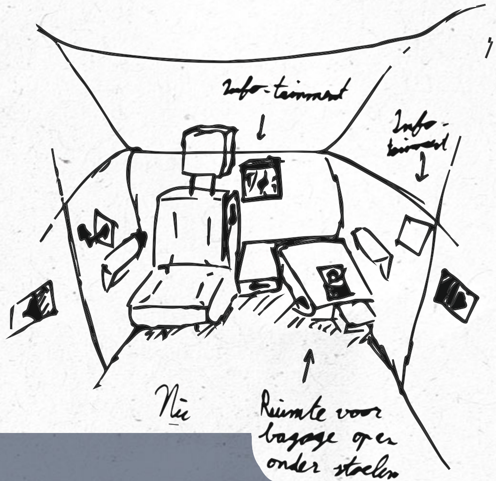


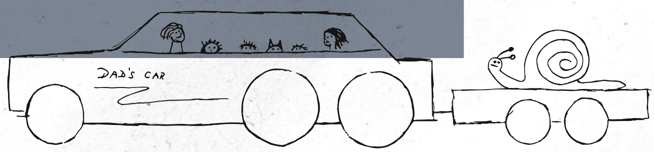


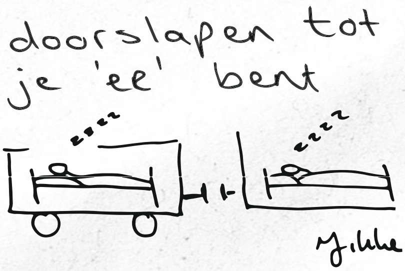
CHAPTER 3

Self-motion perception without sensory motion

Adapted from
Anna JC Reuten, Jeroen BJ Smeets,
Marieke H Martens & Jelte E Bos (2022)

Experimental Brain Research 240(10): 2677-2685





Abstract

Various studies have demonstrated a role for cognition on self-motion perception. Those studies all concerned modulations of the perception of a physical or visual motion stimulus. In our study however, we investigated whether cognitive cues could elicit a percept of oscillatory self-motion in the absence of sensory motion. If so, we could use this percept to investigate if the resulting mismatch between estimated self-motion and a lack of corresponding sensory signals is motion sickening. To that end, we seated blindfolded participants on a swing that remained motionless during two sessions, apart from a deliberate perturbation at the start of each session. The sessions only differed regarding instructions, a secondary task and a demonstration, which suggested either a quick halt ("Distraction") or continuing oscillations of the swing ("Focus"). Participants reported that the swing oscillated with larger peak-to-peak displacements and for a longer period of time in the Focus session. That increase was not reflected in the reported motion sickness scores, which did not differ between the two sessions. As the reported motion was rather small, the lack of an effect on the motion sickness response can be explained by assuming a subthreshold neural conflict. Our results support the existence of internal models relevant to sensorimotor processing and the potential of cognitive (behavioral) therapies to alleviate undesirable perceptual issues to some extent. We conclude that oscillatory self-motion can be perceived in the absence of related sensory stimulation, which advocates for the acknowledgement of cognitive cues in studies on self-motion perception.

Introduction

Vestibular and visual signals inform us about our self-motion, for example when moving back and forth on a swing. Our perception of such self-motion is not only based on this sensory input, as cognition has been demonstrated to play a role as well (Ferrè and Harris 2015, Mast and Ellis 2015, Ferrè and Haggard 2020). Specifically, several studies demonstrated that mental imagery (Mertz et al. 2000, Nigmatullina et al. 2015), a priori motion expectations (Ellis et al. 2017), and contextual information (Wertheim et al. 2001, Riecke 2009, D'Amour et al. 2021) modulated self-motion perception of a physical or visual motion stimulus. These studies all concerned experiments with motion stimuli and thus reflect modulations of a percept of self-motion that is elicited by sensory stimulation. Because we are not aware of any study on self-motion perception without a motion stimulus, we performed a study investigating whether cognitive cues can elicit a percept of self-motion in the absence of sensory motion. In specific, we minimized physical (inertial), visual, somatosensory and auditory cues about self-motion.

When modeling sensorimotor control, authors frequently include internal forward models that process an efference copy of motor commands (dark blue boxes in Figure 3.1; Oman, 1982; Popa & Ebner, 2019; Wolpert et al., 1998). The internal model of the bodily dynamics (dark blue box) estimates the bodily motion that would result from the motor commands. This estimation controls our perception of self-motion. Under optimal conditions, it equals the actual self-motion produced by the real body (light blue box). As this prediction lacks the delay and other peculiarities of the sensorimotor system, it is the best input for feedback control of self-motion. To ensure that this estimate is indeed accurate, this signal is fed to the internal model predicting the sensory signals (visual, vestibular, and somatosensory; dark blue). If there is a difference between the resulting integrated estimated and actual sensory signal, their discrepancy will be used to update the internal model and hence the estimated bodily motion. The discrepancy itself is assumed to cause motion sickness (Reason 1978). The updating of the internal model is weighted relative to the noise of the actual sensory systems by a gain K (Oman, 1982; Tanaka et al., 2020, see the 'Kalman' gain K in Figure 3.1). A high uncertainty about those signals is then accounted for by a low gain and, vice versa, a low uncertainty by a high gain. In the current study, we are interested whether not only efference copies but also motion expectations generated by cognitive cues influence the estimated bodily motion. Given that the updating of the internal model is based on a Kalman gain, motion will only be reported when there is a low signal to noise ratio of the senses. If so, cognitive cues could result in the perception of self-motion in the actual absence of motion[1]. If this perceived motion is large enough, its difference from the absent sensory signal could accordingly cause individuals to feel motion sick.

[1] Such an 'illusory' percept of self-motion might remind some readers of vection. For the reason that terminology on self-motion perception – including the definition of vection – is ambiguous (Palmisano et al. 2015, Soave et al. 2021), we decided to use the more neutral term "perception of (oscillatory) self-motion" throughout this text.

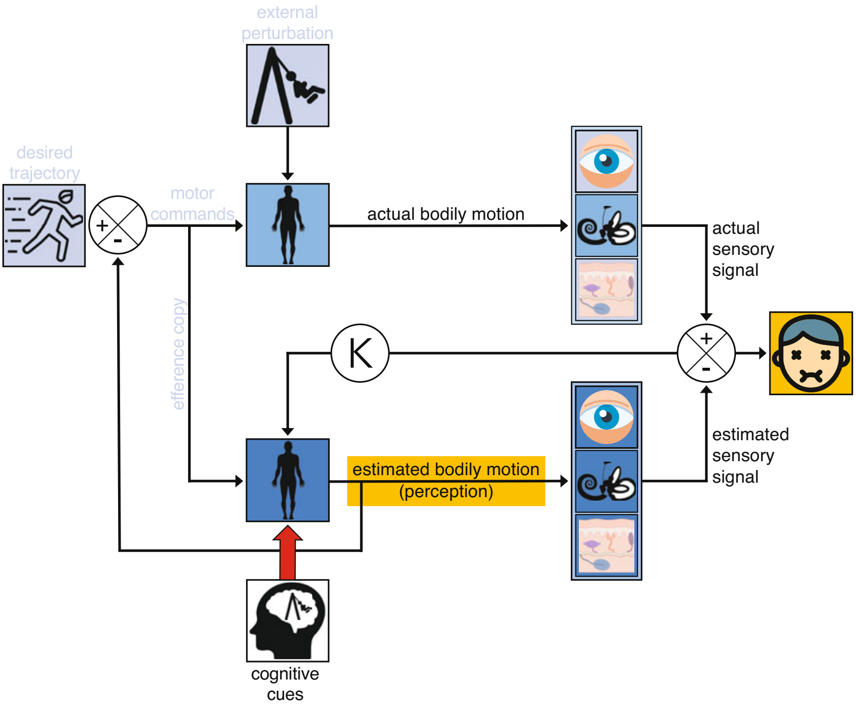


Figure 3.1 Simplified model of sensorimotor control, including the perception of motion and the origin of motion sickness (based on Reason 1978, Oman 1991, Wolpert et al. 1998, Bos et al. 2008, Kuiper 2019). Light blue boxes represent the actual motor and sensory systems; the dark blue boxes represent the internal models of these systems. In our study, we minimized physical (active and passive), visual, somatosensory, and auditory cues about self-motion (in grey). The remaining inputs are cognitive and vestibular cues on (the lack of) motion. Our measures of interest are perceived self-motion and motion sickness (yellow elements).

Our study thus aims to answer the question whether we can indeed induce a systematic percept of self-motion without sensory motion using cognitive cues. If the answer is affirmative, we can answer a second question: does the neural mismatch between this estimated percept of self-motion and a lack of corresponding sensory signals provoke motion sickness? To that end, we seated blindfolded participants on a swing that remained motionless during two sessions, and additionally provided a noise cancelling headphone and airflow to minimize further sensory cues on motion. The only difference between the sessions was a cognitive induced manipulation of expectations regarding the swing's motion. In both sessions, we repeatedly asked participants about their perceived oscillatory self-motion and level of motion sickness (see yellow elements in Figure 3.1).

Methods

We exposed blindfolded participants to two sessions on a parallel swing, between which we differently manipulated expectations regarding the motion of this swing (within-participant design). In reality, we only let the swing move with a transient oscillation at the start of each session. However, in a "*Focus* on motion" session, we aimed at letting participants believe that the swing was moving for the entire session. We therefore told participants before the start of this session that the swing would be oscillating with varying peak-to-peak displacements, and asked them about this motion at regular intervals during the session. We moreover demonstrated to participants that the swing could move back and forth. In a "*Distraction* from motion" session, we aimed at letting participants believe that the swing was only oscillating at the beginning of the session. We therefore told participants before the start of this session that the swing would come to a stop after an initial perturbation, and distracted them from the swing's possible motion by asking motion irrelevant questions about pitch differences of a tune during the session. In summary, the cognitive (non-sensory) cues consisted of 1) instructions about the swing's motion, 2) a discrimination task with different attentional allocation performed during the sessions, and 3) a demonstration of swing motion.

Participants

We recruited 24 participants (16 females) from the Vrije Universiteit Amsterdam in The Netherlands, where the experiment was performed. Participants were allowed to participate if they were 18 years or older, had experienced motion sickness in the last five years, were free of (self-known) vestibular and auditory complaints, were not pregnant, did not suffer from claustrophobia, and never participated in an experiment on our setup before. Our participants were aged between 18 and 24 years. We have obtained ethical approval from the faculty's review board (reference number: VCWE-2020-180R1).

Experimental setup

In both sessions, participants were seated on a parallel swing (Oosterveld, 1970). The swing consisted of a 250x245 cm platform attached to the ceiling with four 6.65 m ropes (Figure 3.2). Given this length, the swing oscillated with a natural frequency of 0.19 Hz when perturbed, close to the peak frequency of motion sickness incidence (ISO 2631-1 1997, Golding et al. 2001).

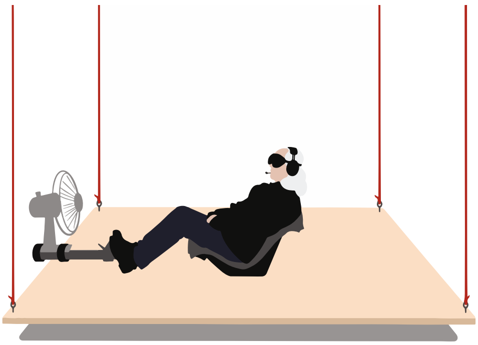


Figure 3.2 Experimental setup. A participant is seated on the swing, wearing blinding goggles and a noise cancelling headphone to remove external motion cues. We used a swiveling fan to mask airflow and a footrest to support a stable seating position.

To support the perception of oscillatory motion in the Focus session, the experimenter unleashed the swing from a 10 cm forward displacement at the beginning of both sessions. This resulted in a transient oscillation returning the swing to a standstill within 1–2 minutes (see Figure 3.3). To check the swing's motion, we recorded its acceleration in the longitudinal direction using the accelerometer of a mobile phone, measuring at 20 Hz using MATLAB Mobile for iOS (version 8.4). We detrended the signal and removed the measurement noise using a bidirectional first order low-pass Butterworth filter with a cutoff frequency of 2 Hz. The resulting root mean square acceleration excluding the first two minutes was 0.003 ± 0.001 m/s^2 (mean ± *SD*) on average in both sessions. This average is considered well below the threshold for motion perception, assumed between 0.1–0.01 m/s^2 (Griffin 1990). Any percept of oscillatory self-motion can thus not be explained by physical motion stimulation. We additionally minimized visual motion cues by blindfolding participants for the entire duration of the session; somatosensory motion cues by airflow generated by a swiveling fan rotating at a frequency of 0.05 Hz, thus uncorrelated to the natural frequency of the swing; and auditory motion cues by a noise cancelling headphone (see also Figure 3.2).

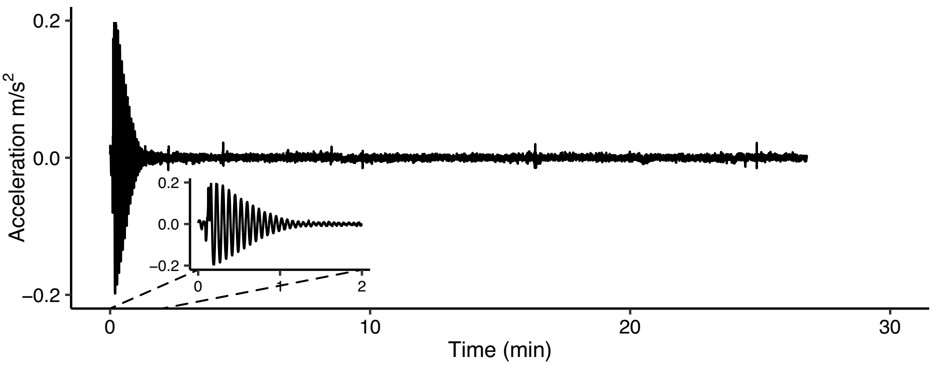


Figure 3.3 The swing's acceleration during a typical condition. The swing was released from an initial forward displacement at the start of the condition, resulting in a transient oscillation reaching standstill within two minutes (see inset). The isolated spikes later in the acceleration trace correspond to small body movements of the participant.

Tasks and measurements

Both conditions contained seven blocks, a break, and a set of three exploratory questions (see Figure 3.4). Each block consisted of a discrimination task that was repeated seven times, followed by a sickness rating using the Motion Illness Symptoms Classification (MISC, Table 3.1, Bos et al., 2005; Reuten et al., 2021) and two additional questions on the perceived swing motion.

In the Focus session, the discrimination task consisted of seven repetitions of 15 s focusing on the swing's motion, each followed by the question whether the swing had moved farther or less far as compared to the previous time asked. After participants completed this task and rated their sickness, we asked them to indicate when the swing reversed direction. This question was added to strengthen the participants' cognitive

Class description		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, yawning, headache, tiredness, sweating, stomach awareness, burping, blurred vision, salivation, … but no nausea	vague	2
	little	3
	rather	4
	severe	5
Nausea	little	6
	rather	7
	severe	8
	retching	9
Vomiting		10

Table 3.1 The Motion Illness Symptoms Classification (MISC) used to assess motion sickness symptomatology (Bos et al. 2005, Reuten et al. 2021).

involvement with the swing's oscillations. After this, we asked them to indicate the peak-to-peak displacement of the swing's motion about that moment (further referred to as 'displacement'). Four participants expressed their doubts on whether the swing was indeed moving. In these cases, the experimenter once used the encouragement "the swing is moving, but the movements may be very small, thus try to pay close attention to them".

In the Distraction session, the discrimination task consisted of seven repetitions of 15 s listening to a music clip (Jerry Martin's "Under Construction"), each followed by the question whether the sample was played higher or lower in pitch as compared to the previous time asked. Pitch height was truly increased or decreased by 4.8 or 9.6% relative to the previous sample (adapted using Audacity 2.4.2.0) aiming to achieve a comparable level of mental workload and task difficulty compared to the task in the

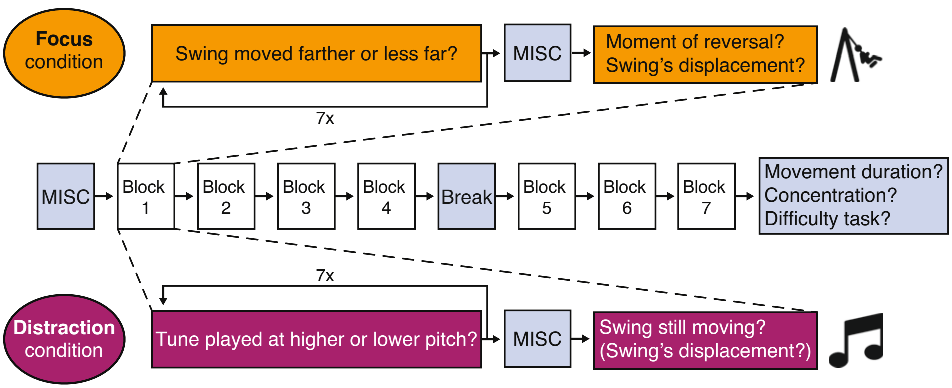


Figure 3.4 Overview of the rating tasks used in the two sessions. Each block had a duration of three to four minutes, the break was two minutes, and the sequence of final questions took three minutes.

Focus session. After completion of the discrimination task and sickness rating, we asked participants to indicate whether they thought the swing was still moving, and if they did, the second question then was which (peak-to-peak) displacement the swing had about that moment.

The blocks succeeded each other without additional manipulation. To offer participants a break from intensely concentrating, we asked them to perform an alternative task between block four and five. They had to list as many words as possible starting with a certain letter of the alphabet within one minute. After participants had completed the seven blocks, we asked them three additional questions whilst still being seated on the swing. The first question was which percentage of time they thought the swing had moved (0% = never moved to 100% = always moved). The second question was on their ability to concentrate on the discrimination task (0 = poor to 10 = good). The last question was on the difficulty of the discrimination task (0 = very easy to 10 = very difficult).

Procedure

After arrival, we instructed participants on the experimental procedure and asked them to sign an informed consent form. Participants filled out the Motion Sickness Susceptibility Questionnaire (MSSQ-Short; Golding, 2006) from which we observed that the sample's susceptibility to motion sickness fell within the 60th percentile. Following completion of the MSSQ-Short, participants performed the two sessions. Because of individual differences in response time and the additional question about the moment the swing reversed direction in the Focus session, the sessions lasted between 25 and 35 minutes. We presented the sessions in counterbalanced order with a 45-minute break in between, to allow for recovery of motion sickness. To minimize an observer-expectancy effect (see Rosenthal, 1963; Rosenthal & Fode, 1963), we provided all instructions via pre-recorded audio files, both before and during the sessions. Although we were interested in the effect of motion expectations on self-motion perception and motion sickness, we told participants that we were interested whether their ability to discriminate small differences in displacement and pitch were related. We introduced the MISC as a measure to monitor their level of well-being as it could influence their task performance. We stopped a session when a participant rated a MISC score of ≥ 6, which occurred once in the Focus session and three times in the Distraction session. After completing the experiment, participants were thanked for their participation and received study credits.

Data analysis

Our primary dependent variables were the displacement and MISC score participants rated at the end of each block in both sessions. Missing data as the result of the exerted MISC stop-criterium were substituted with the last rated displacement and MISC score. To answer our two questions, we averaged the seven displacements and MISC scores given by each participant in the Focus and Distraction session and analyzed the within-participant differences using Wilcoxon Signed Rank tests (with $\alpha = 0.05$). For significant effects, we use r to express the effect size (Tomczak and Tomczak 2014). To explore the data further, we report the averaged within-participant difference between the sessions for various measures, together with the between-participant standard deviation (mean difference ± SD, Focus minus Distraction).

Results

We first investigated the development of displacements and MISC scores reported during the sessions (Figure 3.5). There was a clear and consistent difference in the reported displacements between the Focus and Distraction session (Figure 3.5a), implying that our manipulation on motion expectations was effective. Regarding the MISC scores, we did observe an increase in motion sickness as the sessions continued. However, this increase in sickness was very limited: the average maximum MISC score corresponded to some discomfort without symptoms. Most importantly, there was no difference in sickness level between the sessions (Figure 3.5b). We present the temporal response traces per participant in Supplementary Figure S3.1. 3

Because we were mainly interested in a comparison within participants, we averaged the displacements and MISC scores within sessions across the seven blocks and plotted the resulting values per participant in Figure 3.6. We observed a systematic difference in the percepts between the sessions: all participants (except one) reported a larger average displacement in the Focus compared to Distraction session (Figure 3.6a). On average, the difference was 23.6 ± 17.7 cm, which was significant ($W = 1$, $p < .001$, $r = -0.87$). In contrast, the MISC scores were very similar between the two sessions (average difference −0.1 ± 1.7; $W = 92.5$, $p = 0.936$; Figure 3.6b), without any apparent effect of session order. We explored whether there was a correlation between displacement and MISC score independent of session, but observed no such evidence (see Supplementary Figure S3.2a).

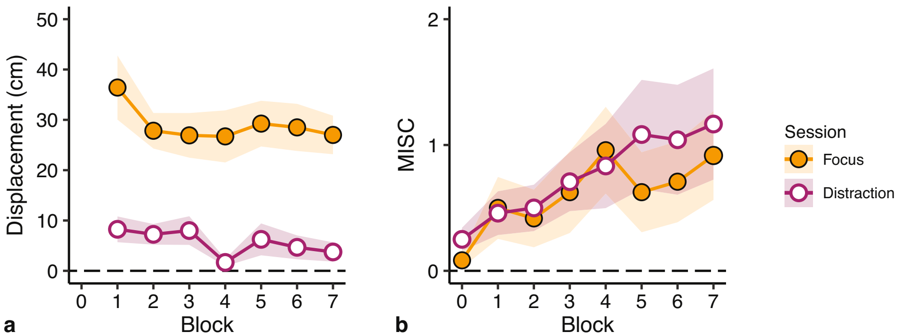


Figure 3.5 The temporal development of **a.** displacements and **b.** MISC scores in the Focus and Distraction session. Each symbol represents the average across participants, with shaded areas representing the standard errors of the mean.

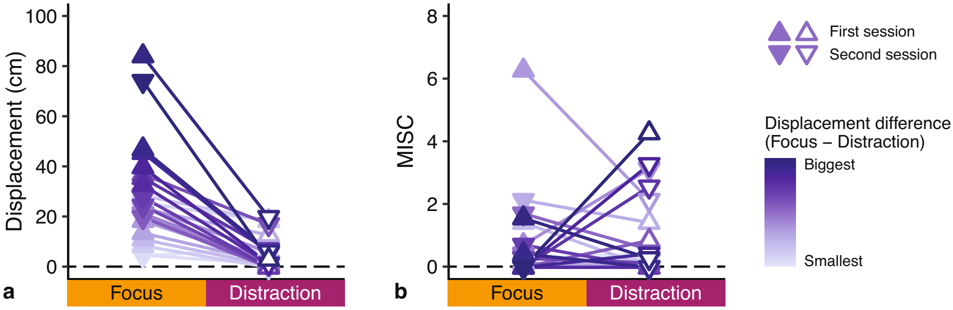


Figure 3.6 The **a.** displacements and **b.** MISC scores reported in the two sessions. Each symbol represents the average value of an individual participant in that session. We used a gradient to contrast the participant with the biggest displacement difference between sessions (in dark purple) to the participant with the smallest displacement difference (in light purple). To visualize a possible effect of session order, we used different symbols indicating the order of sessions for each participant.

At the end of each session, we asked participants to indicate which percentage of time they thought the swing had moved (Figure 3.7a). The majority of participants indicated that the swing moved longer in the Focus compared to Distraction session, with a mean difference of 27 ± 35%. Evidently, many reacted with surprise upon hearing that the swing had only moved at the beginning of both sessions. We also explored whether there was a correlation between motion duration and MISC score, but again observed no evidence (see Supplementary Figure S3.2b). We additionally asked participants to report their ability to concentrate on the discrimination task and to indicate how difficult they thought this task was. Most of them indicated that they were well able to concentrate on both tasks (mean difference −0.2 ± 2.0; Figure 3.7b). The responses for task difficulty were more variable across participants, but similar in the two sessions (mean difference 1.4 ± 2.7; Figure 3.7c). On average, 65 ± 18% of the given answers for the pitch discrimination task in the Distraction session were correct. For the motion

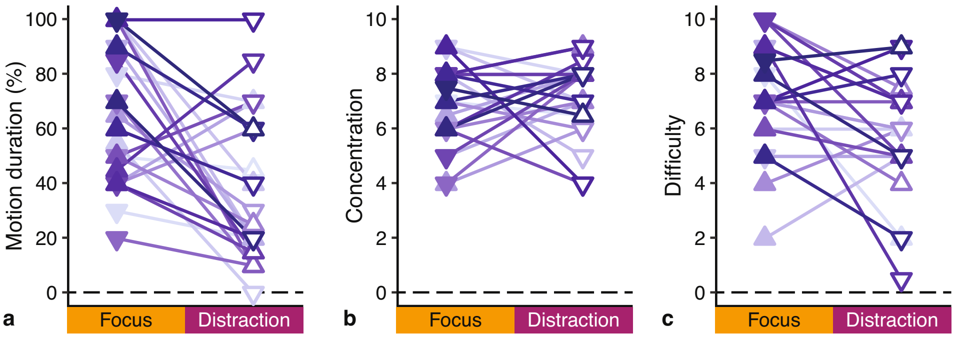


Figure 3.7 Responses to the questions asked at the end of each session. **a.** The reported motion duration of the swing (0% = never moved to 100% = always moved). **b.** The reported ability to concentrate (0 = poor to 10 = good) on the discrimination tasks performed during the sessions. **c.** The reported difficulty (0 = very easy to 10 = very difficult) of these discrimination tasks. Details as in Figure 3.6.

discrimination task in the Focus session, participants also responded close to chance: they reported that the swing was moving with a larger displacement in 44% of the time, and with a smaller displacement in 56% of the time. These numbers indicate that we succeeded in designing tasks that were comparable in difficulty.

Discussion

In this study, we first investigated whether cognitive cues manipulating motion expectations could elicit a percept of oscillatory self-motion in the absence of sensory motion. If so, we could use this percept to investigate if the resulting mismatch between estimated self-motion and a lack of corresponding sensory signals is motion sickening. To that end, we seated blindfolded participants on a swing that remained motionless during two sessions, apart from a deliberate perturbation at the start of each session. The two sessions only differed regarding cognitive cues suggesting either a quick halt ("Distraction") or continuing oscillations of the swing ("Focus"). This manipulation let participants perceive that the swing oscillated with larger peak-to-peak displacements and for a longer period of time in the Focus session. As the size of the perceived displacement was rather limited, the reported levels of motion sickness were low, with no observable difference between the two sessions.

Our interpretation of the experimental results is that participants can perceive oscillatory self-motion in the absence of sensory stimulation related to motion. Of course, the participants sensed a transient oscillation for the first 1—2 minutes in both sessions. As this motion had stopped well before the end of the first block, all reports on the perception of motion were made without sensory motion. Though participants shifting position caused some acceleration (see Figure 3.3), the reported displacements were consistent across the whole session and should thus be considered independent of these distortions. A limitation of this study is that the perceived motion was of a displacement too small to elicit motion sickness. The average reported displacement in the Focus session was 29 cm; estimated to result in a sickness incidence of only 1% when assuming a physical motion stimulus of 30 minutes (ISO 2631-1 1997)[2]. This prevents us from answering our second question of interest. It might be worthwhile to explore whether our paradigm could yield the perception of larger displacements by changing some aspects of the experiment.

One aspect that may have limited the reported displacements is the positioning of the experimenter's desk one meter in front of the swing. Participants might have assumed in their responses that the swing would remain at a safe distance from the desk. After all, Wertheim et al. (2001) demonstrated that a priori knowledge on motion direction had likely guided participants' responses in other studies. Follow-up studies should be aware

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[2] Neglecting the fact that ISO 2631-1 (1997) only calculates the percentage of people who may vomit due to vertical motion, this percentage is given by $^1/_3 a_w \sqrt{T}$ with a_w the frequency weighted RMS acceleration, and T the exposure duration in seconds. For a sinusoidal displacement over 29 cm at a frequency of ~0.2 Hz, the RMS acceleration is 0.103 m/s^2, the read frequency weighting $w_f = 0.992$ and $a_w = 0.992 * 0.103 = 0.102$ m/s^2. This leads to a percentage of $^1/_3 * 0.102 * \sqrt{1800} = 1.4\%$.

of this possible consequence and may expose participants to the experimental setup only when blindfolded.

One might be concerned that the reports of swing motion reflect our instructions, instead of reflecting a true belief that the swing was moving. Some parts of the communication with participants contradict this claim. For instance, four participants openly expressed their doubts about whether the swing was really moving. We probed them to pay close attention to the possibly very small oscillations, after which three participants reported a 1– or 2–cm displacement, and the fourth 10 cm. These reported displacements reflecting the instructions were much smaller than the average displacement of 29 cm reported in the Focus session. Moreover, when also considering the surprised reaction of other participants upon receiving the debriefing information, we deem it unlikely for an observer-expectancy effect to explain the observed difference in reported displacement between the Focus and Distraction session.

It may seem surprising that participants perceived some oscillatory self-motion in the Distraction session as well. There are some aspects in the design of our experiment that might have caused this percept. First of all, we instructed participants that the swing would oscillate at the beginning of the session, and asked them when they thought the swing stopped moving. Second, participants experienced that the swing could oscillate as the platform moved when getting seated. Third, the frequency of respiration in rest may come close to the natural frequency of the swing, which might generate a sense of motion in a state of introspection. Lastly, sensory signals are noisy, and could incorrectly register some sense of self-motion.

The reported level of motion sickness developed equally in both sessions until block four (Figure 3.5b), after which the average MISC score steadily increased in the Distraction session whilst it temporarily decreased in the Focus session. After this brief reduction, the motion sickness scores regained their initial increase. This temporary drop might be related to the break provided between blocks four and five, although it is unclear why it is then only affecting motion sickness in the Focus session.

Despite all participants (except one) reporting larger displacements in the Focus as compared to Distraction session, there were rather large between-participant differences in the size of the reported displacements (Figure 3.6a). In fact, mean differences were ranging from −2 to +71 cm (Focus minus Distraction). We wanted to demonstrate that our analysis was not driven by a few extreme responses, yet we observed that none of the percepts met the common outlier criterion of three times the standard deviation. The large differences might reflect underlying trait variations in phenomenological control, which is the ability to construct an experience that meets certain expectancies (Dienes et al. 2022).

An analogy to the observed percepts of self-motion may be given by tinnitus, the perception of sound in the absence of an acoustic stimulus. Apart from a sensory defect, its occurrence can also be explained by neural structures generating the sound. This latter explanation has gained recognition and already resulted in the development of cognitive behavioral therapies (Langguth et al., 2013). Our results may point in the same direction when considering diseases like mal de débarquement syndrome (Mucci et al.

2018) or persistent postural-perceptual dizziness (Dieterich and Staab 2017), where patients report persistent motion sensations or dizziness in the absence of related sensory input.

Although our participants experienced similar levels of motion sickness in the two sessions, the reported percepts of oscillatory self-motion show some support for the existence of internal models. They may explain the effectiveness of anticipatory cues that communicate upcoming vehicle motion in reducing motion sickness (e.g., Diels et al., 2021; Feenstra et al., 2011; Hainich et al., 2021; Kuiper et al., 2020a). Such cues allow for a more accurate prediction of self-motion, thereby minimizing a (potential) neural conflict and hence the development of motion sickness.

Different from previous studies which showed that cognition can modulate the perception of self-motion elicited by sensory stimulation, we here demonstrated that cognitive cues can induce percepts of oscillatory self-motion in the absence of sensory motion. We argue that the strong influence of cognitive cues on self-motion perception may be explained by internal models of the motor and sensory systems within our central nervous system that provide predictions of self-motion and sensory signals. This finding supports the assumption that undesirable perceptual issues can be somewhat alleviated by cognitive (behavioral) therapy. In any case, our results show that studies on self-motion perception require a detailed description of experimental details such as task instruction, attentional allocation and distraction, and demonstration of motion stimuli that might involve cognitive cues.

SUPPLEMENTARY INFORMATION

Development of displacement and MISC scores per participant

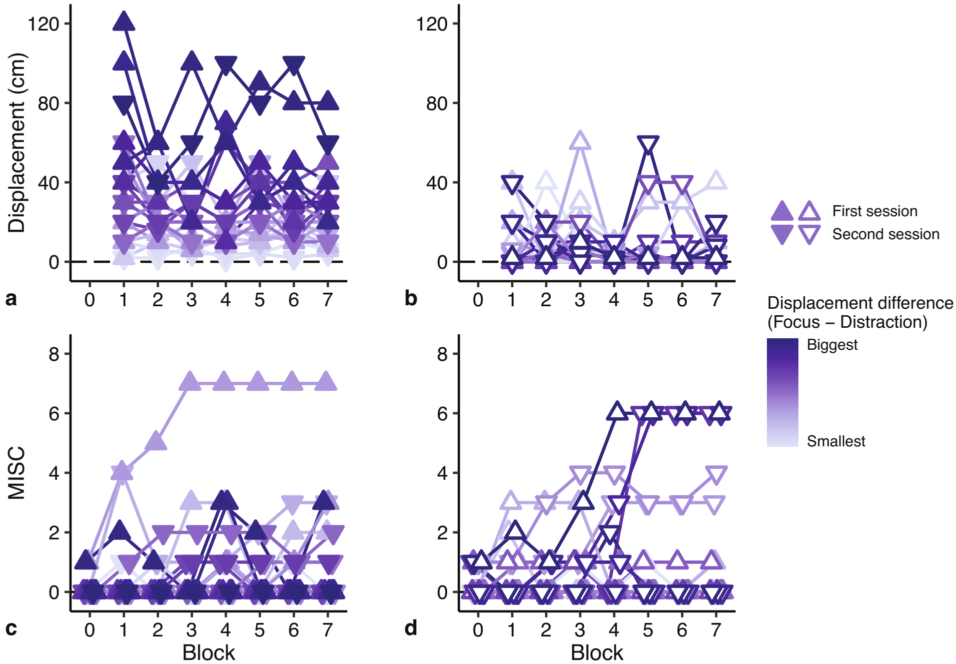


Figure S3.1 The development of **a.** and **b.** displacements, and **c.** and **d.** MISC scores in the Focus and Distraction session reported by individual participants. We used a gradient to contrast the participant with the biggest displacement difference between sessions (in dark purple) to the participant with the smallest displacement difference (in light purple). To visualize a possible effect of session order, we used different symbols indicating the order of sessions for each participant.

Exploratory correlational analyses

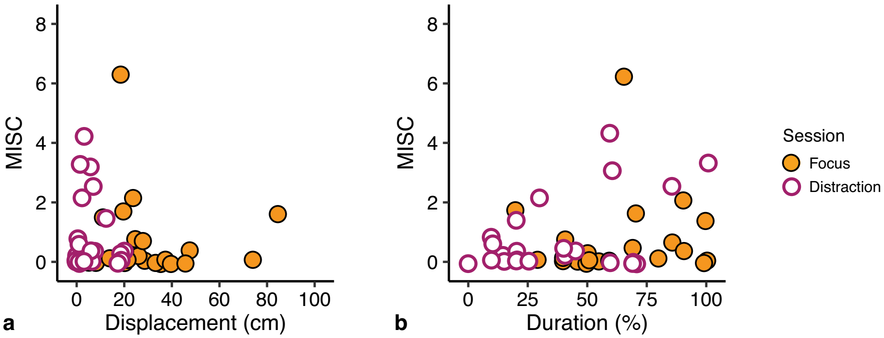
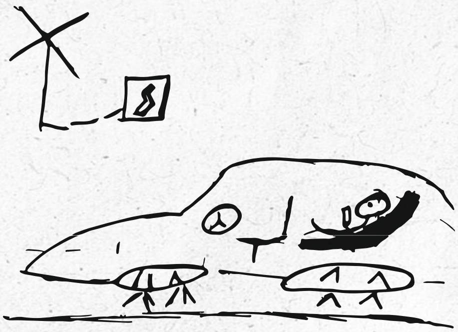
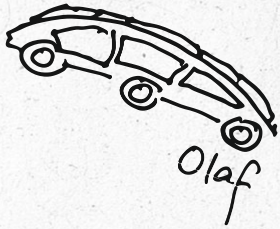


Figure S3.2 We explored possible correlations between measures of self-motion perception and motion sickness independent of session. **a.** There was neither evidence for a correlation between the reported displacements and MISC scores ($\rho = -0.04$, $p = 0.805$), **b.** nor between the motion durations (0% = never moved to 100% = always moved) and MISC scores ($\rho = 0.12$, $p = 0.405$). Data points of displacements and MISC scores represent the average value of an individual participant across the seven blocks within a session. Jitter was added to help discriminate between individual data points.

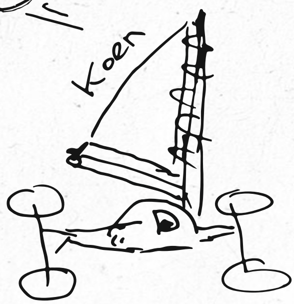



Olaf


Fijn dat er geen file meer is ?
BURPS
Katinka


Kurt


Jelte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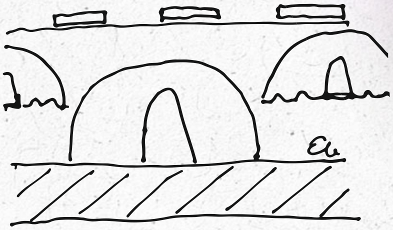
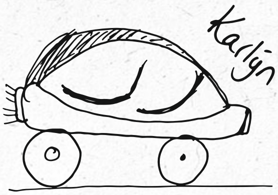


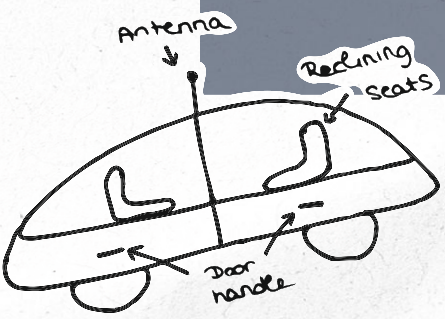


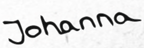
CHAPTER 4

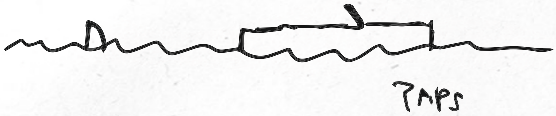
The (in)effectiveness of anticipatory vibrotactile cues in mitigating motion sickness

Adapted from
Anna JC Reuten, Jeroen BJ Smeets, Jessica Rausch, Marieke H Martens, Eike A Schmidt & Jelte E Bos
(2023)

Experimental Brain Research 241(5): 1251-1261







Abstract

The introduction of (fully) automated vehicles has generated a re-interest in motion sickness, given that passengers suffer much more from motion sickness compared to car drivers. A suggested solution is to improve the anticipation of passive self-motion via cues that alert passengers of changes in the upcoming motion trajectory. We already know that auditory or visual cues can mitigate motion sickness. In this study, we used anticipatory vibrotactile cues that do not interfere with the (audio)visual tasks passengers may want to perform. We wanted to investigate 1) whether anticipatory vibrotactile cues mitigate motion sickness, and 2) whether the timing of the cue is of influence. We therefore exposed participants to four sessions on a linear sled with displacements unpredictable in motion onset. In three sessions, an anticipatory cue was presented 0.33, 1, or 3 s prior to the onset of forward motion. Using a new pre-registered measure, we quantified the reduction in motion sickness across multiple sickness scores in these sessions relative to a control session. Under the chosen experimental conditions, our results did not show a significant mitigation of motion sickness by the anticipatory vibrotactile cues, irrespective of their timing. Participants yet indicated that the cues were helpful. Considering that motion sickness is influenced by the unpredictability of displacements, vibrotactile cues may mitigate sickness when motions have more (unpredictable) variability than those studied here.

Introduction

All individuals with functioning organs of balance are susceptible to motion sickness (Irwin 1881, James 1883). It is a syndrome of discomfort with symptoms such as dizziness, headaches, nausea and vomiting (Money 1970). The earliest reports date back hundreds of years, with narratives of sea-sickness, cart-sickness, and camel-sickness documented in ancient literature (Brandt et al. 2016, Huppert et al. 2017). Many have ever since attempted to explain its origin, and foremost, the ways to mitigate it (Lackner 2014, Golding 2016).

The neural mismatch theory identified the root cause of motion sickness as a mismatch between sensory signals on self-motion and estimations, predictions, or expectations thereof (Reason and Brand 1975, Reason 1978, Oman 1991). Improving these expectations would hence offer a way to mitigate motion sickness. The easiest solution then seems to provide someone control of self-motion, as was demonstrated by Rolnick and Lubow (1991). They reported that participants in control of their head motion reported less motion sickness compared to participants passively exposed to the same stimulus. This could explain why car drivers suffer less from sickness compared to car passengers (Schmidt et al. 2020). The introduction of (fully) automated vehicles thereby comes with an additional challenge. As their essence is to eliminate human interference with driving, their usage is inherently paired with an expected increase in motion sickness prevalence (Iskander et al. 2019). The aim of our study is to investigate the effectiveness of a potential solution.

Helping individuals to anticipate certain vehicle motions has shown to be a promising solution to mitigate motion sickness. This anticipation can be provided via *anticipatory cues* which alert occupants of changes in the upcoming motion trajectory via vision (Feenstra et al. 2011, Karjanto et al. 2018, Hainich et al. 2021) or sound (Kuiper et al. 2020a, Diels and Bos 2021, Maculewicz et al. 2021). However, visual cues sometimes aggravate a neural mismatch, provoking rather than mitigating motion sickness (Stauffert et al. 2020, Karjanto et al. 2021). Furthermore, the opportunity to engage in non-driving related tasks already occupying the visual or auditory system (Kyriakidis et al. 2015) could result in occupants missing a cue (Lerner et al. 2015, Meng and Spence 2015) or feeling disturbed by it (Diels and Bos 2021). As an alternative, anticipatory cues could be presented via a third channel unaffected by these disadvantages: the vibrotactile modality. Vibrotactile cues are less intrusive whilst they are still hard to ignore and attention capturing (Scott and Gray 2008, Prewett et al. 2012, Petermeijer et al. 2016). Tactile displays have been used to augment human-machine interaction, for example to improve communication and navigation in the military or to recover from spatial disorientation during flight (Bos et al. 2005, Hancock et al. 2015). Vibrotactile cues have also been successfully implemented in driver assistance systems such as navigation, lane keeping and collision avoidance (Petermeijer et al. 2015, Gaffary and Lécuyer 2018). In this current study, we will investigate whether anticipatory vibrotactile cues can successfully mitigate motion sickness when being passively exposed to motion sickening displacements.

As far as our knowledge concerns, three studies have investigated the use of anticipatory vibrotactile cues for lateral displacements. Yusof et al. (2020) found no significant effect on motion sickness, whilst Karjanto et al. (2021) and Li and Chen (2022) reported a significant reduction. However, for the two studies that reported significant beneficial effects, we think their results have limited validity. First, the intervention used in Karjanto et al. (2021) was very similar to the one used by Yusof et al. (2020), except that it not only consisted of vibrotactile cues, but also included movable plates that pushed the participant's upper body into the direction of a turn. Actively tilting head position into the centripetal force has been demonstrated to reduce motion sickness (Golding et al. 2003, Wada et al. 2012, Wada and Yoshida 2016). Given that the vibrotactile cues used in the study of Yusof et al. (2020) were not effective, the reduction of motion sickness in the study of Karjanto et al. (2021) might be attributed to the moving plates. Second, Li and Chen (2022) asked participants to indicate the direction of anticipated car motion by steering the wheel into the direction of the perceived vibration. Some participants afterwards expressed to have felt in control of the vehicle's motion. As control of self-motion is hypothesized to strongly reduce motion sickness (Rolnick and Lubow 1991), the finding of Li and Chen (2022) might not be due to the cue itself. Furthermore, in both studies the reported levels of motion sickness were rather low, which may make one wonder if these studies succeeded in provoking motion sickness at all. Overall, we think that the evidence on the effectiveness of purely anticipatory vibrotactile cues is yet inconclusive.

In this study, we will re-evaluate the effectiveness of vibrotactile cues only for mitigating motion sickness caused by longitudinal displacements. If we can confirm their effectiveness, a next question would be how much time in advance of motion onset they should be presented. Our research question is thus twofold: first, we question whether anticipatory vibrotactile cues successfully mitigate motion sickness, and second, which of our selected anticipatory intervals between the cue and motion onset is most effective. To that end, we exposed participants to four sessions of sickening motion that differed in the timing of vibrotactile stimulation. We hypothesized that the anticipatory vibrotactile cues would mitigate motion sickness, though we had no expectations which anticipatory interval would be most effective.

Methods

To investigate whether the effectiveness of anticipatory vibrotactile cues is dependent on their timing, we examined self-reported motion sickness in four sessions. These sessions only differed in the anticipatory time interval between a vibrotactile cue and motion onset of a linear sled. In three sessions, the cue was predictive and alerted participants of the onset of a displacement. We compared motion sickness in these anticipatory sessions to that in a control session, in which the cue was only presented until after the onset of motion. We preregistered our study on the Open Science Framework (https://doi.org/10.17605/OSF.IO/SYVU9).

Participants

Our aim was to have a fully counterbalanced within-subjects design, which required 24 participants to complete all four sessions. Accounting for dropouts, we set our recruitment criterion at 30 participants. To be included in our study, participants had to be 18 years or older, experienced car sickness in the last five years, and free of self-known vestibular disorders. Participants additionally had to be in good health according to self-report, for example not suffering from cardiovascular or neurological disorders. After being recruited, ten participants could not be included in the results because of no-show ($n = 7$), a severe motion sickness response resulting in the decision to cancel participation ($n = 2$), or mechanical failure of the device ($n = 1$). This left 20 participants to complete all sessions, which sample size should provide sufficient statistical power when comparing to similar experiments reporting significant effects (Feenstra et al. 2011, Kuiper et al. 2020a). Participants were aged between 18 and 61 years ($M = 26$ years, 17 females), the majority being students from the Vrije Universiteit Amsterdam. We have obtained ethical approval from the institutional review board of TNO, which is the organization where the experiment was performed.

Motion stimuli

In each session, we exposed participants to a series of 65 sickening fore-aft displacements on a linear sled (Figure 4.1a). This linear sled is ideally suited to consistently produce linear accelerations which succeed one another rapidly. We used the displacements by Kuiper et al. (2020a) as a starting point for defining our motion stimulus. Because we here wanted to isolate the effect of the anticipatory interval, we used displacements predictable in direction that all followed an identical asymmetrical acceleration profile (see Supplementary Figure S4.1). Each displacement consisted of a fast forward motion (peak acceleration 3.5 m/s^2) followed by a deceleration leading to a slow (theoretically unprovocative) backward motion at constant velocity. This asymmetry ensured the most provocative part of the displacement was closest to the anticipatory cue. The fore and aft motion took about 9 s in total. The amplitude of each displacement was 7.2 m, with the cabin repeatedly returning to its starting position. The start of consecutive displacements was randomly varied between 12 and 20 s according to a uniform distribution, making it impossible for participants to reliably predict the onset of the displacement without an anticipatory cue. This type of motion somewhat resembles driving in a traffic jam, with short forward accelerations at inconsistent intervals. As inertial motion with constant velocity cannot be perceived, the stationary intervals could also represent intervals of any constant velocity during a real car ride, with the displacements representing periods of acceleration and deceleration. We generated four variations of the series of displacements and stationary intervals, and exposed all participants to each variation once, with all variations equally distributed across sessions. The exposure duration was 15 minutes per session, which is comparable to the duration used in other cueing studies (Feenstra et al. 2011, Kuiper et al. 2020a, Hainich et al. 2021).

Figure 4.1 a. The linear sled that was used in this study. The illuminated cabin offered an enclosed space that removed external visual and airflow cues. **b.** Interior view of the cabin where the participants were seated. The stationary visual frame of reference provided by the cabin resembles the context of a car ride without looking outside. A printed version of the used motion sickness scale was taped onto the wall in front of the participants. Participants could also see a webcam which was used for observation. The rally seat offered a head rest and a five-point seat belt for safety. The orange dots indicate the position of the six vibrotactile actuators.

Vibrotactile cues

We presented the vibrotactile cues by means of six small (approximately 5 x 20 mm) eccentric rotatory mass vibration motors embedded horizontally in a 2 cm foam cushion placed on top of the seat pan (Figure 4.1b). The cue consisted of simultaneously activating the six actuators at 125 Hz for a duration of 150 ms. In three anticipatory sessions, the onset of the cue was always *prior* to the onset of forward motion: either at 0.33, 1, or 3 s. We selected these three equidistant anticipatory intervals, because previous cueing studies used intervals within this range (Karjanto et al. 2018, Kuiper et al. 2020a, Yusof et al. 2020, Diels and Bos 2021, Hainich et al. 2021, Karjanto et al. 2021, Maculewicz et al. 2021, de Winkel et al. 2021, Li and Chen 2022). To account for any effect of the cue itself (rather than its predictive information), we included a control session in which the onset of a non-informative cue was 2–6 s *after* the onset of forward motion. We chose this variable interval to minimize any predictability associated with this cue, equal to the interval selected by Kuiper et al. (2020a). The presentation of vibrotactile cues in relation to the displacements is visualized in Figure 4.2. The order of sessions was counterbalanced and then randomly assigned to participants.

Measures

We quantified the progression of motion sickness by asking the participants for a Motion Illness Symptoms Classification score (MISC; see Table 4.1; Bos et al. 2005, Reuten et al. 2021) at 1-minute intervals in each of the four sessions. We also asked participants to fill out the Motion Sickness Susceptibility Questionnaire (MSSQ-Short; Golding 2006) and

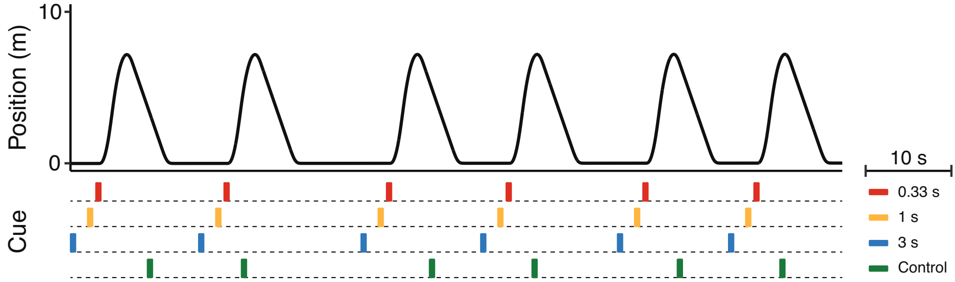


Figure 4.2 Schematic overview of the timing of vibrotactile stimulation relative to the onset of motion in the four sessions.

a self-developed user experience questionnaire. After each session, we asked participants if and when they felt the cues (multiple-choice); how often they felt the cues (multiple-choice); and how they evaluated the cues along a range of user dimensions (Likert scale). After the fourth session, we asked participants if they noticed that the cues in each session were presented at fixed times relative to the start of the displacements (multiple-choice), which cue they preferred in announcing the onset of motion (multiple-choice), if they would want to use that cue in their (automated) car (multiple-choice), how much money they would be willing to spend extra on a car preventing motion sickness (open-ended), and if they had suggestions to adjust the cue (open-ended).

Class description		**MISC**
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, yawning, headache, tiredness, sweating, stomach awareness, burping, blurred vision, salivation, … but no nausea	vague	2
	little	3
	rather	4
	severe	5
Nausea	little	6
	rather	7
	severe	8
	retching	9
Vomiting		10

Table 4.1 The Motion Illness Symptoms Classification (MISC) used to assess motion sickness symptomatology (Bos et al. 2005, Reuten et al. 2021).

Procedure

Participants performed the four sessions divided across two days. On the first day, participants received instructions on the experimental procedure and signed an informed consent form. They subsequently filled out the MSSQ-Short (Golding 2006) from which we observed that the average susceptibility towards motion sickness of our

20 participants corresponds to the 76th percentile. We instructed participants that our study was on the effectiveness of vibrotactile cues in mitigating motion sickness, and that a vibrotactile cue would be presented prior to the sled's forward motion in some sessions, and during the motion in other sessions. Participants subsequently performed a familiarization trial of three displacements (<1 minute; see Motion Stimuli) without vibrotactile stimulation, followed by a 10-minute break. They then performed two out of the four sessions, with a 1-hour break in between to recover from any motion sickness. To control for carry-over effects, participants performed the remaining two sessions 7 days later. This period was extended for five participants (mainly due to the COVID-19 virus): 3 participants performed the sessions 14 days later, 1 participant 22 days later, and 1 participant 42 days later.

Participants could only start a session when they rated a MISC score of 0 or 1 at the start of the session (i.e., t = 0). Two participants rated a higher pre-test MISC score, wherefore we aborted the experiment for one participant and waited until the symptoms disappeared for another participant. During the sessions, we could observe the participant via a video connection, and remained in contact via a two-way audio connection. We asked participants to perform an auditory 1-back task to control their focus of attention, in which they needed to count the number of duplicate vowels heard. We also instructed participants to keep their eyes open and head upright. If they rated MISC ≥ 6, we aborted the session. After each session and at the end of the experiment, we asked participants to fill out a user experience questionnaire. They received study credits or a monetary reward for their participation in the experiment.

Data analysis

To determine the effect of the anticipatory vibrotactile cues, we developed a way to express their effectiveness into a single value that captured the difference in the development of motion sickness between each of the anticipatory sessions relative to the control session. This value is meaningful when the cue provides a constant effect during a session. We tested our approach with data obtained in a similar experiment by Kuiper et al. (2020a), who presented an auditory cue before (anticipatory session) or after (control session) motion onset of a linear sled. In this section, we illustrate our analysis method using their data.

Assuming a positive effect of the anticipatory (A) session relative to the control (C) session, we first calculate the reduction R_{ti} of MISC scores per time point (t) and individual participant (i) by

$$R_{ti} = \frac{(C_{ti} - A_{ti})}{(C_{ti} + A_{ti})} \qquad (1)$$

We use the measure R instead of a percentage change (i.e., $S = (1 - A/C) \times 100$), because for R_{ti} exchanging C and A only results in a change of sign. This makes it suitable for averaging: if C and A are drawn from a random distribution, the average of R will be zero, whereas the average of S will become negative. To provide the reader guidance

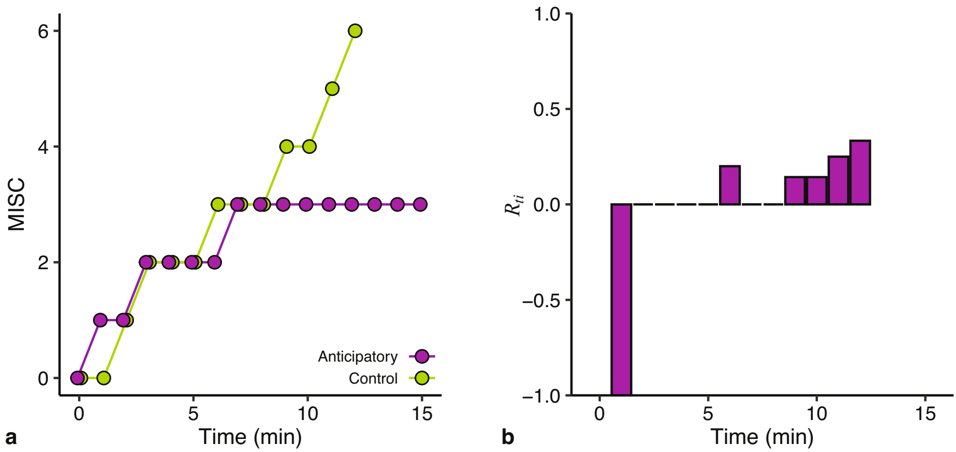


Figure 4.3 The initial steps of our method illustrated using data from participant 12 of Kuiper et al. (2020a). **a.** The development of MISC scores. **b.** The reduction R_{ti} that results from the MISC scores in a. R_{ti} has a low resolution for the first time points, with values either being -1 or 0.

on the interpretation of our measure, we provide a conversion of R to a percentual change in MISC scores in Supplementary Figure S4.2.

When $C_{ti} = A_{ti} = 0$, R_{ti} becomes undefined. This is not problematic for our analysis as we will weigh the data as explained below; this undefined R_{ti} value will receive a weight of zero. The range of possible R values is symmetrical around zero (no reduction), ranging from -1 (maximum worsening, $A_{ti} \neq 0,\ C_{ti} = 0$) to $+1$ (maximum mitigation, $A_{ti} = 0,\ C_{ti} \neq 0$), see also Supplementary Figure S4.3. One of the advantages of our measure R is that we can determine the effectiveness of the cue for each of the 15 time points within a session. Because participants only rate MISC 0 or 1 early on in a session, the resolution of R_{ti} is low for the first time points: R_{ti} will either be 0, 1, or -1. This consequence is visualized in Figure 4.3, where we present the MISC scores (a) and resulting R_{ti} values (b) for one participant. Note that we do not calculate R_{ti} at $t = 0$ (pre-test measurement), and cannot determine R_{ti} for those time points with a missing MISC score as the result of the exerted stop-criterion.

To take the resolution of R_{ti} into account when determining the average reduction of the cue, we weight (w_{ti}) each of the 15 obtained R_{ti} values by the sum of the two underlying MISC scores

$$w_{ti} = C_{ti} + A_{ti} \tag{2}$$

We can then calculate the average reduction per participant i by

$$\bar{R}_i = \frac{\sum_t w_{ti} R_{ti}}{\sum_t w_{ti}} = \frac{\sum_t (C_{ti} - A_{ti})}{\sum_t w_{ti}} \tag{3}$$

and for each time point t by

$$\bar{R}_t = \frac{\sum_i w_{ti} R_{ti}}{\sum_i w_{ti}} = \frac{\sum_i (C_{ti} - A_{ti})}{\sum_i w_{ti}} \tag{4}$$

Equation 3 indicates that $\bar{R}_i$ is proportional to the difference between the two sessions (i.e., the area between the two curves in Figure 4.3a).

Fifteen of the 20 participants in Kuiper et al. (2020a) showed a reduction by the cue ($\bar{R}_i > 0$, Figure 4.4a). Across the whole experiment, the reduction is fairly constant (none of the data-points in Figure 4.4b deviates by more than its confidence interval), which supports our approach to use the MISC scores during the whole session to capture the reduction in motion sickness by a single number. We hence express the effectiveness of the cue across all time points and participants, again weighted by considering the resolution of R_{ti} in

$$\bar{R} = \frac{\sum_t \sum_i w_{ti} R_{ti}}{\sum_t \sum_i w_{ti}} = \frac{\sum_i w_i \bar{R}_i}{\sum_i w_i}, \text{ with } w_i = \sum_t w_{ti} \quad (5)$$

The resulting overall weighted average reduction is $\bar{R} = 0.10$ (one-sided 95% confidence interval 0.02, ∞). The conclusion resulting from our new method of analysis corresponds with the original conclusion: a significant reduction in motion sickness using anticipatory auditory cues.

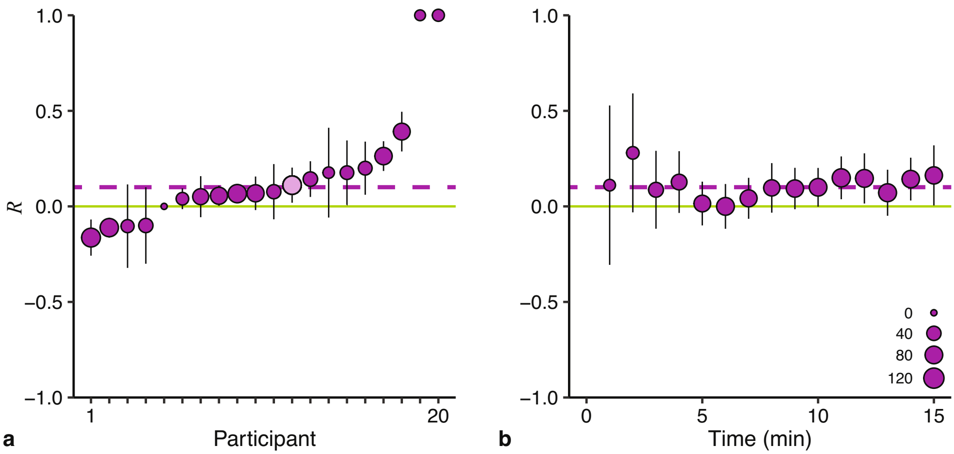


Figure 4.4 Our method to determine the reduction (R) of motion sickness illustrated with data from Kuiper et al. (2020a). **a.** The average for individual participants (i), who are ordered based on the size of $\bar{R}_i$. Participant 12 (data point in light purple) was the example participant whose data we presented in Figure 4.3. **b.** The average for each time point (t). For both panels, the averages are weighted based on the sum of MISC scores underlying the data. The size of the points reflects the sum of these weights (see legend in panel b). The horizontal lines at zero correspond to no reduction. The dashed lines represent the overall reduction $\bar{R}$ in this experiment. The error bars are 95% confidence intervals calculated with bootstrapping of R_{ti} and corresponding weights.

Statistical analysis

Our first question of interest is whether our anticipatory vibrotactile cues mitigate motion sickness. We therefore performed a weighted one-sided *t* test (with α = 0.05) to examine whether the grand mean of $\bar{R}$ across the three anticipatory sessions is larger than zero, with the grand mean of $\bar{R}_i$ of each participant weighted by the sum of their three w_i scores. Our second question of interest is which of our selected time intervals between the anticipatory vibrotactile cue and motion onset mitigates motion sickness best. We therefore performed a weighted repeated measures ANOVA (α = 0.05) on the $\bar{R}_i$ values (each weighted by their respective w_i) of the three anticipatory sessions (0.33, 1, and 3 s).

All other analyses are not part of our pre-registration and should therefore be considered exploratory. To express the confidence of our estimates of R, we report two-sided 95% confidence intervals by default. When interested in whether R was larger than zero, we instead report one-sided 95% confidence intervals using the format [lower bound, ∞].

Results

Our first question of interest is whether our anticipatory vibrotactile cues mitigated motion sickness. The pattern of MISC scores in Figure 4.5a suggests a slight advantage for the anticipatory cues (see Supplementary Figures S4.4 and S4.5 for more details). We used our pre-registered analysis to quantify the effectiveness of each anticipatory cue by calculating R (see Methods). As $\bar{R}_t$ did not vary systematically across the 15 time points within the sessions (see Supplementary Figure S4.6), we only provide the overall reductions $\bar{R}$ per session (Figure 4.5b). In line with visual inspection of this figure, a weighted one-sided t test confirmed that the grand mean of $\bar{R}$ across the three anticipatory sessions was not larger than zero (grand $\bar{R}$ = 0.03, t = 0.79, p = 0.22, 95% confidence interval [−0.01, ∞]). Our second question of interest is which of our selected anticipatory intervals between the cue and motion onset is most effective. A weighted repeated measures ANOVA indicated there was no difference between the $\bar{R}_i$ values of the three anticipatory sessions ($F(2,51)$ = 0.13, p = 0.88). Under the chosen experimental conditions, our results did not show a mitigation of motion sickness by the anticipatory vibrotactile cues, irrespective of their timing. The R values of the individual sessions can be found in Supplementary Figure S4.6. To explore the existence of an order effect, we compared the MISC scores in the second, third, and fourth session to those rated in the first session. There is a tendency for the MISC scores to decrease with the greater number of sessions performed, though all confidence intervals include zero; suggesting no effect of session order (Supplementary Figure S4.7).

Using the results of the user experience questionnaire, we first wanted to confirm if participants noticed the cues and could correctly identify when they were presented. All participants noticed them, and the majority indeed indicated that the cue was presented prior to the onset of the displacement in the anticipatory sessions and during the displacement in the control session (Figure 4.6a). Noticeable is a decreasing accuracy with longer anticipatory intervals. We also asked participants if they noticed that the cues were presented at a fixed moment relative to the onset of the displacements. All except for one participant did, with 50% of participants being aware of this in all sessions and 45% in some of the sessions. When asking how often participants felt the

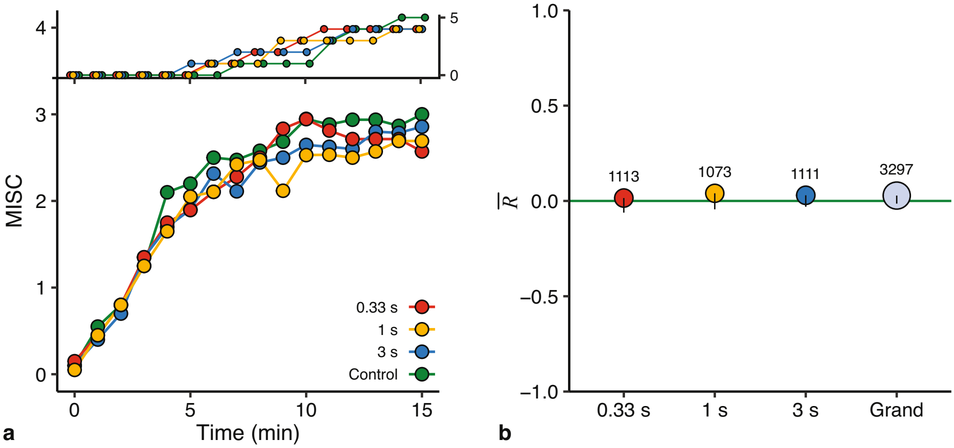


Figure 4.5 a. The development of raw MISC scores averaged across participants for each of the four sessions. To enable a better comparison to Figure 4.5b, we excluded data on those time points where participants reached the stop-criterion of MISC ≥ 6 in the control session. The inset figure displays the number of participants reaching the stop-criterion per time point. **b.** The overall reduction ($\bar{R}$) in motion sickness generated by each anticipatory cue and their combined grand mean in gray. The line in dark green corresponds to no reduction. The size of the data points reflects the sum of MISC scores underlying the data (the overall weight, see legend). The error bars are one-sided 95% confidence intervals (coherent with our one-sided analysis) calculated with bootstrapping of $\bar{R}_i$ and corresponding weights.

vibrations, about 75% indicated to have felt them for every displacement in the anticipatory sessions (Figure 4.6b). This percentage was considerably lower in the control session, possibly indicating that participants paid less attention to this cue as it did not have any anticipatory value.

The cues in the 0.33 s and 1 s anticipatory sessions were rated the most helpful to predict the onset of upcoming displacements (Figure 4.6c). As was intended, the cue in the control session was rated the least helpful. All cues were furthermore rated positively in terms of pleasantness and comfort. Even though their duration and intensity were judged as appropriate, the few suggestions to improve the cue were mainly targeted at modification of these two aspects.

We also asked which anticipatory interval participants preferred in announcing the upcoming displacements (Figure 4.6d). The 1 s interval was favored by most participants, followed by the 0.33 s interval. Several participants explicitly reported that the 3 s interval was too long, which complicated the exact estimation of motion onset. In congruence with those reasons, it was the least preferred cue with only 10% of all votes.

Four-fifths of the participants indicated they would want to use the cue they preferred in their (automated) car if it proved effective in mitigating motion sickness (Figure 4.6e). There was a lot of variation in the amount of money participants were willing to spend extra on a car preventing motion sickness (SD = €744), with an average amount of €691. The three participants who indicated they would not want to use a cue reported they only suffered mild motion sickness and did not deem its use necessary.

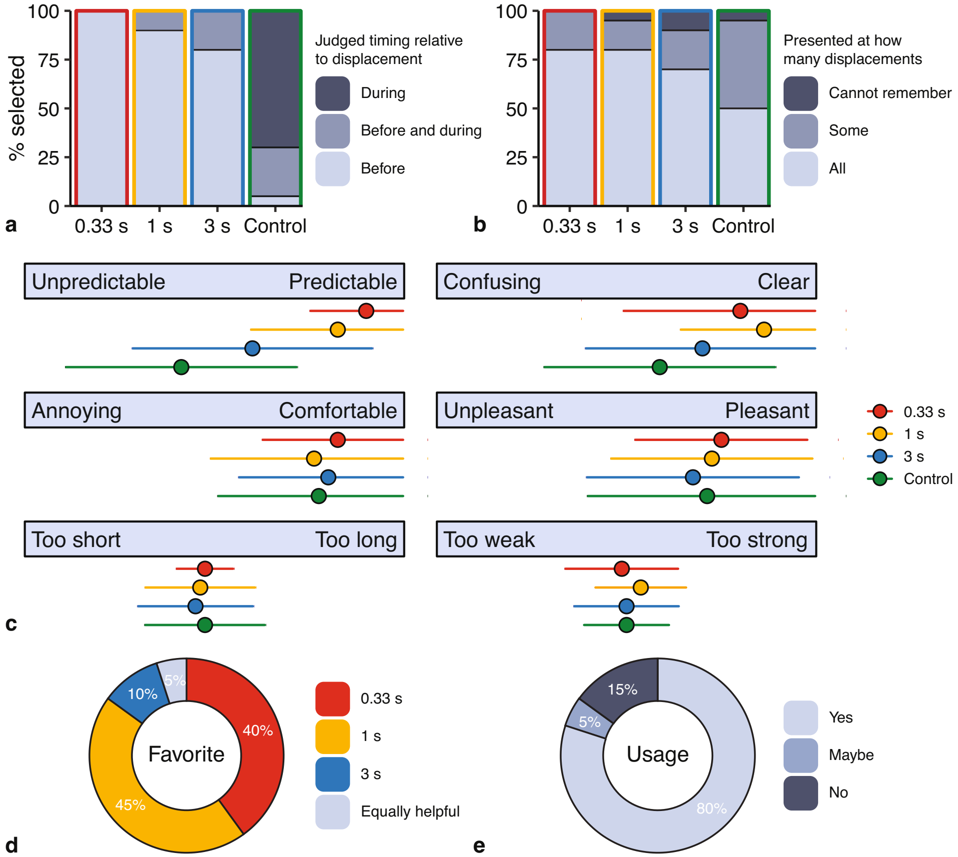


Figure 4.6 Results of the user experience questionnaire. Participants indicated **a.** when they thought the cues were presented, **b.** how often they felt the cues, **c.** how they evaluated the cues along a range of user dimensions (error bars indicate standard deviations), **d.** which type of cue they preferred in announcing upcoming displacements, and **e.** if they would want to use the cue of their preference in their (automated) car. For the questions in panels a and d, the participants were given additional answer options that none of them selected.

Discussion

We here investigated whether anticipatory vibrotactile cues are effective in mitigating motion sickness. We were also interested whether the timing of the cue influences its effectiveness. To that end, we exposed participants to four sessions of fore-aft motion on a linear sled. In three sessions, an anticipatory cue was presented prior to the onset of forward motion, either at 0.33, 1, or 3 s. We compared the scores on a motion sickness scale given within these sessions to the scores given in a control session with a non-anticipatory cue presented 2 to 6 s after motion onset. In contrast to our expectations, we found no evidence that the anticipatory cues were mitigating motion sickness, irrespective of their timing (Figure 4.5). This conclusion following our newly defined method R aligns with that of a more traditional analysis approach using a repeated measures ANOVA on the raw MISC scores which we reported at a conference (Reuten et al. 2022).

For the anticipatory cues to work, participants should associate them with the upcoming displacement. A limitation of our study is that this might not have been easy in the session with a 3 s anticipatory interval, as the shortest interval between consecutive displacements was 4 s. This may explain why about a quarter of the participants indicated that the cue was presented both before and during (instead of only before) the displacements of this session (Figure 4.6a). If we re-analyze the reduction of motion sickness including only those participants who correctly identified the timing of the cues, the confidence interval of the cue with the 3 s anticipatory interval does not include zero, which suggests this cue mitigated motion sickness (see Supplementary Figure S4.8a). However, given that this analysis was not pre-registered and only included twelve participants, this finding should be interpreted with caution. Moreover, the fact that the remaining participants rated the 3 s cue less helpful compared to the cues with shorter anticipatory intervals (see the user experience ratings in Supplementary Figure S4.8b), contradicts the argument that linking the cue to the previous displacement is causing the lack of a significant reduction of motion sickness.

Another potential limitation of our study is that the linear sled sporadically deviated from the programmed motion stimulus, resulting in some displacements getting a bit jerky. This means that some part of the motion was not announced by the cues, which may explain why our results did not show a mitigation of motion sickness. At the same time, it can be reasoned that in a real-world scenario not all motions can correctly be predicted and accompanied by an appropriate anticipatory cue, so an ideal cue should be effective despite the presence of some unpredictable motion.

Kuiper et al. (2020a) performed a comparable study on the effectiveness of anticipatory auditory cues. They used the same linear sled as we used to subject 20 participants to a motion stimulus similar in provocativeness to ours (see Supplementary Figure S4.9). The participants' motion sickness susceptibility scores on the MSSQ were also comparable (76^{th} versus 70^{th} percentile). As we reported in our Methods section, our analysis method yields a significant advantage of the anticipatory auditory cue in that experiment, whereas the vibrotactile cue in this experiment did not. This may suggest superiority of the auditory modality over the vibrotactile modality for anticipatory cueing. However, two arguments challenge that suggestion. First, a weighted independent samples *t* test indicates there is no difference in the grand $\bar{R}$ = 0.03 of our study and $\bar{R}$ = 0.10 in Kuiper et al. (2020a), with t = 1.15 and p = 0.26. Though only the reduction in Kuiper et al. (2020a) was significantly larger than zero, this does not by definition imply that their intervention was more effective than ours. Such a conclusion requires a direct comparison, see the second common mistake in Makin and Orban de Xivry (2019). Second, the experiments differed in the variability of the displacements: we only varied the onset of the displacements, whereas Kuiper et al. (2020a) additionally varied their direction (forward or backward). Because unpredictability about motion onset and direction individually contribute to the motion sickness response (Kuiper et al. 2020b), the additional unpredictability of motion direction may explain why the cue in Kuiper et al. (2020a) was more effective compared to our study. These arguments necessitate a direct comparison between the effectiveness of auditory and vibrotactile cues. We will therefore re-evaluate the effectiveness of directional vibrotactile cues with displacements unpredictable in both onset and direction, together with a comparison of auditory cues in a follow-up study (pre-registered at https://doi.org/10.17605/OSF.IO/8FZU7).

Though our results did not provide evidence that anticipatory vibrotactile cues are effective in mitigating motion sickness, we think several reasons make it worthwhile to investigate how their effectiveness can be improved. First of all, despite the fact that our cues did not significantly reduce motion sickness, a comparison to the auditory cues of Kuiper et al. (2020a) indicated the vibrotactile cues were not performing significantly worse. Second, most of our participants indicated that the vibrotactile cues with short anticipatory intervals (i.e., 0.33 and 1 s) were helpful in announcing the onset of upcoming displacements, and also expressed the willingness to have them in their (automated) car. Lastly, the vibrotactile modality seems specifically suited for usage in automated vehicles. For example, vibrotactile cues will not interfere with the non-driving related tasks passengers may want to perform. We will first re-evaluate if vibrotactile cues mitigate motion sickness when motions are harder to anticipate, in particular when considering changes in vehicle velocity in multiple directions as representative for real on-road driving, instead of one only as studied here. Other work could focus on including a training to familiarize with the cues or the additive effect of combining multiple mitigation approaches like studied by Karjanto et al. (2021). Alternatives are investigating the positioning of the actuators or the advantage of self-adjustable intensity settings to match individual preferences (Duthoit et al. 2018). Longer anticipatory time intervals might be studied as well, though previous cueing studies (Karjanto et al. 2018, Kuiper et al. 2020a, Hainich et al. 2021, Maculewicz et al. 2021) reported significant effects when using time intervals comparable to those studied here. Despite not finding a significant reduction in motion sickness, we still conclude it is worthwhile to elaborate further on the effectiveness of anticipatory vibrotactile cues in future research.

SUPPLEMENTARY INFORMATION

Motion stimulus

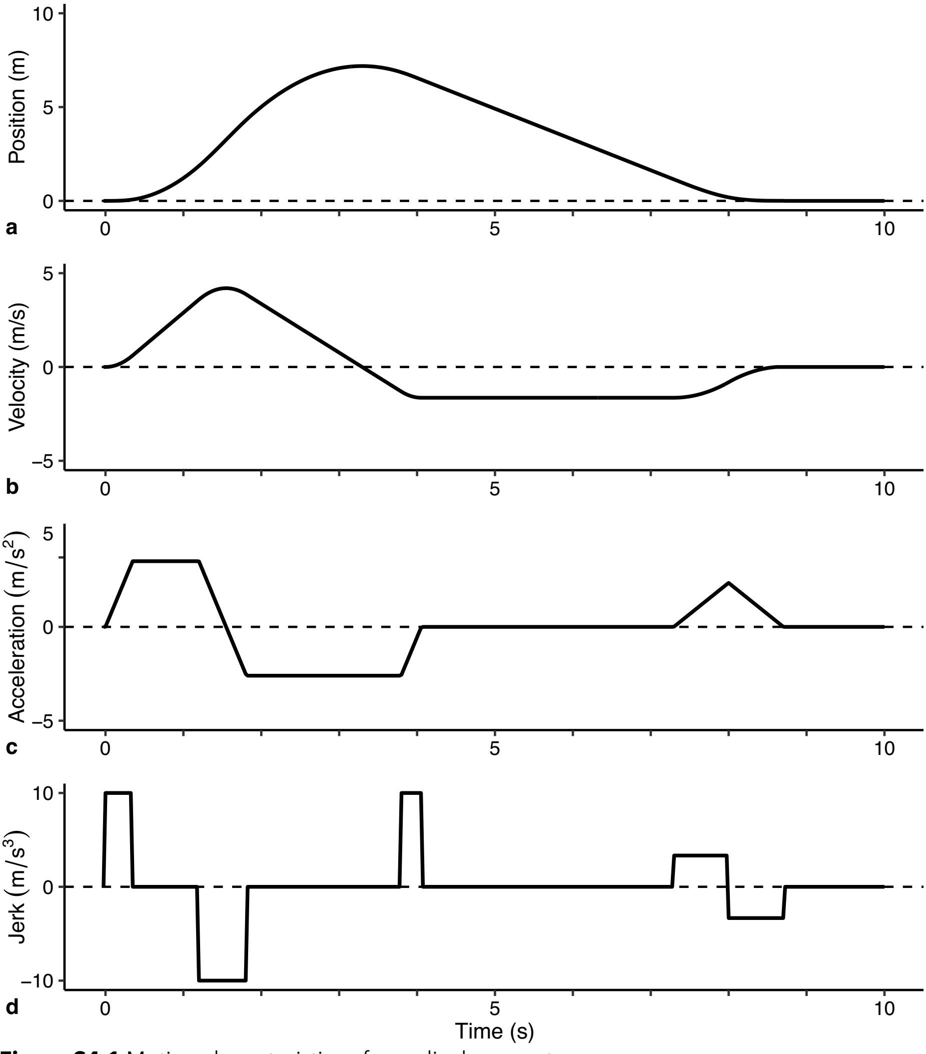


Figure S4.1 Motion characteristics of one displacement.

4

Interpretation of the measure R

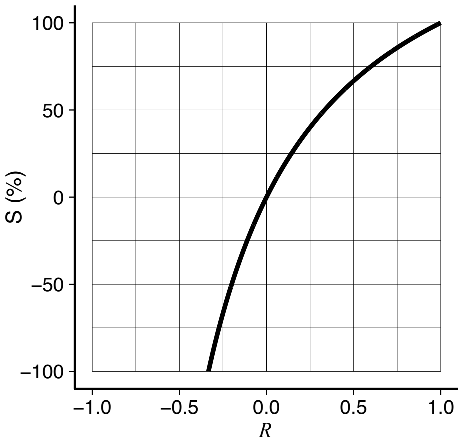


Figure S4.2 Guidance to the interpretation of our measure R expressed in terms of the percentual change in MISC scores from the anticipatory to the control session ($S = (1 - A/C) \times 100$). Note that because S is an asymmetrical measure, R values lower than -0.4 correspond to extremely large negative values of S.

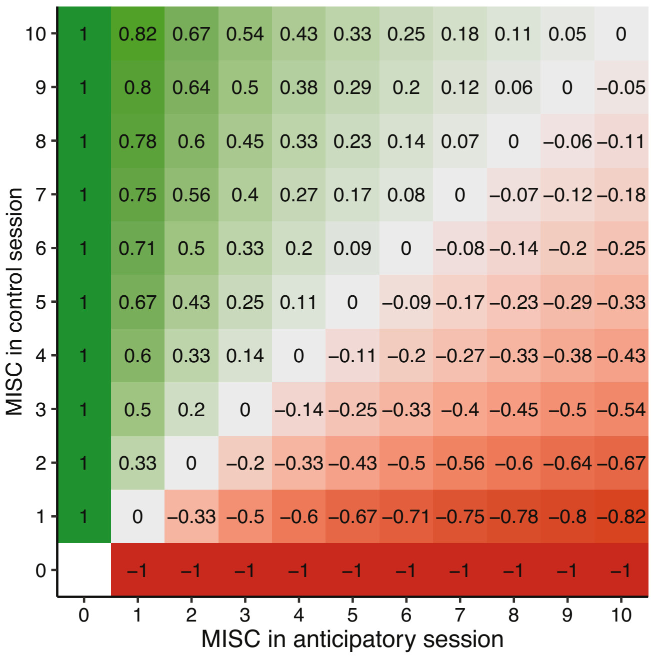


Figure S4.3 Illustration of the distribution of possible R_{ti} values (see 'Methods' of the main text). When $C_{ti} = A_{ti} = 0$, R_{ti} becomes undefined. This does not interfere with our analysis as it will receive a weighting of 0.

Development of MISC scores per participant

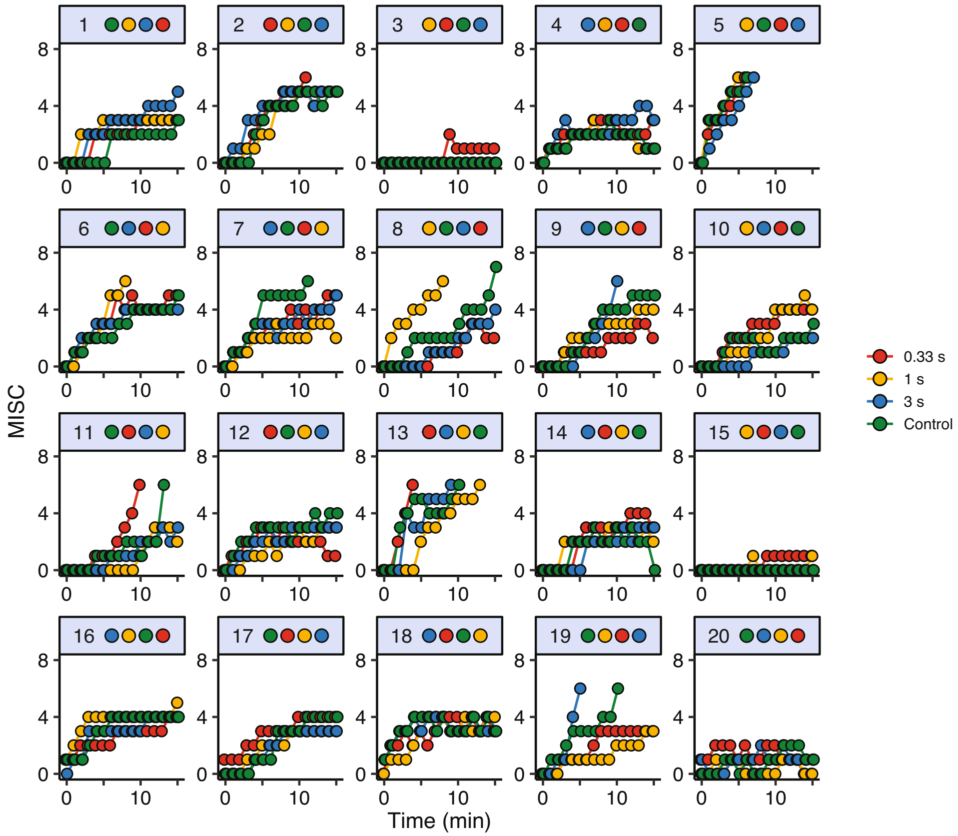


Figure S4.4 The development of raw MISC scores as a function of the time in a session. The red, yellow, and blue sessions are the three anticipatory sessions. The control session is presented in green. Each panel reflects the order of four sessions of a single participant.

4

Development of average MISC scores per session with replacement of missing data

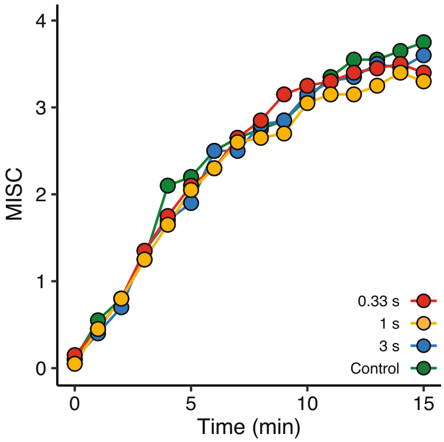


Figure S4.5 The development of raw MISC scores averaged across participants for each of the four sessions. In comparison to our main analysis, we here replaced missing data as the result of the exerted stop-criterion at MISC 6 with the last rated MISC score. In agreement with Figure 4.5a of the main text, the pattern of results again suggest a slight advantage for the anticipatory cues.

Reduction values per participant and time point

Here we present the reduction values per participant (i) and time point (t) for each of the anticipatory sessions. The R values reflect the effectiveness of the anticipatory cues. These values express the amount of reduction in MISC scores from an anticipatory session (0.33 s, 1 s, 3 s) relative to the control session whilst accounting for the resolution of R. That is, each R value is weighted by the sum of MISC scores underlying the data. Positive R values indicate a reduction in motion sickness. The $\bar{R}_i$ values of participants 3 and 15 are small, because they reported no or only minimal symptoms of motion sickness (MISC ≤ 2). Their reduction values do accordingly not or only minimally contribute to the calculation of $\bar{R}$, which expresses the overall reduction per anticipatory session.

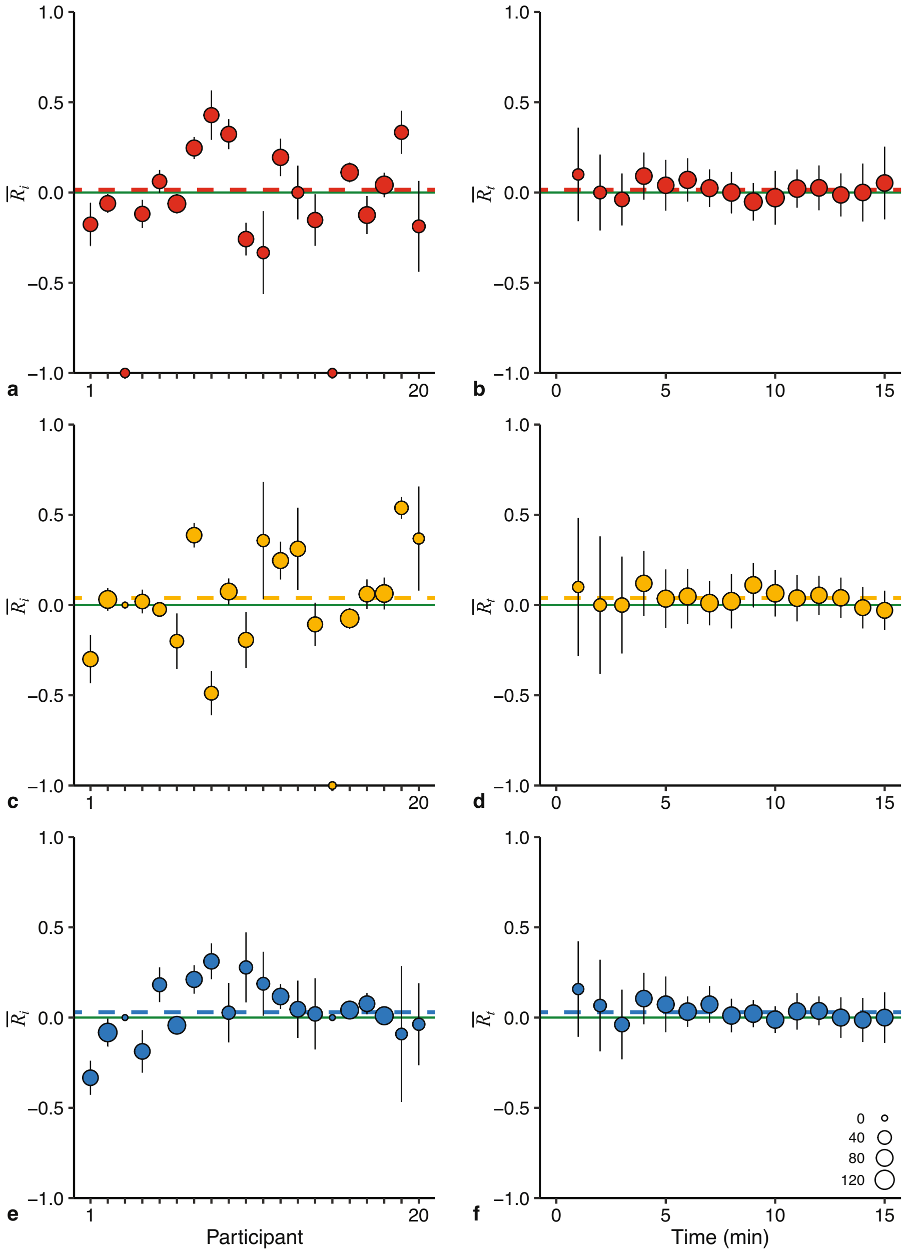


Figure S4.6 The reduction (R) values calculated for the three anticipatory sessions with a 0.33 s (in red), 1 s (in orange), and 3 s (in blue) time interval. **a.**, **c.**, **e.** The average for individual participants (i). **b.**, **d.**, **f.** The average for each time point (t). For all panels, the averages are weighted based on the sum of MISC scores underlying the data. The size of the data points reflects the sum of these weights (see legend in panel f). The line in dark green corresponds to no reduction (i.e., $R = 0$). The dashed lines represent the overall reduction $\bar{R}$ per anticipatory session. The error bars are 95% confidence intervals calculated with bootstrapping of R_{ti} and corresponding weights.

4

Investigation of order effect

To explore the existence of an order effect, we compared the MISC scores in the second, third, and fourth session to those rated in the first session. There is a tendency for the MISC scores to decrease with the greater number of sessions performed. However, all confidence intervals include zero, suggesting the MISC scores did not deviate from those in the first session.

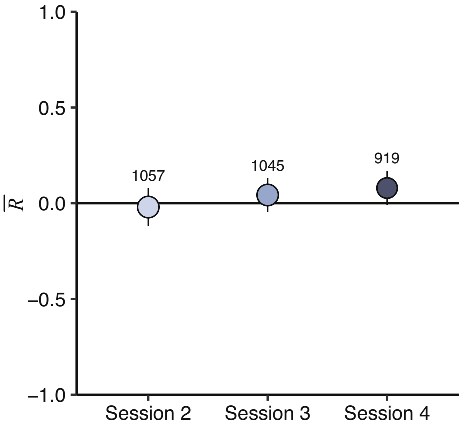
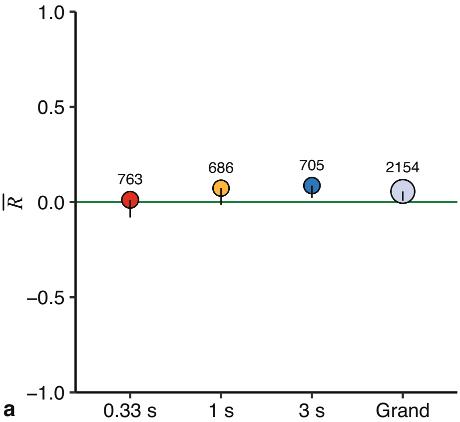


Figure S4.7 The overall reduction ($\bar{R}$) in motion sickness calculated from the MISC scores provided in the second, third, and fourth session respective to the first session (black line). The black line hence corresponds to no difference in MISC scores. The size of the data points reflects the sum of MISC scores underlying the data (the overall weight, see legend). The error bars are 95% confidence intervals calculated with bootstrapping of $\bar{R}_i$ and corresponding weights.

Re-analysis of reduction values based on subsample

We re-calculated the R values based on a subsample including only those participants who correctly identified when the cues were presented (i.e., before motion onset in the anticipatory sessions and after motion onset in the control session, see Figure 4.6a of the main text). Given that the lower bound of the 95% confidence interval of the cue with the 3 s anticipatory interval [0.02, ∞] does not overlap the dark green line (indicating no reduction), the results in Figure S4.8a suggest this cue mitigated motion sickness. However, a re-analysis of the user experience ratings in Figure S4.8b does not support that conclusion.



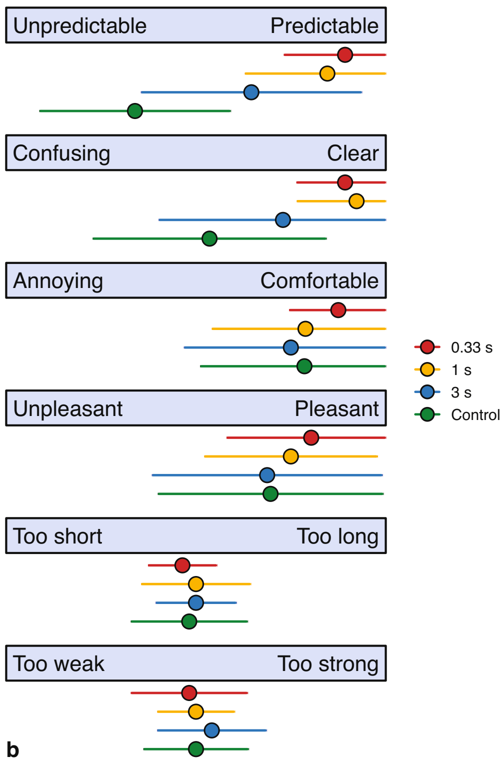


Figure S4.8 Re-analysis of the data based on a subsample of participants who correctly identified when the cues were presented relative to motion onset. **a.** The overall reduction ($\bar{R}$) in motion sickness generated by each anticipatory cue and their combined grand mean in gray. The line in dark green corresponds to no reduction. Reductions were weighted according to the sum of MISC scores underlying the data, which is reflected in the size of the data point. The error bars are one-sided 95% confidence intervals calculated with bootstrapping of $\bar{R}_i$ and corresponding w_i values. 0.33 s: n = 14, 1 s: n = 13, 3 s: n = 12. **b.** Ratings along several user dimensions. Error bars indicate standard deviations.

Development of average MISC scores between control sessions

Kuiper et al. (2020a) performed a comparable study on the effectiveness of anticipatory auditory cues. Based on the overlapping standard deviations (shaded areas), we can conclude that the motion stimulus used in the current study is comparable in provocativeness compared to the study of Kuiper et al. (2020a).

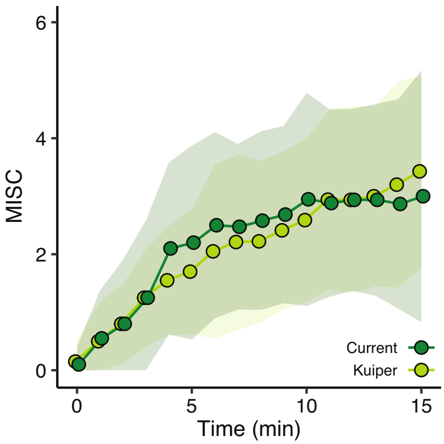
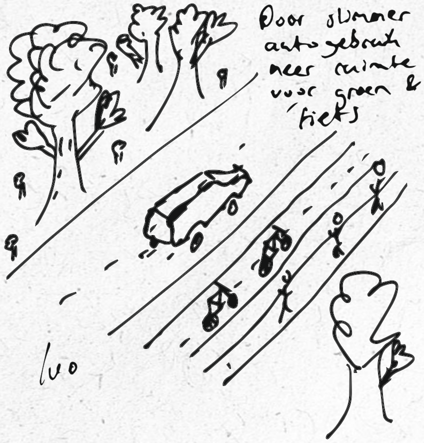


Figure S4.9 The development of raw MISC scores averaged across participants for the control session of our current study in dark green and for the study of Kuiper et al. (2020a) in light green. The shaded areas represent standard deviations.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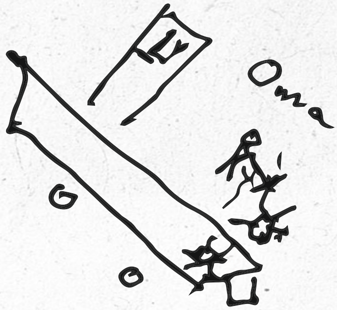
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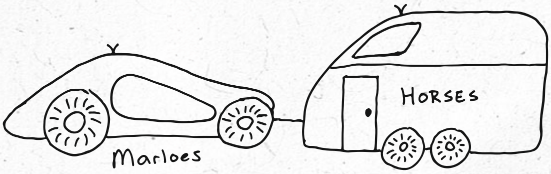
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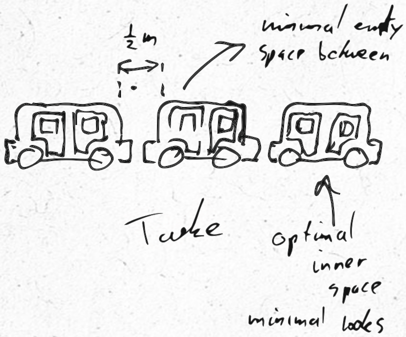
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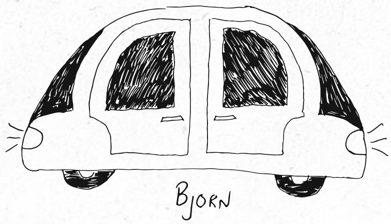
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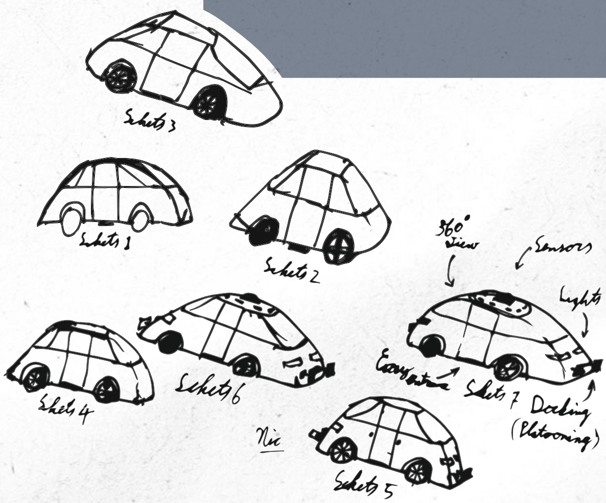
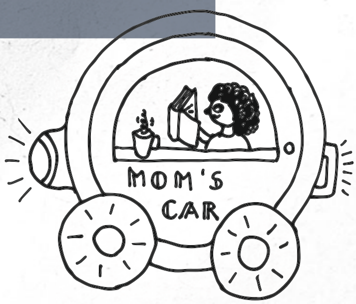
CHAPTER 5

Mitigating motion sickness by anticipatory cues

Anna JC Reuten, Jelte E Bos, Marieke H Martens,
Jessica Rausch & Jeroen BJ Smeets (2024a)

Under Review





Abstract

Car passengers suffer much more from motion sickness compared to car drivers, presumably because drivers can better anticipate the car's motions. Visual and auditory cues that announce upcoming motions have accordingly been demonstrated to mitigate motion sickness. In automated vehicles, vibrotactile cues might be more desirable but it is yet unclear whether they are as effective. In this study, we directly compared the effectiveness of anticipatory auditory and vibrotactile cues to mitigate motion sickness evoked on a linear sled. We determined their effectiveness by examining self-reported motion sickness within participants in four sessions. In two anticipatory sessions, an auditory or vibrotactile cue alerted participants of the onset and direction of upcoming motion. In two control sessions the same cues had no predictive value as they were presented during the motions. Our preregistered analysis did not show a significant difference in mitigation between the cues, but also showed no significant overall effect of the cues. As this lack of an effect may be due to the limited power of our study, we performed an internal meta-analysis. This analysis demonstrated an overall effect of anticipatory cues. We conclude that anticipatory cues are overall effective in mitigating motion sickness, making it worthwhile to investigate how their effectiveness can be enhanced in real-life car driving.

Introduction

Exposure to physical or visual motion may result in the unpleasant experience of motion sickness. Symptoms include dizziness, headache, sweating, nausea, and vomiting, often accompanied by a general feeling of malaise (Money, 1970). One of the most acknowledged theories on motion sickness, the sensory conflict theory, proposes that motion sickness results from conflicting sensory signals on self-motion (Oman, 1982; Reason, 1978; Reason & Brand, 1975). These signals may involve anticipation of self-motion. Car passengers suffer much more from motion sickness compared to car drivers (Schmidt et al., 2020), presumably because drivers can better anticipate the car's motions. The increased susceptibility of passengers constitutes a problem as highly advanced automated driving functions will transform car drivers into passengers. This will consequently increase motion sickness prevalence (Bos et al., 2022; Iskander et al., 2019).

In this study, we want to gain more insight into the effectiveness of a possible method to mitigate motion sickness: anticipatory cueing. In this method, passengers receive warning signals that alert them of changes in the vehicle's trajectory. Helping passengers to anticipate motions could reduce a sensory conflict on self-motion. Previous studies demonstrated the effectiveness of anticipatory cues using the auditory (Diels & Bos, 2021; Kuiper, Bos, Diels, et al., 2020; Maculewicz et al., 2021) as well as visual modality (Feenstra et al., 2011; Hainich et al., 2021; Karjanto et al., 2018). However, both auditory and visual cues have some clear disadvantages. For instance, visual displays sometimes aggravate, rather than mitigate motion sickness (Karjanto et al., 2021; Stauffert et al., 2020). Furthermore, passengers may perform tasks that often involve the auditory and visual modality, such as talking, reading, or using electronic devices (Pfleging et al., 2016; Schmidt et al., 2020). Passengers could accordingly miss a cue (Meng & Spence, 2015) or feel disturbed by it (Diels & Bos, 2021).

An alternative to the use of auditory or visual cues in anticipatory cueing is to present cues via the tactile modality, for instance by applying local vibrations via the seat pan. As the seat is in constant contact with the passenger, cues can be conveyed passively without requiring special action from the passenger. Moreover, the tactile modality is not involved in the various non-driving tasks passengers may want to perform. Because of these advantages, we investigated the effectiveness of anticipatory vibrotactile cues in a prior study (Reuten et al., 2023). There we found no clear evidence that the vibrotactile cues mitigated motion sickness, irrespective of the time interval between the cue and onset of motion.

Whereas the vibrotactile cues did not mitigate motion sickness significantly (Reuten et al., 2023), auditory cues were demonstrated effective in an earlier study using the same motion apparatus, an equally provocative motion stimulus, and a similar experimental protocol (Kuiper et al., 2020a). This may suggest superiority of the auditory modality for anticipatory cueing, though two reasons might negate that suggestion. First, although the auditory cue in Kuiper et al. (2020a) significantly mitigated motion sickness in contrast to the vibrotactile cue in Reuten et al. (2023), this does not imply that their cue was more effective. To draw such a conclusion, a direct comparison of their effectiveness is needed (Makin and Orban de Xivry, 2019). When making this comparison, we observed that the auditory cue was not significantly more effective than the vibrotactile cue (see Reuten et al. 2023). Second, the studies differed in the unpredictability of the used motion stimuli. In Reuten et al. (2023), only the onset of motion was unknown to the participants, whilst in Kuiper et al. (2020a) also the direction of motion (forward or backward) was unknown. Because unpredictability about the onset and direction of motion individually contribute to the motion sickness response (Kuiper et al., 2020b), the more unpredictable motion stimuli used in Kuiper et al. (2020a) might explain the effectiveness of their auditory cues. To conclude, a direct comparison between anticipatory auditory and vibrotactile cues using the same motion stimulus is needed.

To that end, here we will compare the effectiveness of directional anticipatory auditory and vibrotactile cues in mitigating motion sickness while replicating the experimental conditions in Kuiper et al. (2020a). Our primary aim is to determine if both cues mitigate motion sickness. Our second aim is to find out whether their effectiveness differs. Our third aim is to investigate how participants experience using anticipatory cues, and if this differs between auditory and vibrotactile cues.

Methods

We investigated the effectiveness of anticipatory auditory and vibrotactile cues to mitigate motion sickness evoked by a linearly accelerating sled. We did so by examining self-reported motion sickness within participants in four sessions. In two anticipatory sessions (performed on different days), an auditory or vibrotactile cue was predictive and alerted participants of the direction of upcoming motion. On each day, participants also took part in a control session, in which the same type of cue had no predictive value as it was presented during the motion. By comparing the development of motion sickness in the two sessions performed on the same day, we determined if the anticipatory cues mitigated motion sickness. We preregistered our study, with a focus on the statistical analysis, on the Open Science Framework (https://doi.org/10.17605/OSF.IO/8FZU7).

Participants

Considering that Kuiper et al. (2020a) reported a significant effect with a sample of 20 participants, we expected that a sample of 24 participants would provide sufficient statistial power. All of our participants (*M* = 33 years old, 13 males) indicated to be in good overall health, free from self-known vestibular disturbances, and have experienced symptoms of car sickness in the last five years. Two participants needed to be replaced due to mechanical failure of the used motion apparatus. The average motion sickness susceptibility of our sample fell within the 78th percentile of the population (based on the Motion Sickness Susceptibility Questionnaire, MSSQ-Short; Golding 2006). The experimental protocol was approved by TNO's Institutional Review Board and was in accordance with the tenets of the Declaration of Helsinki. All participants provided written informed consent. They were paid for their contribution.

Motion apparatus and stimuli

In each session, we exposed participants to a preprogrammed series of 54 fore-aft motions on a linear sled (see Figure 5.1a). We used very similar raised cosine motions as used by Kuiper et al. (2020a). Each displacement had a 9 m peak-to-peak amplitude, peak acceleration of 2.6 m/s2, and a duration of 9 s (Supplementary Figure S5.1). We pseudorandomly varied the onset of consecutive motions with an interval between 12 and 20 seconds according to a uniform distribution. The initial direction (50% forward, 50% backward) of the motions was pseudorandomly chosen. We varied these aspects to make it improbable for participants to predict the onset and direction of motion reliably without anticipatory cue. To minimize recognizability of the order of motion directions, we mirrored the motion stimulus in direction and exposed participants to both variants on the same day (counterbalanced across the anticipatory and control sessions). The exposure duration was 15 minutes, which duration was also used by Kuiper et al. (2020a) and Reuten et al. (2023).

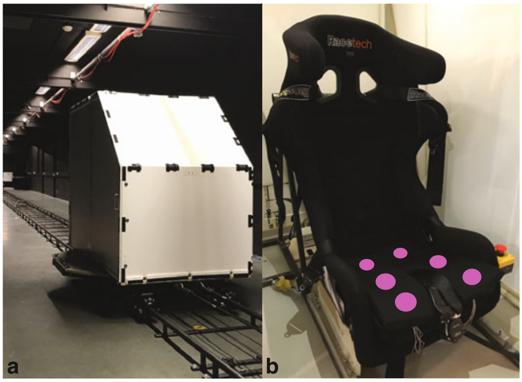


Figure 5.1 Experimental apparatus. **a.** The cabin of the linear sled offered an enclosed space which removed airflow and visual cues on motion. **b.** Interior view of the cabin. The purple dots indicate the positions of six actuators used to present the vibrotactile cues. Replicated from Reuten et al. (2023).

Auditory and vibrotactile cues

In the anticipatory sessions, the cues specified the initial motion direction of the linear sled (Figure 5.2). The onset of the cues was 1 s *prior* to motion onset, equal to the interval used by Kuiper et al. (2020a). The auditory cues consisted of prerecorded voice clips (250 ms) saying "forward" or "backward" in Dutch (respectively "voor" or "achter") that were presented via a headphone. We presented the vibrotactile cues by means of a seat cushion, in which six small eccentric rotatory mass vibration motors were embedded (see Figure 5.1b). After conducting a pilot test, we decided to indicate forward motions by a sequential cueing pattern from hip to knee and backward motions by the same pattern in opposite direction. To generate this pattern, the two motors in each row vibrated for 50 ms with an inter-row interval of 50 ms (250 ms). Replicating the design of Kuiper et al. (2020a) and Reuten et al. (2023), we also presented cues in the control sessions to make sure that any effect of the anticipatory cues was not caused by the effect of the cue in itself. The onset of these non-anticipatory cues was pseudorandomly chosen at 2, 3.5, 5 or 6.5 s *after* motion onset and the direction they specified was independent of the sled's initial motion direction (Figure 5.2).

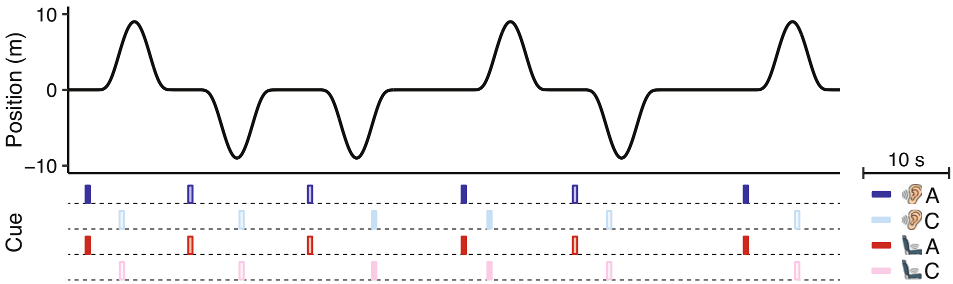


Figure 5.2 Presentation of the cues in relation to the motion stimulus. Bluish colors indicate the auditory sessions, reddish colors indicate the vibrotactile sessions. Filled bars represent cues indicating a forward motion; open bars represent cues indicating a backward motion. In the anticipatory sessions (A, darker colors), the cues were presented 1 s in advance of motion onset and always indicated the initial motion direction. In the control sessions (C, lighter colors), the cues were presented 2 to 6.5 s after motion onset and independent of the initial motion direction.

Procedure

Participants performed the four sessions divided over two days. We grouped the auditory sessions on one day (and consequently the vibrotactile sessions on the other day) to resemble the study design of Kuiper et al. (2020a). We counterbalanced the order of these two days, as well as the order of the anticipatory and control sessions within each day.

Before starting the first session, we explained participants how to use the Motion Illness Symptoms Classification scale (MISC; Bos et al., 2005; Reuten et al., 2021; see Table 5.1) we used throughout the experiment. We instructed that if they rated MISC ≥ 6 or expressed the wish to stop, we would abort the session. They subsequently filled out the MSSQ-Short (Golding 2006). We then asked participants to perform a familiarization trial of two motions on the linear sled: one starting in the forward direction and one starting in the backward direction.

The remaining part of the procedure was also used on the second day. While seated in the stationary cabin, participants performed a short training on the motion direction the anticipatory cues would indicate. The first session started directly after this training. We instructed participants to keep their head upright and eyes open. After completing the first session, participants were given a break lasting at least one hour until reaching a MISC < 2 before starting the second session.

Data collection

To capture the progression of motion sickness, we asked participants to classify their motion sickness symptoms using the MISC every 1 minute during the sessions. The MISC is the main measure of our study. We additionally collected information on the user experience of the cues via multiple questionnaires. After each session, we asked participants if, when and how many times the cues were presented (multiple-choice) and how they evaluated the cues along a range of user experience dimensions (Likert scale). After completing the auditory or vibrotactile sessions (i.e., at the end of one day), we

Class description		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, yawning, headache, tiredness, sweating, stomach awareness, burping, blurred vision, salivation, … but no nausea	vague	2
	little	3
	rather	4
	severe	5
Nausea	little	6
	rather	7
	severe	8
	retching	9
Vomiting		10

Table 5.1 The Motion Illness Symptoms Classification (MISC) used to assess motion sickness symptomatology.

asked participants if the cues in any session helped to mitigate motion sickness (multiple-choice). After the last session, we asked participants if they realized that the cues had always been presented either before or during the motions (multiple-choice); which cue they preferred to announce upcoming motions (multiple-choice); to rank the cues from most to least favorite in announcing upcoming motions (rank); to indicate if they would want to use their favorite cue in their (automated) car (multiple-choice); how much money they would be willing to spend extra on a car preventing motion sickness (open-ended); and if they wanted to alter the cue in some aspect (open-ended).

Data analysis

In our previous study (Reuten et al. 2023), we developed a way to express the effectiveness of the anticipatory cues during the whole session in one value. We termed this value R, denoting the relative reduction in motion sickness in the anticipatory session relative to the control session. Here we will use the same data analysis approach.

For each cueing modality, we determine R by comparing the MISC scores between the anticipatory (A) and control (C) session. We first calculate the reduction R_{ti} of MISC scores per time point (t) and individual participant (i) by

$$R_{ti} = \frac{(C_{ti} - A_{ti})}{(C_{ti} + A_{ti})} \quad (1)$$

This relative reduction value facilitates the interpretation of the effectiveness of the cues as the distribution of R is symmetrical around zero (indicating no effect), with a maximum value of 1 ($A_{ti} = 0$, $C_{ti} \neq 0$) and minimum value of -1 ($A_{ti} \neq 0$, $C_{ti} = 0$). We do not calculate R_{ti} at t=0 (i.e., pre-test measurement) and cannot determine R_{ti} for those time points with missing MISC scores as the result of the stop-criterion at MISC 6. When $C_{ti} = A_{ti} = 0$, R_{ti} becomes undefined. This is not problematic for our analysis as we will weigh the data as explained below; undefined R_{ti} values will receive a weight of zero.

Because participants generally rate MISC 0 or 1 at the beginning of a session, the resolution of R_{ti} is low for the first time points: R_{ti} will either be 0, 1, or −1. Therefore, when determining the average reduction of the cue across all time points, we weigh (w_{ti}) each of the 15 obtained R_{ti} values (i.e., one for each time point in the session) by the sum of the two underlying MISC scores. Consequently, R_{ti} values that are calculated on higher MISC scores will receive a larger weight

$$w_{ti} = C_{ti} + A_{ti} \tag{2}$$

We can then calculate the average reduction per participant i by

$$\bar{R}_i = \frac{\sum_t w_{ti} R_{ti}}{\sum_t w_{ti}} = \frac{\sum_t (C_{ti} - A_{ti})}{\sum_t w_{ti}} \tag{3}$$

and for each time point t by

$$\bar{R}_t = \frac{\sum_i w_{ti} R_{ti}}{\sum_i w_{ti}} = \frac{\sum_i (C_{ti} - A_{ti})}{\sum_i w_{ti}} \tag{4}$$

Equation 3 indicates that $\bar{R}_i$ is proportional to the sum of the differences in MISC scores between the anticipatory and control session of a participant. To express the effectiveness of the anticipatory cue in one value across all time points and participants within a session, we again consider the resolution of R_{ti} by

$$\bar{R} = \frac{\sum_t \sum_i w_{ti} R_{ti}}{\sum_t \sum_i w_{ti}} = \frac{\sum_i w_i \bar{R}_i}{\sum_i w_i}, \text{ with } w_i = \sum_t w_{ti} \tag{5}$$

We perform this analysis twice: once for the auditory sessions and once for the vibrotactile sessions. To provide the reader some intuition for our measure, we provide a conversion of R to a percentual change in MISC scores (i.e., $S = (1 - A/C) \times 100$) in Supplementary Figure S5.2. Note that for R, exchanging C and A only results in a change of sign, whereas S has an asymmetrical distribution.

Statistical analysis

The first part of the analysis focuses on determining if our anticipatory auditory and vibrotactile cues mitigated motion sickness. We hence performed two weighted one-sided *t* tests (α = 0.05) on the auditory and vibrotactile $\bar{R}_i$ values (each weighted by w_i) to establish whether the generated reduction is larger than zero (i.e., corresponding to no reduction). The second part of the analysis focuses on investigating whether the effectiveness of our anticipatory cues differed. We therefore performed a weighted paired-samples *t* test (α = 0.05) on the auditory and vibrotactile $\bar{R}_i$ values (each weighted by w_i). To express the confidence of our estimates of $\bar{R}$, we report two-sided 95% confidence intervals. When interested in determining whether there was a reduction ($\bar{R} > 0$), we instead report one-sided 95% confidence intervals using the format: [lower bound, ∞]. The two parts of the analysis described in this section were preregistered.

The third part of the analysis presents the user experience of the cues via visualizations of descriptive statistics. As this third part was not preregistered, it should be considered as exploratory. The same holds for the additional analyses that we will present in the discussion section.

Results

Our primary aim was to determine if our anticipatory auditory and vibrotactile cues mitigated motion sickness. We present the temporal development of MISC scores in Figure 5.3a (see Supplementary Figure S5.3 for the individual data). On visual inspection, participants rated lower MISC scores in both anticipatory sessions compared to the control sessions. We quantified the reduction in the development of motion sickness per participant using our pre-registered measure R (Figure 5.3b). The amount of benefit received from each anticipatory cue varied between participants: some benefitted from both cues, one cue, or neither cue. For both cues, $\bar{R}_t$ did not vary systematically across time points (Supplementary Figure S5.4). As the cues generated a constant effect across a session, it is meaningful to express the effectiveness of each cue in one value. When expressing the overall reduction across all time points and participants in a session, neither of the anticipatory cues generated a reduction that was significantly larger than zero (Figure 5.3c). For the anticipatory auditory session ($\bar{R}$ = 0.08), the weighted one sample t-test indicated t = 1.1 and p = 0.133 ([−0.03, ∞]). For the anticipatory vibrotactile session ($\bar{R}$ = 0.09), the test indicated t = 1.6 and p = 0.059 ([0.00, ∞]). Our second aim was to investigate whether the effectiveness of the

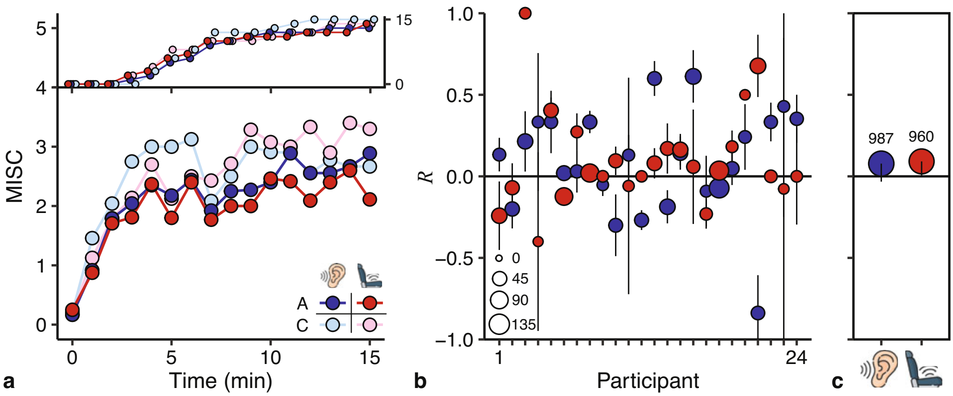


Figure 5.3 a. The development of MISC scores averaged across participants for each of the four sessions. After a participant reached the stop-criterion, they do not longer contribute to the average of that session, resulting in a decrease of the average MISC. We excluded data on those time points in the anticipatory sessions when a participant reached the stop-criterion in the corresponding control session (similar to our measure R). The inset displays the number of participants reaching the stop-criterion per time point. **b.** The reduction values for individual participants ($\bar{R}_i$) calculated for the auditory (blue) and vibrotactile (red) anticipatory sessions. The error bars are 95% confidence intervals. **c.** The overall weighted average of the reduction ($\bar{R}$) in motion sickness generated by each anticipatory cue. The error bars are 95% one-sided confidence intervals (coherent with our one-sided analysis). The size of the data points in panels b and c reflects the sum of MISC scores underlying the data. The horizontal lines at zero correspond to no reduction.

anticipatory auditory and vibrotactile cue differed. The weighted paired-samples t test indicated there was no significant difference, with a weighted mean $\bar{R}$ difference of -0.04, $t = -0.4$, and $p = 0.697$ ([-0.24, 0.16]).

Our third aim was to investigate how participants evaluated the cues in terms of user experience. The results of our questionnaire indicated that most participants correctly remembered when the cues were presented (Figure 5.4a). However, some participants incorrectly indicated that the cues had also been presented before motion onset in the control sessions. We asked participants to indicate how often they noticed the cues (Figure 5.4b). Whereas most participants indicated that the cues in the anticipatory sessions were presented at all motions, this percentage was much lower in the

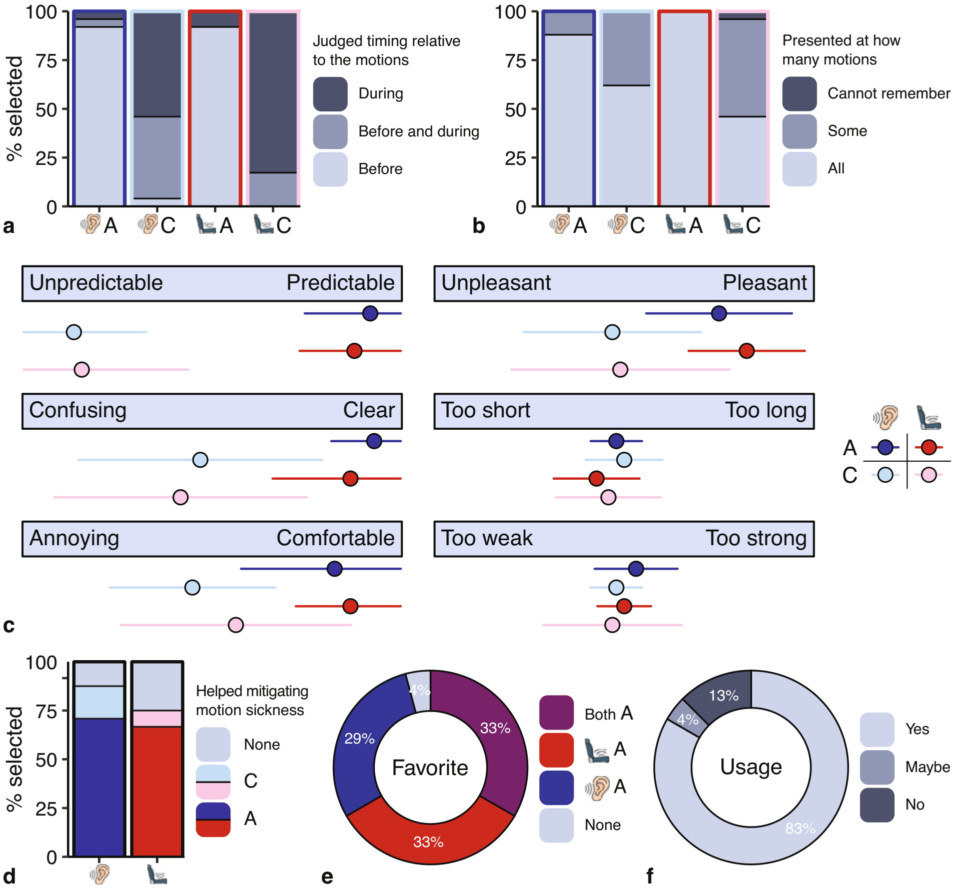


Figure 5.4 Results of the user experience questionnaire. Participants indicated **a.** when they thought the cues were presented, **b.** how often they perceived the cues, **c.** how they evaluated the cues along a range of user dimensions (error bars indicate standard deviations), **d.** which cue helped to mitigate motion sickness, **e.** which cue they preferred to announce upcoming motions, and **f.** if they would want to use the cue they preferred in their (automated) car. For the questions in panels a, d and e, the participants were given additional answer options that none of them selected.

control sessions. This might be related to the misjudgment of the timing of the cues in the control session: if participants paid less attention to the cues in the control sessions, they might not accurately remember when they were presented.

We asked participants to rate the cues along several user dimensions (Figure 5.4c). There was a clear difference in user experience between the cues in the anticipatory and control sessions, but only small differences between the auditory and vibrotactile cues. The anticipatory cues made the motions more predictable (Figure 5.4c), and about 70% of the participants indicated that they helped to mitigate motion sickness (Figure 5.4d). All except for one participant also indicated that they preferred the sessions with anticipatory cues (Figure 5.4e). Moreover, about 80% of the participants indicated they would want to use the cue they preferred in their (automated) car (Figure 5.4f). Additional information on the user experience questionnaire is provided in the Supplementary Information.

Discussion

The primary aim of our study was to investigate if anticipatory auditory and vibrotactile cues mitigate motion sickness. We additionally wanted to find out whether their effectiveness differed and how participants experienced using them. Even though the results of a user experience questionnaire indicated that the anticipatory cues were useful, our pre-registered analysis measure R provided no evidence that the cues significantly mitigated motion sickness. There was no difference in the effectiveness of the anticipatory auditory and vibrotactile cues.

5

Based on our measure R, there is no statistical evidence that our anticipatory cues mitigated motion sickness under the chosen experimental conditions. The lack of a significant reduction in motion sickness is in line with the results we found in our previous study (Reuten et al. 2023). Does this repeated lack of a significant reduction imply that anticipatory cues do not mitigate motion sickness, and that the statistical evidence that Kuiper et al. (2020a) reported was based on sheer chance? Several aspects of our data suggest that the anticipatory cues in our studies did mitigate motion sickness, but that statistical power was too low. First, in Reuten et al. (2023), we quantified the mitigating effect of the auditory cues of Kuiper et al. (2020a) using R and concluded it did not differ significantly from the effectiveness of the cues in that study. Also, in our current study the effectiveness of the anticipatory auditory ($\bar{R}$ = 0.08) and vibrotactile ($\bar{R}$ = 0.09) cues is similar to the overall reduction ($\bar{R}$ = 0.10) in Kuiper et al. (2020a). Second, the answers given in response to the user experience questionnaires in our studies indicated a clear preference for using anticipatory cues. For these two reasons, we explored the results from several additional analyses in the following section.

Exploratory analyses

Repeated measures ANOVA

Our first attempt to investigate why — despite using the same experimental conditions as Kuiper et al. (2020a) — we did not find a significant effect of our anticipatory cues, was to apply their analysis approach to our data. We accordingly replaced missing data due to the stop-criterion with the last rated MISC score (Supplementary Figure S5.5). We then analyzed the resulting new dataset using the factors time (16 levels) and session (4 levels) in a repeated measures ANOVA. The results of this ANOVA with Greenhouse-Geisser correction indicated there was a significant main effect of time with $F(15, 345) = 75.8$, $p < .001$, partial $\eta^2 = 0.77$, but – in contrast with Kuiper et al. (2020a) – no significant effect of session ($p = 0.089$) and also no interaction ($p = 0.730$). These results imply that the MISC scores increased over time within the sessions, but not differently between the sessions; hence indicating no significant of the anticipatory cues. The conclusion drawn from our analysis based on R thus aligns with those of a repeated measures ANOVA, indicating that our analysis using the reduction R is not underestimating the effect of the anticipatory cues.

Internal meta-analysis

The studies by Kuiper et al. (2020a) and Reuten et al. (2023) were conducted under similar experimental conditions as the current study. The comparability of the three studies provides the possibility to combine their datasets, which results in more statistical power to detect small but meaningful effects. We hence performed an internal meta-analysis on this combined dataset using our measure R. Because we included multiple anticipatory sessions in our current and previous study (Reuten et al. 2023), for these studies we first determined a weighted reduction across the anticipatory sessions per participant. We subsequently determined the overall reduction across the three studies using a weighted average of the $\bar{R}_i$ values (Figure 5.5). The resulting $\bar{R} = 0.06$, with the lower bound of the 95% one-sided confidence interval at 0.02, indicates that anticipatory cues are overall effective in mitigating motion sickness.

Some readers might be concerned that the outcome of this analysis is driven by the results of Kuiper et al. (2020a). However, the effectiveness of the cues in Kuiper et al. (2020a) did not differ from that in our current and previous study (Reuten et al. 2023). Another reason negating this concern is that the experiment in Kuiper et al. (2020a) consisted of two sessions while the two other studies consisted of four. Consequently, the $\bar{R}_i$ values in Kuiper et al. (2020a) have smaller weights (equation 2), and thus determine the outcome less than those from the other studies (i.e., the green data points are smaller than the yellow and purple data points in Figure 5.5). For these two reasons, we interpret the observed overall effect of anticipatory cueing the result of more statistical power.

Between-participant variability

We observed large between-participant differences in the reduction generated by the anticipatory cues: the $\bar{R}_i$ values in Figures 5.3b and 5.5 range from -1 to $+1$. We wanted to investigate whether these differences are characteristic for idiosyncratic differences in the benefit participants obtained from the cue, or the result of uncontrollable variability (e.g., rating noise). To answer this question, we performed two additional exploratory analyses on the data of the current study.

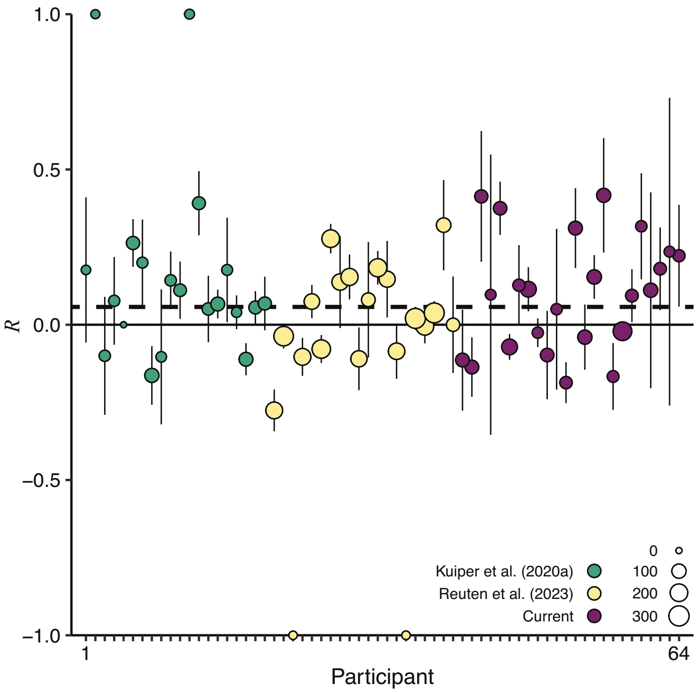


Figure 5.5 Results of an internal meta-analysis with the reduction values calculated for each participant ($\bar{R}_i$) in three comparable studies on anticipatory cueing. The dashed line represents the overall reduction $\bar{R}$ across all studies. Further details as in Figure 5.3.

First, we investigated the between-participant variability in a sham comparison: between the development of motion sickness in the two control sessions. In this analysis, neither cue is of benefit, so the largest component is uncontrollable variability. If the between-participant variability in this analysis is just as large as in Figure 5.3b, this would suggest that the differences between participants are due to uncontrollable variability. Not surprisingly, the comparison of the control sessions (Figure 5.6a) generates an overall reduction of about zero. More interesting is the between-participant variability: it is equally large as in Figure 5.3b, suggesting that uncontrollable variability can explain the differences between participants observed in Figures 5.3b and 5.5.

Second, we reasoned that if the participants would differ in the amount of benefit obtained from the anticipatory cues, one would expect that the benefit in the two anticipatory sessions correlates. We therefore calculated a weighted correlation between the $\bar{R}_i$ values of the anticipatory sessions (Figure 5.6b). The results do not provide evidence for a correlation ($r = -0.23$, $[-0.77, 0.31]$), again suggesting that the observed between-participant differences are more likely the result of uncontrollable variability.

The conclusion of both exploratory analyses is thus in agreement with each other. The effect of anticipatory cues does not seem to be idiosyncratic. This implies that we should interpret our data as showing that all individuals can benefit slightly from anticipatory cues, rather than that some benefit considerably and others not.

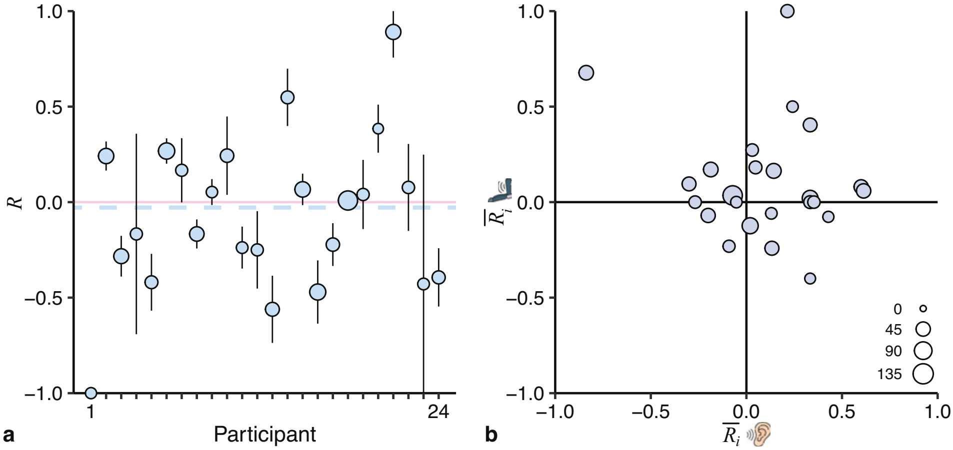


Figure 5.6 Exploratory analyses to investigate whether the between-participant variability in Figures 5.3b and 5.5 is characteristic for idiosyncratic benefits, or the result of uncontrollable variability. **a.** The reduction values for a sham comparison (the auditory control relative to the vibrotactile control session), for which one expects $\bar{R}_i = 0$. The dashed line represents the overall reduction $\bar{R}$, which is indeed close to zero. Further details as in Figure 5.3b. **b.** The $\bar{R}_i$ values for the anticipatory auditory session plotted against those in the anticipatory vibrotactile session. In this panel, the size of the data points is determined by the square root of the product of auditory and vibrotactile w_i values. The large between-participant variability in the sham comparison in panel a and the absence of a correlation in panel b suggest that the differences in $\bar{R}_i$ between participants in Figures 5.3c and 5.5 are more likely to reflect uncontrollable variability.

Conclusion

We here investigated the effectiveness of anticipatory auditory and vibrotactile cues as a possible solution to mitigate motion sickness. The results of our pre-registered analysis of the reduction measure R could not demonstrate that our anticipatory cues significantly mitigated motion sickness. Nevertheless, we had several reasons to assume that the cues did mitigate motion sickness to some extent. An internal meta-analysis performed on three comparable studies confirmed this assumption: the anticipatory cues mitigated motion sickness with a grand $\bar{R}$ of 0.06 (95% one-sided confidence interval [0.02, ∞]; see Figure 5.5). When converting this reduction to a measure of percentage change, the anticipatory cues reduced motion sickness by 11%. Based on this analysis, we consider anticipatory cues a viable solution to mitigate motion sickness, with more research needed to determine if their effectiveness can be enhanced. Automated vehicles can predict their motion well. They could thus provide accurate anticipatory cues to mitigate motion sickness in their passengers.

SUPPLEMENTARY INFORMATION

Motion stimulus

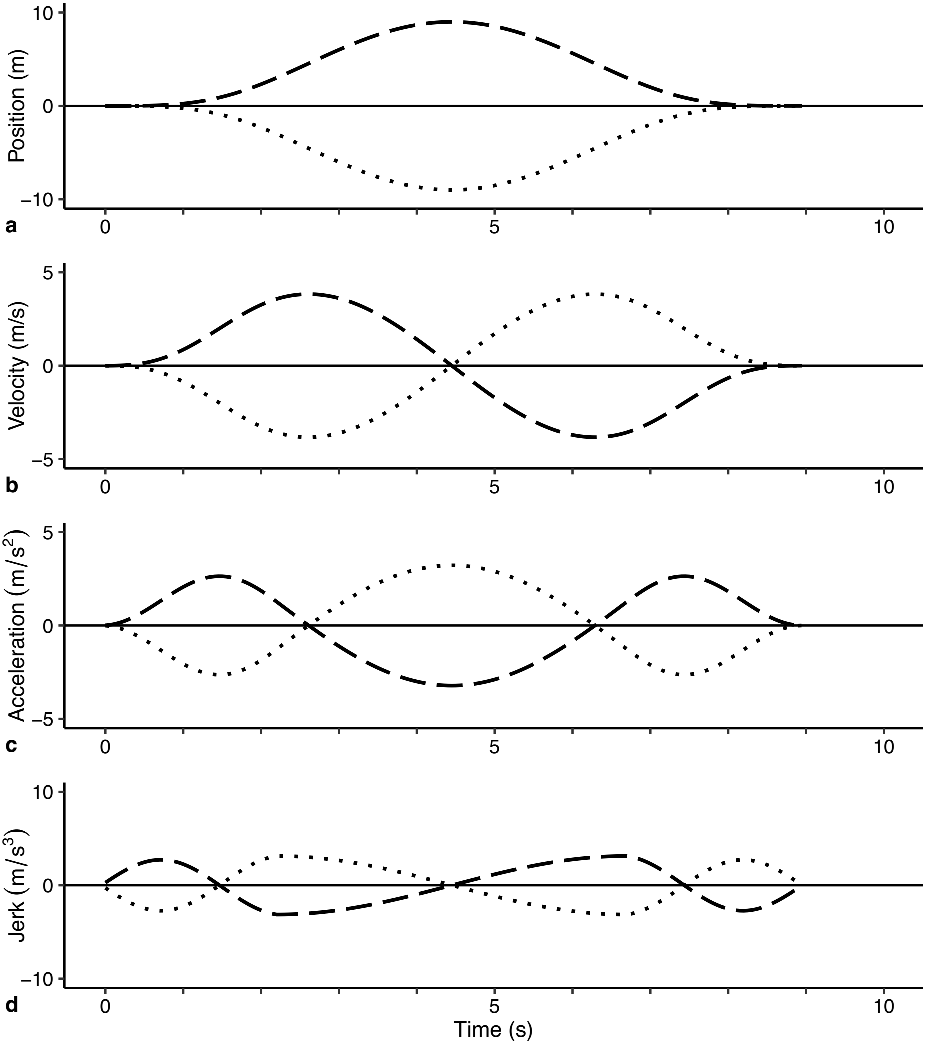


Figure S5.1 The parameters for one motion starting in the forward direction (dashed lines) and one motion starting in the backward direction (dotted lines).

Converting R to a measure of percentage change

To provide the reader guidance on the interpretation of our measure, we provide a conversion of R to a percentual change in MISC scores (i.e., $S = (1 - A/C) \times 100$) in the figure below. Note that we use the measure R instead of a percentage change because for R_{ti} exchanging C and A only results in a change of sign. This makes it suitable for averaging: if C and A are drawn from a random distribution, the average of R will be zero, whereas the average of S will become negative.

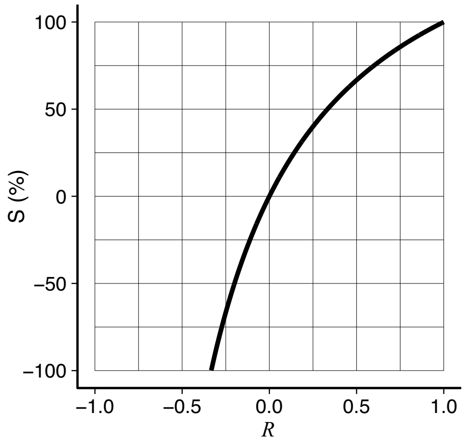


Figure S5.2 Guidance to the interpretation of our measure R expressed in terms of a percentual change in MISC scores from the anticipatory to the control session ($S = (1 - A/C) \times 100$). Note that because S is an asymmetrical measure, R values lower than -0.4 correspond to extremely large negative values of S.

5

Development of MISC scores per participant

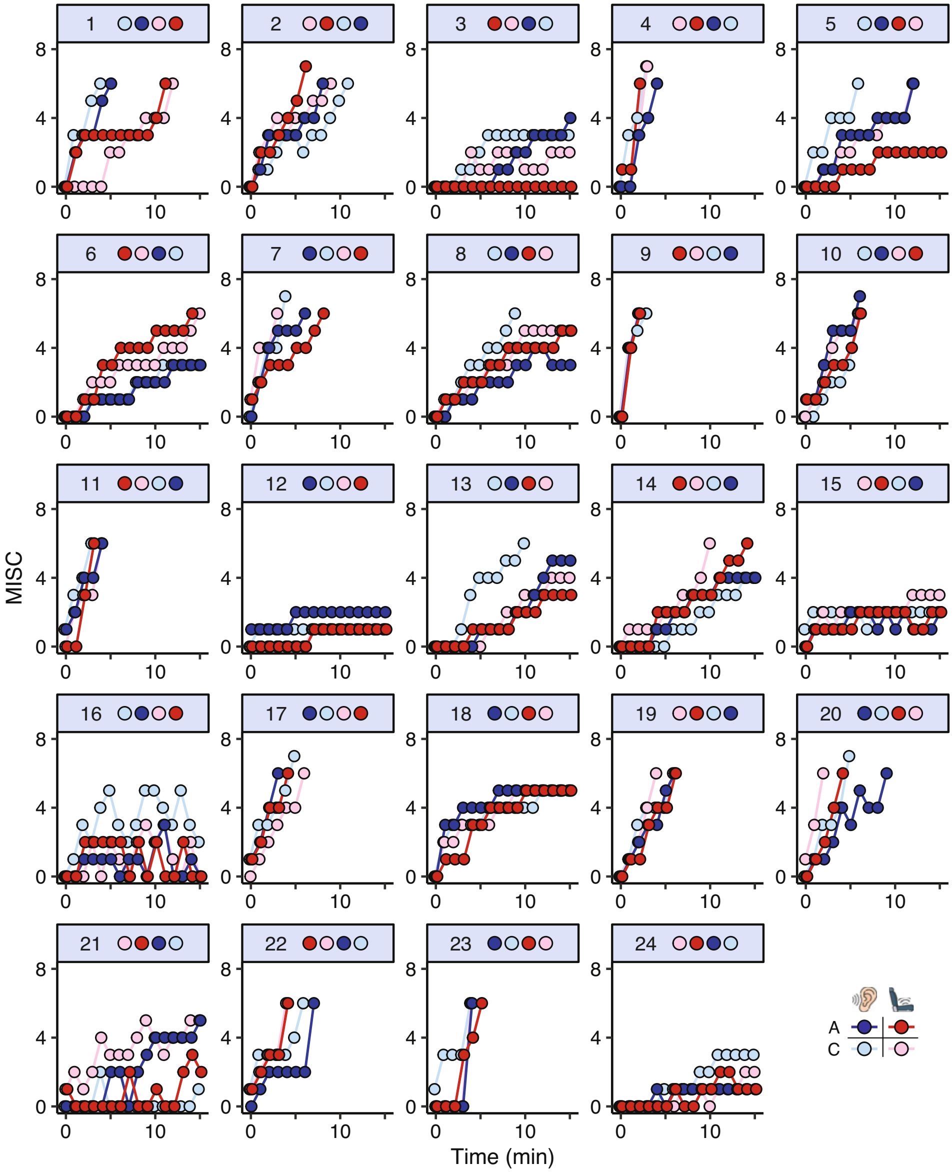
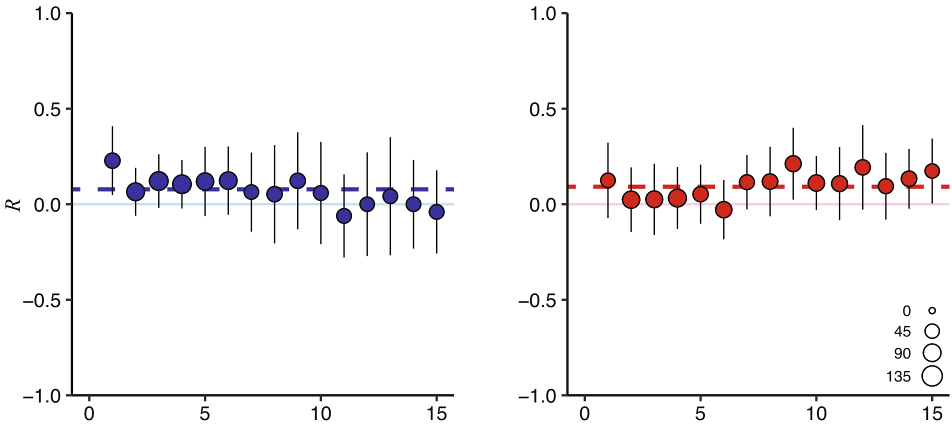


Figure S5.3. The development of raw MISC scores as a function of time for each session. Darker colors represent the anticipatory (A) sessions, lighter colors the control (C) sessions. Bluish colors indicate the auditory sessions, reddish colors the vibrotactile sessions. Each panel reflects the order of four sessions of a single participant. Participants are ordered according to Figure 5.3b of the main text.

Reduction values per time point

Expressing the effectiveness of the cue in a single value across all time points becomes meaningful when the cue generates a constant reduction across a session. Below we plot the R values for each of the 15 time points within the auditory and vibrotactile sessions. $\bar{R}_t$ did not vary systematically for either cueing modality, with the 95% confidence intervals overlapping for each time point.



a b

Figure S5.4 The reduction values for each time point ($\bar{R}_t$) calculated for the **a.** auditory and **b.** vibrotactile anticipatory sessions. The lines at zero correspond to no reduction. The dashed lines represent the overall reduction $\bar{R}$ per anticipatory session. The size of the data points reflects the sum of MISC scores underlying the data (see legend). The error bars are 95% confidence intervals calculated with bootstrapping of R_{ti} and corresponding weights.

5

Additional information on user experience questionnaire

Here we present additional information obtained from the user experience questionnaire which was not presented in the main text.

First, we also asked participants if they noticed that the cues had always been presented either before or during the motions. This was noticed in all sessions by 71% of participants, in only the auditory sessions by 4%, in only the vibrotactile sessions by 8%, and not at all by 17%.

Second, we also asked participants to rank the cues from most (rank 1; 4 points) to least favorite (rank 4; 1 point) in announcing upcoming motions. The maximum score is 96 (24 participants × 4 points); the minimum score is 24 (24 participants × 1 point). We calculated the overall total score per cue (i.e., session) by summing the products (i.e., frequency × the number of points) of each cell. We then obtain the following ranking across all participants: 1) anticipatory auditory cue, 2) anticipatory vibrotactile cue, 3) auditory control cue, and 4) vibrotactile control cue. Only slightly more participants favored the auditory over the vibrotactile anticipatory cue, suggesting there is no clear preference for one cueing modality

Table S5.1. Frequency table on the ranks assigned to each session. The last column represents the resulting end positions (higher values represent a higher preference).

Session	Rank 1	Rank 2	Rank 3	Rank 4	Total score
A	13	8	2	1	81
A	10	11	3	0	79
C	1	4	7	12	42
C	0	4	12	11	38

Third, we also asked participants how much money they were willing to spend extra on a car that prevents motion sickness. The responses varied greatly, from €0 to €5000, with an average of €778.

Lastly, we also asked participants if they wanted to alter the cue in some aspect. The most frequently given answer was related to personalization of the cues. For example, changing the voice of the auditory cues or using non-speech cues. Other suggestions relating to the vibrotactile cues were to alter its duration, extend the signal to the lower back, and to create a more gradual cueing pattern. No suggestions were made regarding the motion direction the vibrotactile cues indicated. We explicitly mitigated possible ambiguity on this aspect by including a short training session in the experiment (see Procedure). This decision was partly motivated after observing that participants disagreed on the motion direction the vibrotactile cues would indicate in a pilot study (using a different sample). Some participants thought a cue from hip to knee announced a forward motion, while others thought it announced a backward motion. The same ambiguity applied for the cue from knee to hip. This may suggest that some participants relate the directionality of the cue to position in space whereas others relate it to optic flow during self-motion. The results of our pilot test point out that some training on the use of vibrotactile cues is important. Additionally, providing the opportunity to personalize the directionality of the cues could be among the aspects through which the effectiveness of vibrotactile cues may be enhanced.

Development of average MISC scores per session with replacement of missing data

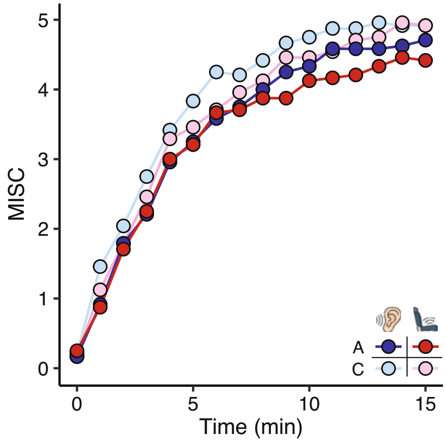


Figure S5.5 The development of raw MISC scores averaged across participants for each of the four sessions. In contrast to Figure 5.3a of the main text, we here replaced missing data (as the result of a stop-criterion at MISC ≥ 6) with the last rated MISC score.

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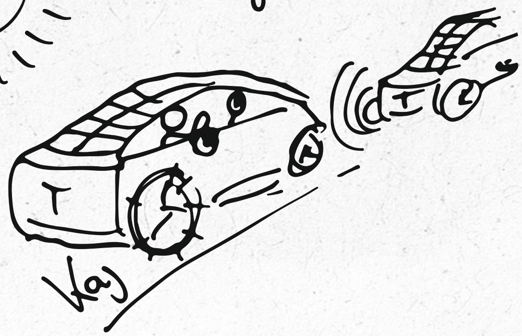
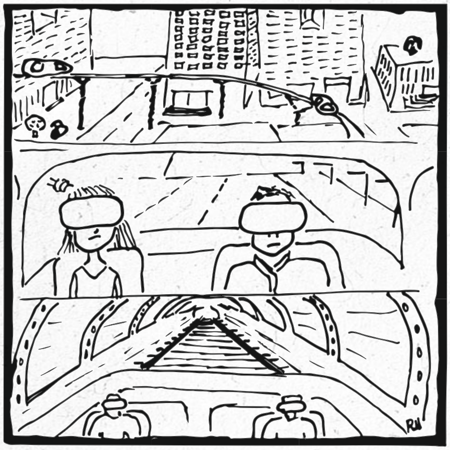
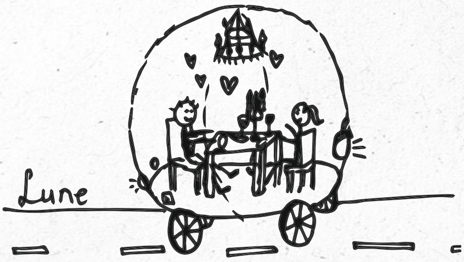
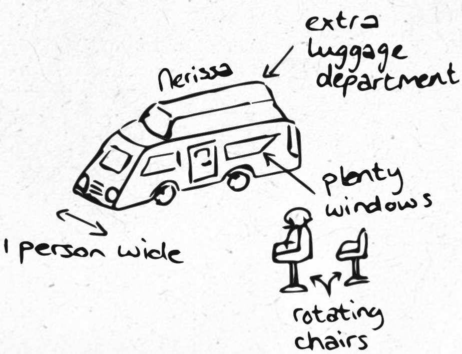
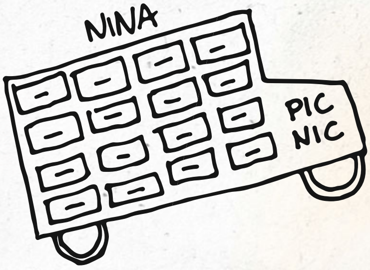
Groen en file-vrij









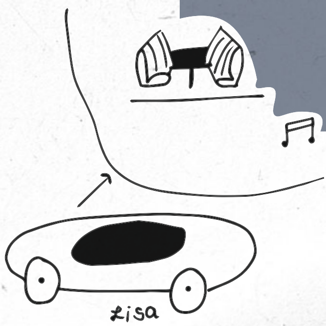


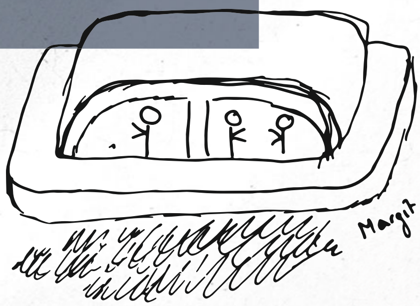
CHAPTER 6

Anticipatory cues can mitigate car sickness on the road

Anna JC Reuten, Ilhan Yunus, Jelte E Bos,
Marieke H Martens & Jeroen BJ Smeets (2024b)

Under Review





Abstract

Car passengers experience much more car sickness than car drivers. We assume that this is because drivers can better anticipate the car's motions. Does helping passengers to anticipate the car's motions then mitigate car sickness? Indeed, laboratory studies have shown that anticipatory cues which announce one-dimensional motions of a linear sled mitigate sickness to a small extent. Does this mitigation generalize to real car driving? We tested this in a car ride on a test track along a trajectory involving lane changes, accelerations, and decelerations. We show that vibrotactile cues mitigated car sickness in passengers. Auditory cues were less effective. The mitigating effect of the vibrotactile cue was considerable: a 40% decrease in car sickness symptoms, a larger effect than we found in the laboratory. Automated vehicles can predict their own motion very well. They could thus provide vibrotactile cues to mitigate car sickness in their passengers.

Introduction

The lifetime incidence of car sickness may be as high as 58% (Reason and Brand 1975), and predominantly concerns car passengers rather than drivers (Schmidt et al. 2020). As the majority of car occupants currently are drivers (Armoogum et al. 2014, TSGB 2022, BTS 2023), the number of car travelers who may experience car sickness will multiply following a human-to-automated driving transition (reviewed by Iskander et al. 2019). Additionally, this transition will include a phase of conditional or high driving automation during which the system could require a take-over of vehicle control (SAE 2021). Motion sickness, an umbrella term for car sickness, sea sickness and other variants, has been observed to impair human performance (Bos 2004, Matsangas et al. 2014, Dobie 2019). Needing to take over vehicle control whilst feeling car sick could thus potentially compromise road traffic safety (Diels and Bos 2016). For these reasons of comfort and safety, it is essential to find a solution to mitigate car sickness in passengers.

Understanding why car drivers experience less car sickness compared to car passengers provides a starting point for finding a solution. Whereas passengers are passively subjected to the car's motions, drivers actively control them. Rolnick and Lubow (1991) demonstrated that participants in active control of self-motion reported less motion sickness compared to yoked participants passively exposed to the same stimulus. The sensory conflict, or more specifically, neural mismatch theory may provide an explanation for this observation (Reason and Brand 1975, Reason 1978, Oman 1982). The theory proposes that motion sickness develops following a neural mismatch between integrated vestibular, visual, and somatosensory signals on self-motion, and expectations or predictions thereof as generated by an internal model. During active self-motion, efference copies resulting from motor commands may be used by this internal model to predict afferent sensory output. This could minimize a possible neural mismatch and consequently mitigate motion sickness. The decreased susceptibility of car drivers might thus be explained by their advantage to anticipate self-motion. Finding a way for passengers to better anticipate passive self-motion may accordingly mitigate car sickness.

Automated vehicles can predict their own motion very well, and should be able to respond to unexpected situations quickly. They could provide cues to alert passengers of upcoming driving maneuvers such as braking or overtaking. Several studies investigated the effectiveness of *anticipatory cues* using visual (Feenstra et al. 2011, Karjanto et al. 2018, 2021, de Winkel et al. 2021, Hainich et al. 2021), auditory (Kuiper et al. 2020a, Diels and Bos 2021, Maculewicz et al. 2021), or tactile (Yusof et al. 2020, Karjanto et al. 2021, Kremer et al. 2022, Li and Chen 2022, Reuten et al. 2023, 2024a) stimuli. A limitation of visual and auditory cues is that they could interfere with tasks that passengers of fully automated vehicles may want to perform. Examples include listening to music, reading, and watching videos – tasks that occupy the auditory and/or visual modality (Pfleging et al. 2016, Detjen et al. 2020, Schmidt et al. 2020). Passengers could accordingly miss a cue (Meng and Spence 2015) or feel disturbed by it (Diels and Bos 2021). Visual cues could moreover aggravate, rather than mitigate motion sickness (Stauffert et al. 2020, Karjanto et al. 2021). Providing cues via the tactile modality may therefore be more desirable in automated vehicles. Studies differ regarding their conclusion on the effectiveness of tactile cues: some report a significant reduction in motion sickness (Karjanto et al. 2021; Li and Chen 2022) whereas others do not (Yusof et al. 2020, Kremer et al. 2022, Reuten et al. 2023, 2024a). We argued that the statistical power of our studies was too low (Reuten et al. 2024a). An internal meta-analysis of our studies, including a study on auditory cues (Kuiper et al. 2020a), showed that anticipatory cues are overall effective in mitigating motion sickness (Reuten et al. 2024a). All of these studies were performed in the same laboratory, in which we exposed participants to one-dimensional motion in fore-aft direction on a linear sled. The goal of the current study is to investigate whether the mitigating effect of anticipatory cues generalizes to real car driving.

Here we expose participants sitting in the back seat of a car to trajectories resembling those of everyday car driving, including variations in speed and direction of motion at irregular intervals. It is more difficult to anticipate upcoming motion when it consists of multiple degrees of freedom. Anticipatory cues may therefore be of greater benefit to participants in the current study. Their predictions of upcoming motions are prone to larger errors compared to those of participants in the laboratory subjected to one-dimensional motion. On the other hand, variability in driving behavior may result in some part of the motion being unannounced by the cues, which could lessen their effectiveness. We investigate three research questions in our study. Our first question is whether anticipatory auditory and vibrotactile cues mitigate car sickness in passengers during real car driving. Our second question is whether one of the cues is more effective. Our third question is how users experience anticipatory cues during a real car drive. Car passengers might consider the cues helpful but too intrusive, which could limit their effectiveness as a solution.

Methods

We asked participants to take part in three sessions in which they were sitting in the back seat of a car without outside view. A trained driver performed scripted driving maneuvers that were unpredictable in onset, speed, and direction. In one session, there were no anticipatory cues (control session). In the other two sessions, either an auditory or vibrotactile cue announced the upcoming maneuver (anticipatory sessions). To determine if the cues mitigated car sickness, we compared the development of self-reported car sickness symptoms in each anticipatory session to that in the control session. We quantified the reduction in car sickness using the same analysis approach as in our prior studies performed on a linear sled (Reuten et al. 2023, 2024a).

Participants

We intended to recruit a sample larger than in our prior cueing studies to increase statistical power. Because of limited resources, we could however only recruit 15 participants. One participant could not be included in the results because he dropped out after the first session, resulting in a sample size of 14 participants (*M* = 34 years old, 7 females). All participants were Volvo Cars employees who had not participated in studies on anticipatory cueing before. Participants could participate if they had experienced symptoms of motion sickness in the last five years and were in overall good health according to self-report, which included not suffering from vestibular disorders. We asked participants to fill in the Motion Sickness Susceptibility Questionnaire (MSSQ-Short; Golding 2006) from which we observed that the average susceptibility of our sample fell within the 59th percentile, which is within one standard deviation of the general population mean. The study received ethical approval from the Swedish Ethical Review Authority (reference number: 2022-07311-01).

Motion apparatus and stimulus

We performed the study at a test track (the Hällered Proving Ground in Sandhult, Sweden) to prevent interference from other traffic. We used a left-hand drive Volvo XC90 in which participants sat in the back seat diagonal to the driver. Because vision on the road ahead is known to modulate car sickness (Griffin and Newman 2004), we used opaque materials to block outside view (see Figure 6.1a). Participants could hear engine noises as we did not manipulate auditory information. We set the air conditioning to 20°C with nonzero but minimal airflow.

All sessions consisted of 16 sequences of driving maneuvers performed at a straight 630 m long track (Figure 6.1b). We included the following maneuvers: accelerations, decelerations, left lane changes, and right lane changes. Drivers practiced performing the maneuvers in a way that they would reach a peak acceleration of 2 m/s^2 as guided by direct feedback from an accelerometer. This value corresponded for accelerations

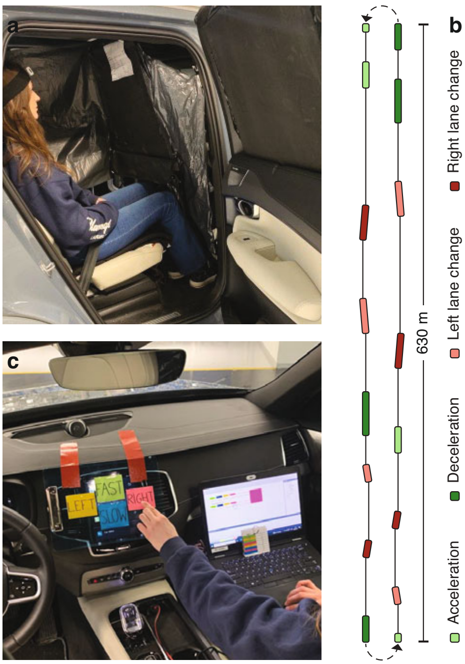


Figure 6.1 **a.** Participants sat in the back seat of a car without outside view. We instructed them to keep to their head upright and eyes open. **b.** Example of two sequences, connected by low velocity U-turns. Driving maneuvers (colored bars) were separated by intervals of 5 or 10 s driving at constant speed (black lines). Long bars correspond to a maneuver performed at 40 km/h, short bars to ones at 20 km/h. **c.** The setup used to trigger the cues and to coordinate initiation of the corresponding driving maneuver.

and decelerations to a change in speed of 20 km/h in 3 s. Accelerations corresponded to speed increases from 0 to 20 km/h or 20 to 40 km/h; decelerations corresponded to speed decreases from 40 to 20 km/h or 20 to 0 km/h. As our test track was 630 m, we limited maximum speed to 40 km/h because driving at higher speeds would take up a substantial portion of the available track distance. Lane changes consisted of a lateral acceleration immediately followed by a slightly lower deceleration lasting about 3 s in total, resulting in a 3 m lateral displacement. Both left and right lane changes were performed at 20 and 40 km/h. Given that each type of maneuver was performed at two speeds, the number of driving maneuvers totalled to eight. We separated the maneuvers by pseudorandom intervals of 5 or 10 s driving at constant speed (20 or 40 km/h) to reduce the predictability of motion onset.

To prevent participants from anticipating the next maneuver from memory, we predefined four sequences with a different order of the driving maneuvers (see Supplementary Table S6.1). Three of the sequences contained all eight maneuvers, implying that the deceleration to 0 km/h occurred at the end. We created one sequence in which the car also decelerated to 0 km/h halfway the sequence, instead of accelerating to 40 km/h. The lower average speed in this sequence would result in a shorter distance travelled, implying that the car would stop before the starting position of the next sequence. Because the other sequences covered the maximum track distance available, we used longer intervals of driving at constant speed in this sequence. This resulted in a longer sequence duration (~109 s) in comparison to the other three sequences (~74 s). We repeated the four sequences four times, totaling to 16 sequences per session. We created three variations of the order of the 16 sequences and exposed all participants to each variation once – distributing the variations approximately equally across the anticipatory and control sessions. Sequences were connected by verbally announced left U-turns that were performed at minimal driving speed (< 5 km/h). We used three drivers throughout the experiment. All participants performed at least two sessions with the same driver.

Anticipatory cues

In the two anticipatory sessions, participants received either auditory or vibrotactile cues which announced upcoming driving maneuvers. We based the design of our cues on the results of an office pilot study in which we asked colleagues' opinions about the clarity and comfort of various auditory and vibrotactile cues. For the auditory cues, we selected voice recordings of a female voice in a British accent. We used short words (550 ms) to alert the participants: "fast" to indicate accelerations, "slow" to indicate decelerations, "left" to indicate left lane changes, and "right" to indicate right lane changes. To present the vibrotactile cues, we used a seat cushion in which six small (approximately 5 x 20 mm) eccentric rotatory mass vibration motors were embedded across two columns aligned with the upper legs and three lateral rows. Each cue consisted of two 225 ms vibrations bursts of one row or column of motors, with 100 ms between the two bursts (Supplementary Figure S6.1). We used the row positioned close to the knees and that close to the hips to indicate accelerations and decelerations respectively. Vibrations of the column of motors beneath the left and right upper leg indicated left and right lane changes respectively.

Following the predefined maneuver sequence, the experimenter in the front seat (same person throughout all sessions) activated the cues manually by clicking the corresponding button in a custom-made software program. About half a second after the cue had ended, the experimenter tapped a card of the corresponding maneuver on a clipboard mounted on top of the center console to prompt the driver to initiate the maneuver (Figure 6.1c). In conclusion, the onset of each cue was approximately 1 s prior to the start of the maneuver.

Procedure

Participants performed the three sessions in a random order, with each possible order performed by at least one participant. Sessions were separated with a minimum of 1 and maximum of 9 days, except for two participants for whom the duration between two sessions was limited to several hours due to time constraints in their schedule. Prior to starting the first session, we provided participants the opportunity to read an information letter about the experiment. After answering any questions, we asked them to sign an informed consent sheet and to fill out the MSSQ-Short (Golding 2006). For each session, we drove participants to a test track located five minutes away from the office. During this short journey, participants sat in the front passenger seat with outside view to minimize the risk of developing car sickness.

After arriving at the test track, participants moved to the back seat diagonal to the driver where they received additional instructions. We explained participants how to use the Motion Illness Symptoms Classification scale we used throughout the experiment (MISC; Table 6.1; Bos et al. 2005; Reuten et al. 2021). We also described the four types of driving maneuvers the car would perform. Prior to starting an anticipatory session, we let participants hear or feel all four cues two times. The first time, we explained which

Class description		**MISC**
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, yawning, headache, tiredness, sweating, stomach awareness, burping, blurred vision, salivation, … but no nausea	vague	2
	little	3
	rather	4
	severe	5
Nausea	little	6
	rather	7
	severe	8
	retching	9
Vomiting		10

Table 6.1 The Motion Illness Symptoms Classification (MISC) used to assess motion sickness symptomatology (Bos et al. 2005, Reuten et al. 2021).

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maneuver the cue announced. The second time, we asked participants to indicate which maneuver they thought the cue announced. All participants performed this task without errors. Lastly, we instructed participants to keep their eyes open and head upright during the drive. After the instructions, we asked participants to rate a pre-test MISC score. All ratings were MISC ≤ 1 with a single exception of MISC = 2 for one participant in one session. We aborted a session when a participant rated MISC ≥ 7. After each session and at the end of the experiment, we asked participants to fill out a user experience questionnaire at the office.

Data collection

Our main focus was on the development of car sickness symptomatology during the sessions. The MISC is a single value self-report rating scale that is based on the progression of motion sickness symptoms, with a severity grading within each symptom class (Table 6.1). We asked participants to verbally indicate their MISC score right after each sequence, just before the turn. Additionally, we collected acceleration data of the car and the head motion of the participant (the latter not analyzed in this paper). We used an OxTS RT3000 IMU to measure the car's accelerations, which was configured to provide an estimation of the accelerations acting on the participant.

To gain more insight into the user experience of the anticipatory cues, we asked participants to complete a questionnaire after each session and at the end of the experiment. After each session, we asked participants to indicate if and when they noticed the cues (multiple-choice). If they had noticed cues, we asked them to indicate how many times those were presented (multiple-choice); and to evaluate them along several user experience dimensions (Likert scale). At the end of the experiment, we asked participants if they realized that the cues had always been presented at a fixed moment relative to the onset of the driving maneuvers (multiple-choice); which cue they preferred to announce upcoming driving maneuvers (multiple-choice); to rank the sessions from most to least favorite (rank); if they would want to use the cue they preferred in their (self-driving) car (multiple-choice); and how much money they would be willing to spend extra on a car preventing car sickness (open-ended).

Data analysis

To determine the effectiveness of the anticipatory cues, we use the same data analysis approach as in our prior studies (Reuten et al. 2023, 2024a). Using this approach, we can quantify the reduction in the development of car sickness in each anticipatory session relative to the control session in one value: R. This allows for an easy comparison of the effectiveness of anticipatory cues (or other interventions) between experimental sessions and studies. For each cue, we determine R using the steps described below.

We first calculate the reduction in MISC scores between the anticipatory (A) and control (C) session at each turn (t) and individual participant (i) by

$$R_{ti} = \frac{(C_{ti} - A_{ti})}{(C_{ti} + A_{ti})} \quad (1)$$

This relative reduction value facilitates the interpretation of the effectiveness of the cues as the distribution of R is symmetrical around zero (indicating no effect), with a maximum value of 1 ($A_{ti} = 0$, $C_{ti} \neq 0$) and mimum value of -1 ($A_{ti} \neq 0$, $C_{ti} = 0$). We do not determine R_{ti} for pre-test measurements and cannot determine R_{ti} for sequences without data (i.e., after reaching the stop-criterion). Also, when $C_{ti} = A_{ti} = 0$, it is impossible to determine R_{ti}. This is not problematic for our analysis as we weigh the data as explained below; undefined R_{ti} values will receive a weight of zero. Because participants typically rate MISC 0 or 1 at the beginning of a session, R_{ti} will have a value of -1, 0 or 1 for the first sequences. To take account of the resolution of R_{ti} when determining the average reduction across a session, we weigh each of the 16 obtained R_{ti} values by the sum of the two underlying MISC scores. Consequently, R_{ti} values that are calculated on higher MISC scores will receive a larger weight

$$w_{ti} = C_{ti} + A_{ti} \quad (2)$$

We can then calculate the average reduction per participant i by

$$\bar{R}_i = \frac{\sum_t w_{ti} R_{ti}}{\sum_t w_{ti}} = \frac{\sum_t (C_{ti} - A_{ti})}{\sum_t w_{ti}} \quad (3)$$

and at each turn t by

$$\bar{R}_t = \frac{\sum_i w_{ti} R_{ti}}{\sum_i w_{ti}} = \frac{\sum_i (C_{ti} - A_{ti})}{\sum_i w_{ti}} \quad (4)$$

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Equation 3 indicates that $\bar{R}_i$ is proportional to the sum of MISC score differences between the anticipatory and control session.

To express the overall reduction generated by the cue across all turns and participants, we again consider the resolution of R_{ti} using

$$\bar{R} = \frac{\sum_t \sum_i w_{ti} R_{ti}}{\sum_t \sum_i w_{ti}} = \frac{\sum_i w_i \bar{R}_i}{\sum_i w_i}, \text{ with } w_i = \sum_t w_{ti} \quad (5)$$

To translate this final value into a more intuitive measure, we provide a conversion of R to a percentual decrease in MISC score (i.e., $S = (1 - A/C) \times 100$) in Supplementary Figure S6.2. Note that we use the measure R instead of a percentage change as exchanging C and A only results in a change of sign of R. This makes it suitable for averaging: if C and A are drawn from a random distribution, the average of R will be zero, whereas the average of S will become negative.

Statistical analysis

Our first question is whether our anticipatory auditory and vibrotactile cues mitigated car sickness. For both cues, we accordingly performed a weighted one-sided t test ($\alpha = 0.05$) on the $\bar{R}_i$ values (each weighted by w_i) to determine whether the overall reduction $\bar{R}$ was larger than zero (corresponding to no reduction). We express the confidence of our estimates of $\bar{R}$ in one-sided 95% confidence intervals (coherent with our one-sided analysis) using bootstrapping of $\bar{R}_i$ and corresponding weights. Our second question is whether one cue was more effective in mitigating car sickness. We hence performed a weighted paired-samples t test (α = 0.05) between the $\bar{R}_i$ values (each weighted by w_i) of the auditory and vibrotactile session. We here determine two-sided 95% confidence intervals calculated with bootstrapping of R_{ti} and corresponding weights to express the confidence of our estimates of $\bar{R}_i$. Our last question focused on gaining insight into the user experience of anticipatory cues during a real car ride. We analyzed the results of the user experience questionnaire using visualizations of descriptive statistics without performing statistical tests.

Results

Before answering our research questions, in Figure 6.2a we present an impression of the overall behavior: the average MISC score across participants at each turn as a function of the average cumulative sequence duration (see Supplementary Figure S6.3 for the raw data per participant). The duration of the sequences was comparable across participants in all sessions (the horizontal error bars within each data point are small). The pattern of MISC scores suggests a reduction in car sickness in both anticipatory sessions compared to the control session, with a larger reduction for the vibrotactile cue.

To answer our first question, we used our measure R to quantify the reduction in car sickness for each cue per participant (Figure 6.2b). The resulting $\bar{R}_i$ values differ considerably between participants, but most participants received some benefit from both cues (both data points are above zero). For both cues, $\bar{R}_t$ did not vary systematically across the sequences of a session (Supplementary Figure S6.4). As the cues generated a constant effect, it is meaningful to express the effectiveness of each cue in one value. On average, the overall reduction appears larger for the vibrotactile cue (Figure 6.2c). The weighted one-sided t test indicated that the vibrotactile cue significantly mitigated car sickness, with $\bar{R}$ = 0.26 (t = 2.8, p = 0.014). The reduction generated by the auditory cue was not significantly larger than zero, with $\bar{R}$ = 0.10 (t = 1.9, and p = 0.085).

To answer our second question, we tested whether the two cues differed in the generated reduction of car sickness. In line with visual inspection of the data, the weighted paired-samples t test indicated that the vibrotactile cue generated a significantly larger reduction in car sickness compared to the auditory cue, with a weighted $\bar{R}$ difference of −0.13 (t = −2.6, p = 0.021).

In addition to these planned comparisons, we explored whether the effectiveness of the cues in the current study differed from that in our prior laboratory studies performed on a linear sled. We therefore plot the results from an internal meta-analysis on the overall effect of anticipatory cues ($\bar{R}$ = 0.06; Reuten et al. 2024a) with its 95% confidence interval in Figure 6.2c. The confidence interval of the auditory cue overlaps, whereas that of the vibrotactile cue falls above the upper bound of the overall effect. This suggests that our vibrotactile cue was more effective in mitigating car sickness during a real car drive compared to anticipatory cues in the laboratory.

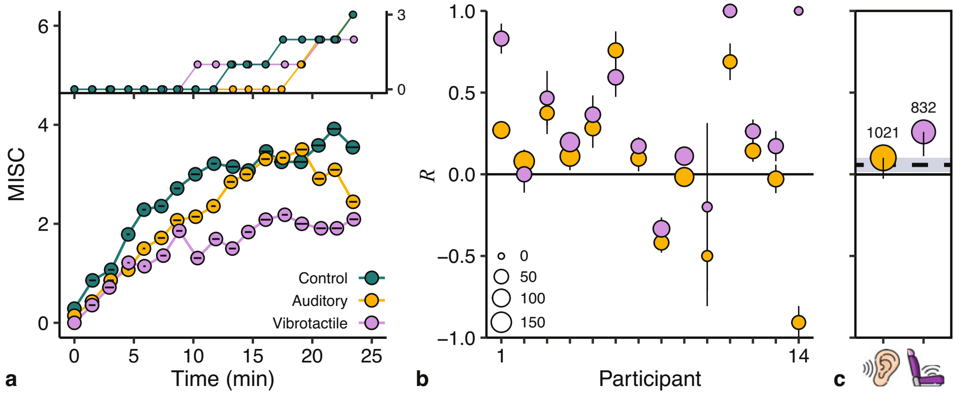


Figure 6.2 a. The development of car sickness during each session as a function of time. The (small) horizontal error bars represent the standard deviation of the cumulative duration of the sequences. After a participant reached the stop-criterion (frequency in inset), they do not longer contribute to the average of that session, resulting in a decrease of the average MISC. If the stop-criterion was reached in the control session, we excluded the data of this participant on the corresponding sequences in the anticipatory sessions (similar to R in the other panels). **b.** The reduction in car sickness for individual participants ($\bar{R}_i$) in the two anticipatory sessions in comparison to the control session. Error bars are 95% confidence intervals. **c.** The overall reduction in car sickness across all sequences and participants for each cue. Coherent with our one-sided analysis, we plot one-sided 95% confidence intervals. The dashed line represents the overall reduction of anticipatory cues we found in the laboratory, with the grey band representing their 95% confidence interval. In panels b and c, the size of a data point reflects its weight, corresponding to the sum of MISC scores underlying the data (see legend).

To answer our third question, we investigated the responses to the user experience questionnaire. The results indicated that all participants had noticed the auditory and vibrotactile cues for all driving maneuvers. The majority of participants also correctly indicated that the cues were presented before the onset of each maneuver (Figure 6.3a). Unsurprisingly, no participant indicated to have noticed cues in the control session. After the experiment, we asked participants if they realized that the cues had always been presented at a fixed moment relative to the onset of the maneuvers. Twelve participants indicated they did in both anticipatory sessions, the two other participants indicated they did only in the vibrotactile sessions.

On the whole, participants rated both cues positively along several user dimensions (Figure 6.3b). The cues helped participants to predict the onset of the maneuvers and the message they conveyed was clear. In terms of comfort and pleasantness, the cues were rated acceptable on a group level. The standard deviation on these dimensions was however large, indicating that participants disagreed concerning these aspects. The duration of the cues was rated neutral, with more variability in responses for the vibrotactile cue. The intensity of the cues was appropriate, with responses tending towards being too strong rather than being too weak. In Supplementary Figure S6.5, we present the results of some exploratory analyses on the relationship between several user dimensions as well as their relationship with $\bar{R}_i$.

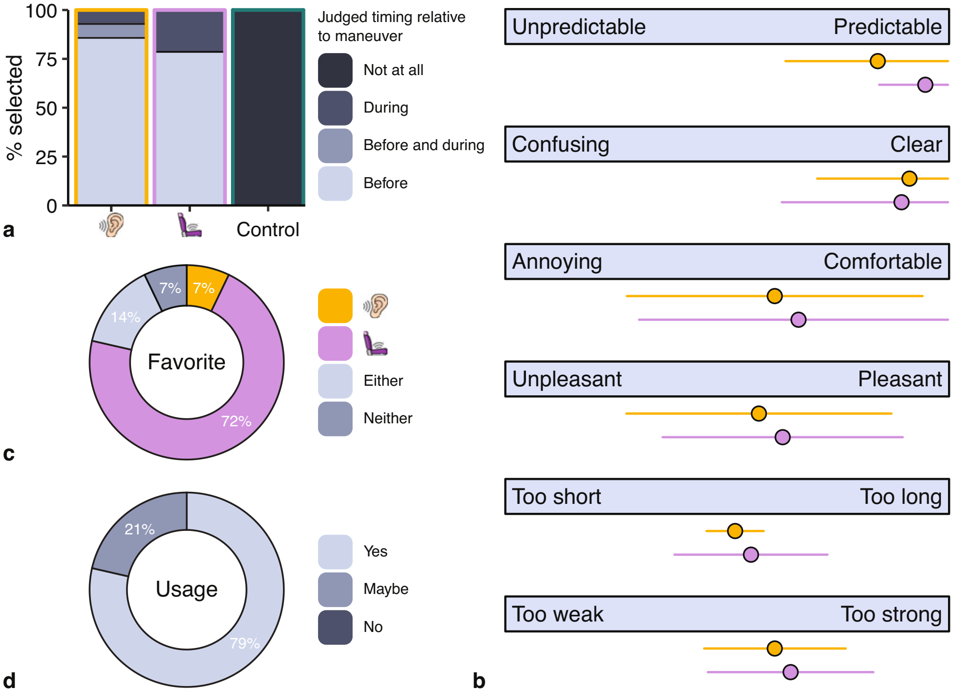


Figure 6.3 Results of the user experience questionnaire in which participants **a.** indicated if and when they thought anticipatory cues were presented, **b.** evaluated the cues along several user dimensions, **c.** indicated which cue they preferred to announce upcoming driving maneuvers, and **d.** if they would want to use their favorite cue in their (automated) car.

By far most participants expressed a preference for the vibrotactile cue (Figure 6.3c). They reported that this cue was more intuitive and easier to understand, as well as less intrusive and annoying compared to the auditory cue. When asking participants to rank the sessions from most to least favorite, we obtained a corresponding overall ranking: 1) vibrotactile session, 2) auditory session, and 3) control session. A frequency table on the rankings can be found in Supplementary Table S6.2.

The majority of participants would want to use the cue they preferred in their (automated) car (Figure 6.3d). Several participants mentioned that a cueing system should be optional in use and implemented as a turn-on/turn-off function. The amount of money participants were willing to pay for a car preventing car sickness varied between €0 and €4400, with an average of €513.

Discussion

In prior laboratory studies, we demonstrated the potential of anticipatory cues as a solution to mitigate motion sickness under controlled experimental conditions for one-dimensional motion. Does their effect generalize to real car driving? We exposed participants sitting in the back seat of a car without outside view to three sessions of unpredictable driving maneuvers. In two anticipatory sessions, either auditory or vibrotactile cues announced whether the car would accelerate, decelerate, make a left lane change, or a right lane change. Using the same analysis approach as in our previous studies (Reuten et al. 2023, 2024a), we determined the reduction in the development of self-reported car sickness in each anticipatory session relative to a control session without cues. The results indicate that the vibrotactile cues mitigated car sickness (Figure 6.2c). Auditory cues were less effective (Figure 6.2b) and generated no mitigation overall (Figure 6.2c). In accordance with the results of the effectiveness of the cues, participants expressed a clear preference for the vibrotactile cue (Figure 6.3c). The reduction in car sickness they generated was larger than the overall reduction generated by anticipatory cues in the laboratory (Figure 6.2c). The mitigating effect of our vibrotactile cue translates to a 40% reduction in car sickness symptoms (Supplementary Figure S6.2).

Besides the anticipatory cues, differences in driving behavior between the sessions could influence R. To rule out that different driving behavior could have caused an apparent reduction in car sickness, we investigated the car's accelerations. We analyzed the difference in the sickening component of the total of linear accelerations between each anticipatory and control session. For all sessions, we first calculated a frequency weighted root mean square acceleration (a_w) wherein we assumed that the frequency weighting as determined for vertical accelerations (ISO 2631-1 1997) also applies to lateral and longitudinal accelerations. This approach accounts for participants stopping a session early as opposed to calculating conventional motion sickness dose values that increase with exposure duration (ISO 2631-1 1997). For all participants, we then calculated the difference in a_w between each anticipatory and control session. Based on these differences, we determined a 95% confidence interval for each comparison. Both included zero, indicating that there was no systematic difference in the sickening component of driving behavior between the anticipatory and control sessions.

The smaller (and non-significant) reduction generated by the auditory cues might indicate that the auditory modality is less suited to mitigate car sickness. However, this interpretation might be incorrect when considering that the significant reduction generated by comparable auditory cues in Kuiper et al. (2020a) was of equal size: R = 0.10 (see Reuten et al. 2023). As our sample consisted of only 14 participants, the statistical power of our study may have been too low to demonstrate a significant reduction by the auditory cue. Nonetheless, two reasons may indicate that it holds greater value to focus future research on optimizing the effect of vibrotactile cues. First, the vibrotactile cues did generate a considerable (and significant) reduction in car sickness despite our small sample. Second, participants preferred the vibrotactile cue. It was described as intuitive and easy to understand whereas the auditory cue was described as intrusive and annoying. Vibrotactile cues may also be more desirable in the context of automated driving: they do not interfere with audiovisual tasks passengers may want to perform (Pfleging et al. 2016, Detjen et al. 2020, Schmidt et al. 2020). Even though auditory cues could possibly be effective, it may be more worthwhile to focus on vibrotactile cues in future studies.

Our study shows that anticipatory vibrotactile cues can mitigate car sickness in passengers. The cues mitigated car sickness despite the fact that some part of the motion was not announced due to variability in human driving behavior. Which motions and nuances therein should cues convey during real-life car driving? Providing car passengers information about the sharpness of a curve or the intensity of braking might enhance the effect of anticipatory cues. However, providing cues for unprovocative motion should be avoided as this could lower user acceptance and may result in passengers disabling the cueing system (Reagan et al. 2018). If found beneficial, nuances in motion parameters may be conveyed by varying the temporal and spatial aspects of a cue. For example, individuals associate shorter intervals between vibration pulses or auditory beeps with a greater sense of urgency (Edworthy et al. 1991, Meng and Spence 2015, Van Erp et al. 2015). As the driving system's prediction accuracy is higher for accelerations in the near future, studies should consider investigating these questions for anticipatory intervals limited to a few seconds. The results from Reuten et al. (2023) suggest that the effectiveness of vibrotactile cues does not depend on their timing for intervals of 0.33, 1 and 3 s, though the statistical power of that study was limited. In any case, human limitations in the ability to detect, distinguish, and understand different cues should be considered in the design of a cueing system (e.g., Jones and Sarter 2008; Fitch et al. 2011; Nees and Walker 2011; Petermeijer et al. 2016; Duthoit et al. 2018).

Large scale surveys indicate that members of the public express concern about perceived risks and safety, or in a broader term those aspects relating to trust in the automated driving system (Schoettle and Sivak 2014, Choi and Ji 2015, Kyriakidis et al. 2015, Ward et al. 2017). Communication of the system's understanding of the environment and its planned driving maneuvers have been proposed as a way to increase trust (Koo et al. 2015, Von Sawitzky et al. 2019, Ha et al. 2020). Besides mitigating car sickness, anticipatory cues could thus have additional advantages for passengers of automated vehicles.

In previous studies, we demonstrated the overall effectiveness of anticipatory cues in the laboratory. Here we show that the effect of vibrotactile cues generalizes to real car driving. They mitigated car sickness in passengers exposed to driving maneuvers resembling those of everyday car driving. The mitigating effect of the vibrotactile cue was considerable: a 40% decrease in car sickness symptoms, a larger effect than we found in the laboratory. To our knowledge, our study is the first to demonstrate the effectiveness of vibrotactile cues to mitigate car sickness for both lateral and longitudinal driving maneuvers. Automated vehicles can predict their own motion very well. They could thus provide vibrotactile cues to mitigate car sickness in their passengers. This could alleviate the expected increase of car sickness in society following the introduction of (fully) automated vehicles. To conclude, our study demonstrates the effectiveness of anticipatory vibrotactile cues as a solution to mitigate car sickness in passengers.

SUPPLEMENTARY INFORMATION

6

Order of driving maneuvers

Table S6.1 We predefined four sequences that each contained eight driving maneuvers. The maneuvers were separated by pseudorandom intervals of 5 or 10 s driving at constant speed (indicated by "–"). Sequences 1–3 contained all eight possible maneuvers. In sequence 4, we included the deceleration to 0 km/h twice and omitted the acceleration maneuver to 40 km/h. We created three variations in which we repeated the four sequences four times in a random order, totaling to 16 sequences per session.

Sequence 1		**Sequence 2**	
Driving maneuver	*Onset (s)*	*Driving maneuver*	*Onset (s)*
0 → 20 km/h	0	0 → 20 km/h	0
–	3	–	3
Left lane change	8	Left lane change	8
–	11	–	11
20 → 40 km/h	21	Right lane change	21
–	24	–	24
Right lane change	34	20 → 40 km/h	34
–	37	–	37
Left lane change	42	Right lane change	42
–	45	–	45
40 → 20 km/h	50	Left lane change	55
–	53	–	58
Right lane change	63	40 → 20 km/h	63
–	66	–	66
20 → 0 km/h	71	20 → 0 km/h	71
Sequence 3		**Sequence 4**	
Driving maneuver	*Onset (s)*	*Driving maneuver*	*Onset (s)*
0 → 20 km/h	0	0 → 20 km/h	0
–	3	–	3
20 → 40 km/h	8	Right lane change	13
–	11	–	16
Right lane change	21	20 → 0 km/h	36
–	24	–	39
Left lane change	29	0 → 20 km/h	44
–	32	–	47
40 → 20 km/h	37	Right lane change	62
–	40	–	65
Left lane change	45	Left lane change	85
–	48	–	88
Right lane change	58	Left lane change	98
–	61	–	101
20 → 0 km/h	71	20 → 0 km/h	106

Spatial and temporal representation of vibrotactile cues

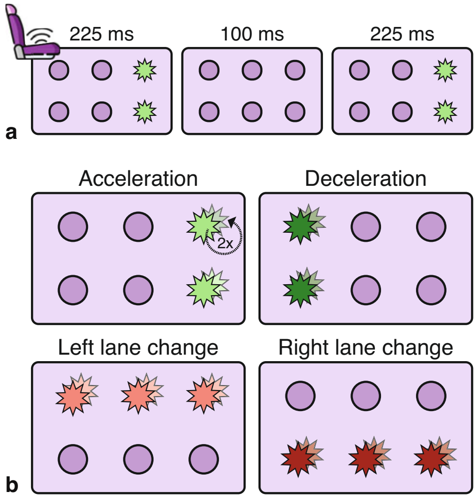


Figure S6.1 Top view of the vibrotactile cushion. **a.** Spatial and temporal representation of the vibrotactile cue indicating an accelerating maneuver. The row of motors positioned near the knees vibrated for 225 ms. After 100 ms without vibration, there was a second vibration burst of 225 ms of the same row of motors. **b.** Illustration of the row or column of motors activated for each driving maneuver. Each cue followed the same temporal pattern as in panel a. All cues thus lasted 550 ms in total.

Converting R to a measure of percentage change

To provide the reader guidance on the interpretation of our measure, we provide a conversion of R to a percentual decrease in MISC scores (i.e., $S = (1 - A/C) \times 100$) in the figure below. Note that we use the measure R instead of a percentage change because for R exchanging C and A only results in a change of sign. This makes it suitable for averaging: if C and A are drawn from a random distribution, the average of R will be zero, whereas the average of S will become negative.

6

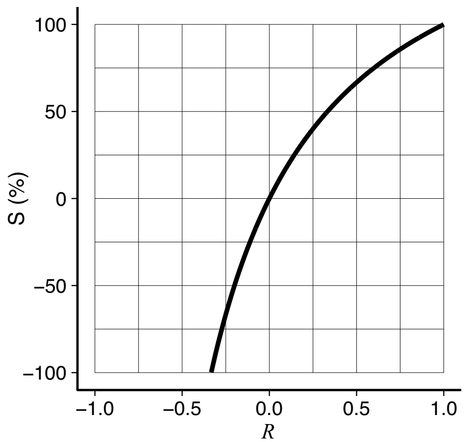


Figure S6.2 Guidance to the interpretation of our measure R in terms of a percentual decrease in MISC scores. Note that R values lower than −0.4 correspond to extremely large negative values of S.

Development of MISC scores per participant

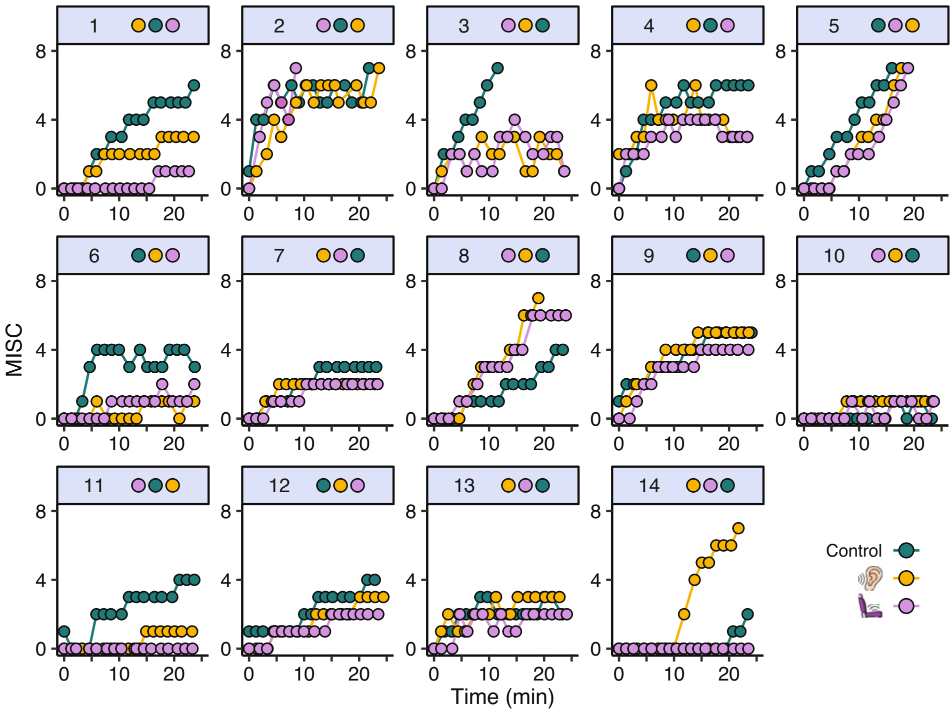


Figure S6.3 The development of raw MISC scores per participant during the 16 sequences within a session. Each panel shows the three sessions of a single participant, the dots in the grey area reflect the order of the sessions for that participant. Participant numbers correspond to those in Figure 6.2b of the main text.

Reduction values per time point

Expressing the reduction in car sickness generated by the cue in one value becomes meaningful when the cue provides a constant effect across a session. For both cues, we observe no systematic differences in the generated reduction across the 16 sequences. All 95% confidence intervals overlap within each session.

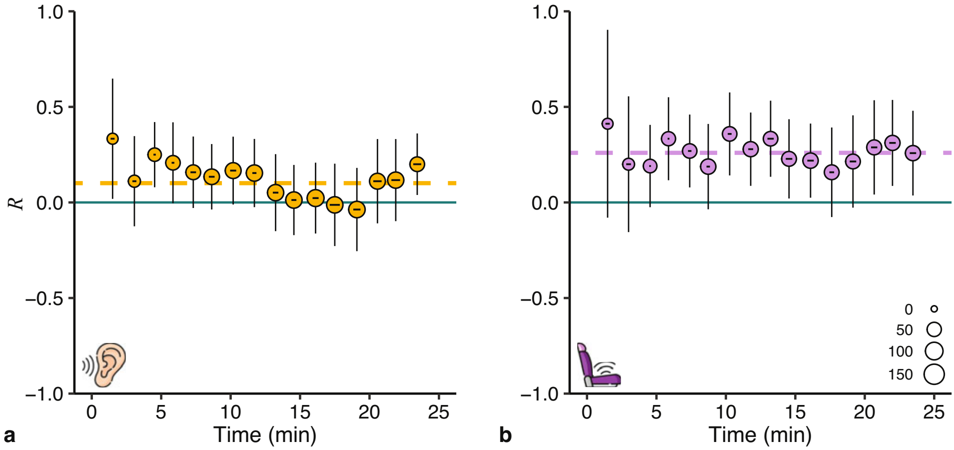


Figure S6.4 The reduction per sequence at each turn ($\bar{R}_t$) for the anticipatory **a.** auditory and **b.** vibrotactile session. The dashed lines correspond to the overall reduction $\bar{R}$. The vertical error bars are 95% confidence intervals calculated with bootstrapping of R_{ti} and corresponding weights. The horizontal error bars are standard deviations which represent the between-participant variability in the mean duration of the anticipatory and control sequence of each participant. The size of a data point reflects its weight for averaging over time, corresponding to the sum of MISC scores underlying the data (see legend).

Exploratory analyses on user experience dimensions

We explored the relationship between the $\bar{R}_i$ values and the results of two user experience dimensions in the figure below. The effectiveness of the cues seems more strongly related to the pleasantness of the cues (panel b) than to their helpfulness to predict upcoming driving maneuvers (panel a). However, the small range in the predictability ratings may hide the existence of a possible correlation. As would be expected, the pattern of results in panel c suggests that the pleasantness and comfortableness of the cues are positively correlated. The comfortableness of the cues seems independent of the judged intensity of the cues (panel d).

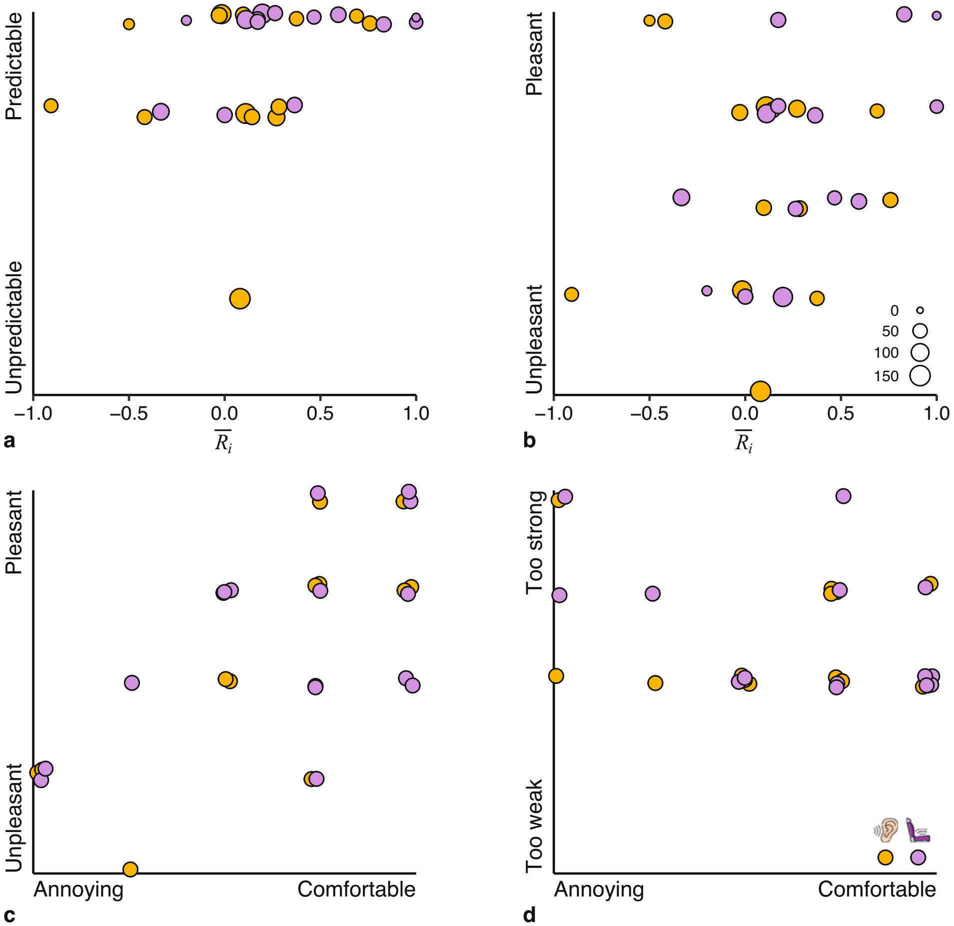


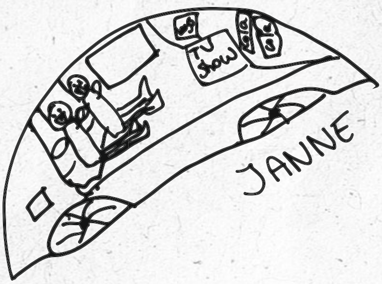
Figure S6.5 Exploratory analyses on several user experience dimensions. In **a.** and **b.**, the size of the data points corresponds to the sum of MISC scores underlying the data (see legend in panel b). We added jitter to the answers on the user experience dimensions for better discriminability of the individual data points.

Frequency table of ranking

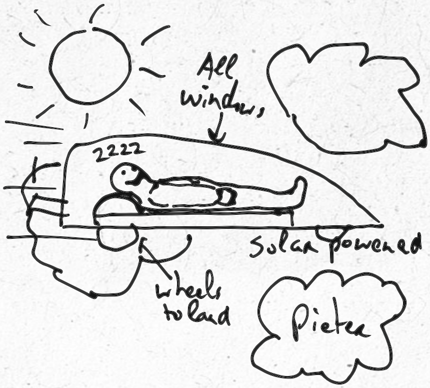
We asked participants to rank the sessions from most (rank 1; 3 points) to least favorite (rank 3; 1 point). The maximum total score is 42 (14 participants × 3 points); the minimum total score is 14 (14 participants × 1 point). We calculated the overall rank per session by summing the products of the frequency × the number of points of each cell.

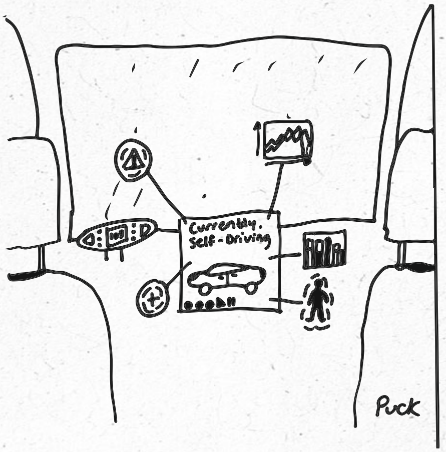
Table S6.2 Frequency table on the ranks our 14 participants assigned to each session. The last column represents the resulting overall rank (higher scores represent a higher preference).

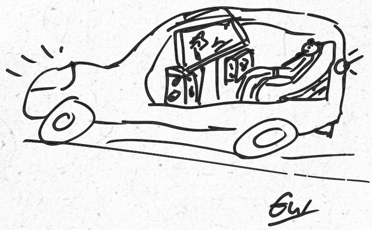
Session	Rank 1	Rank 2	Rank 3	Total score
	3	7	4	27
	10	4	0	38
Control	1	3	10	19

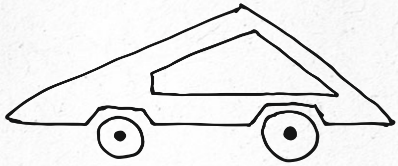


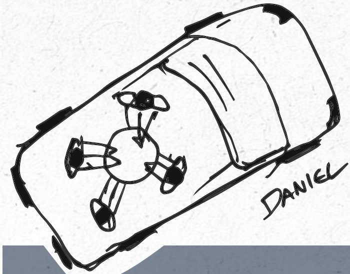
flying car of the future

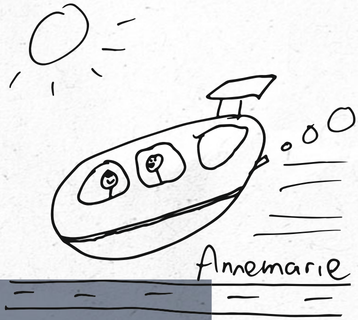






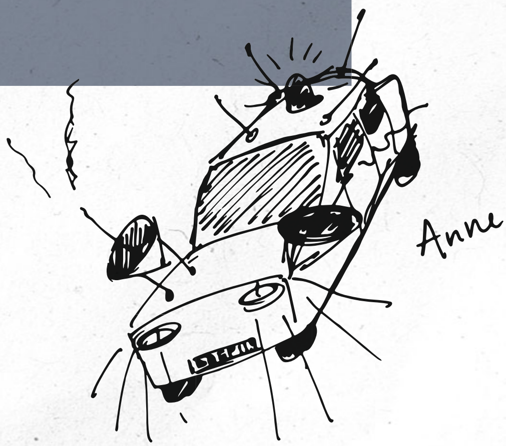


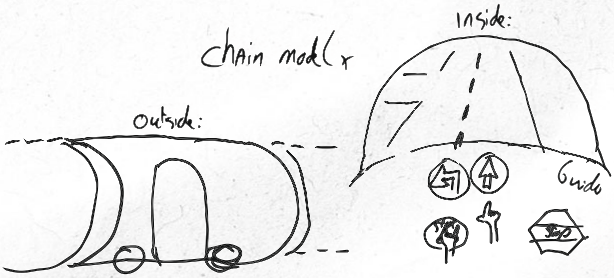




CHAPTER 7

Discussion and conclusion





The overall aim of my dissertation is to contribute to research on the mitigation of motion sickness, particularly in the context of automated driving. To investigate how to mitigate motion sickness, one should be able to quantify its progression unambiguously. In Chapter 2, I therefore investigated the temporal development of ratings on an unpleasantness and symptomatology scale, as well as their mutual dependence using psychophysical rating techniques. In the next Chapter 3, I explored the influence of cognitive cues on the perception of self-motion. The cues had a profound impact, which provided some support for a possible approach to mitigate motion sickness. In Chapters 4 to 6, I investigated the effectiveness of this mitigation approach in the laboratory, and during a real car drive. In the following sections, I will summarize the main results and describe their implications as well as my suggestions for future research. Additionally, I provide an exploratory analysis on the relationship between motion sickness susceptibility and the effectiveness of anticipatory cues. I will close this chapter by listing the three key findings of my work.

Answering the research questions

On the measurement of motion sickness

Numerous self-report rating scales are used to measure motion sickness (for overviews see Lawson 2014b; Cha et al. 2021). They tend to focus on either general unpleasantness (e.g., Reason and Graybiel 1970; Lawther and Griffin 1986; Draper et al. 2001; Keshavarz and Hecht 2011; Jones et al. 2018) or specific symptomatology (e.g., McCauley et al. 1976; Golding and Kerguelen 1992; Golding et al. 2003; Donohew and Griffin 2004; Bos et al. 2005). The plethora of available rating scales indicates that a standard for measuring motion sickness is currently lacking. In **Chapter 2**, I explored how the progression of motion sickness can be unambiguously quantified using single value rating scales: via measuring unpleasantness with the FMS (Keshavarz and Hecht 2011) or symptomatology with the MISC (Bos et al. 2005)? The distribution of rating transitions, indicating whether ratings on consecutive time points within a session increased, decreased, or remained constant, showed that only the ratings on the MISC increased monotonically with exposure duration (Figure 2.1b). The ratings on the FMS showed a peak in decreasing transitions in the center of the scale, suggesting that individuals felt (temporarily) better during a session (Figure 2.1a). Various psychophysical rating tasks indicated that later manifesting symptoms were generally judged as more unpleasant, except for a reduction at nausea onset, which corresponded to feeling better (Figures 2.2–2.5). Independent of the task, feeling slightly nauseated (MISC 6) was consistently associated with less unpleasantness than experiencing severe pre-nausea symptoms such as dizziness, headache, or stomach awareness (MISC 5). These findings indicate that a scale focusing on symptomatology, such as the MISC, captures the progression of motion sickness unambiguously.

On the role of internal models

Prior studies demonstrated that mental imagery, task instructions, and contextual information can modulate self-motion perception of a physical (Mertz et al. 2000, Wertheim et al. 2001, Nigmatullina et al. 2015, Ellis et al. 2017) or visual (Riecke 2009, D'Amour et al. 2021) motion stimulus. Can cognitive cues that suggest self-motion also elicit a percept of self-motion in the absence of a sensory motion stimulus? To answer this question, in **Chapter 3** I seated blindfolded participants on a parallel swing that remained motionless during two sessions, apart from a deliberate perturbation at the start of each session. The only difference between the sessions was a cognitive (non-sensory) induced manipulation of expectations regarding the swing's motion: ceasing or continuing swing oscillations. Participants reported a larger average peak-to-peak displacement of 29 cm in the session with cues suggesting continuing swing oscillations, compared to only 6 cm in the other session (Figures 3.5a and 3.6a). Additionally, the estimated duration of the swing's motion was longer in the session with cues suggesting continuing swing oscillations (65% vs 38% of the session's duration; Figure 3.7a). Thus, when receiving cognitive cues suggesting self-motion, one can perceive self-motion in the absence of sensory motion. This indicates that cognition has a profound impact on self-motion perception, supporting the assumption that our brain uses a predictive mechanism in self-motion perception such as internal models.

On the mitigation of motion sickness

The main part of my dissertation, Chapters 4 to 6, focused on investigating the effectiveness of a possible solution to mitigate motion sickness. The sensory conflict theory proposes that motion sickness develops following a neural mismatch between integrated sensory signals on self-motion, and predictions or expectations thereof as generated by an internal model (Reason and Brand 1975, Reason 1978, Oman 1982). The results of Chapter 3 suggest that this internal model can be influenced via cognition, such that cues which announce changes in car motion may improve passenger's predictions of passive self-motion. Prior studies demonstrated that anticipatory auditory (Kuiper et al. 2020a, Diels and Bos 2021, Maculewicz et al. 2021) and visual (Feenstra et al. 2011, Karjanto et al. 2018, 2021, de Winkel et al. 2021, Hainich et al. 2021) cues indeed mitigate motion sickness. Nevertheless, auditory and visual cues could interfere with non-driving related tasks that passengers want to perform (Pfleging et al. 2016, Detjen et al. 2020, Schmidt et al. 2020), and visual cues may aggravate motion sickness (Stauffert et al. 2020, Karjanto et al. 2021). In automated vehicles, vibrotactile cues may therefore be more desirable – are they effective as well?

In Chapters 4 and 5, I exposed participants to sessions with provocative motion on a linear sled in the laboratory. In **Chapter 4**, I investigated whether anticipatory vibrotactile cues that announced the onset of a forward motion mitigated motion sickness, and if the timing of the cue was of influence. In three anticipatory sessions, the cues were predictive and presented 0.33, 1 or 3 s prior to the onset of motion. For each anticipatory session, I quantified the reduction in MISC scores relative to a control session across all time points and participants in a single value: R. Using the same analysis approach, in **Chapter 5** I compared the effectiveness of anticipatory auditory and vibrotactile cues for a more unpredictable motion stimulus with motions varying in onset and direction (forward or backward). In both studies, the anticipatory cues generated some reduction in motion sickness, but large variability between participants resulted in a lack of statistical power (Figures S4.6 and 5.3b). To increase power, in Chapter 5 I performed an internal meta-analysis in which I combined the data of Chapters 4 and 5, and of a comparable study conducted by Kuiper et al. (2020a). Based on this analysis, I concluded that anticipatory cues are overall effective in mitigating motion sickness (Figure 5.5).

In **Chapter 6**, I performed a test track study to compare the effectiveness of anticipatory auditory and vibrotactile cues in mitigating motion sickness in car passengers during a real car ride. This created the possibility to use a more variable motion stimulus compared to the laboratory studies of Chapters 4 and 5. A trained driver performed driving maneuvers that resembled those of everyday car driving, involving lane changes, accelerations, and decelerations. The maneuvers varied in onset, speed, and direction, making it more difficult for passengers to anticipate upcoming motion. This may increase value for passengers to receive an anticipatory cue, thereby increasing their effectiveness. However, lesser controllability of experimental conditions in comparison to a laboratory study can make it more difficult to demonstrate significant effects. For example, variability in driving behavior causes some part of the motion to go unannounced by the cue, possibly reducing their effectiveness. The vibrotactile cues generated a large reduction: the same analysis using the measure R indicated that they mitigated motion sickness (Figure 6.2c). The auditory cue was significantly less effective (Figure 6.2b) and generated no significant mitigation overall (Figure 6.2c). Remarkably, the mitigating effect of the vibrotactile cue was larger than the overall effect of anticipatory cues found in the internal meta-analysis of Chapter 5 (Figure 6.2c) and corresponded to a 40% reduction in MISC scores relative to the control session. Taken over the whole, the results indicate that anticipatory vibrotactile cues are effective in mitigating motion sickness.

The implications for measuring motion sickness

The results of **Chapter 2** indicate that a scale focusing on symptomatology, such as the Motion Illness Symptoms Classification (MISC), captures the progression of motion sickness unambiguously. Ratings of unpleasantness increased non-monotonically with exposure duration. The observed reduction in unpleasantness at nausea onset indicates that participants could report to feel better, whilst they are actually getting closer to the point of vomiting. This is an important aspect to consider in experimental research, and setting a stop-criterion based on a symptomatology scale is thus the safest choice when wanting to prevent cleaning up smelly body fluids. Besides arriving safely, getting from point A to point B without vomiting may also be considered the most import aspect of transportation. When conducting research aimed at investigating car-, sea-, or airsickness, a rating of symptoms might therefore be considered more relevant. On the other hand, when mainly interested in evaluating the attractiveness of a commercial device, knowing unpleasantness is more useful. Even mild feelings of unpleasantness could be detrimental to user satisfaction when playing a game in virtual reality. Each class of symptoms in the MISC can be associated with a single rating of unpleasantness, which makes it possible to predict unpleasantness from symptomology (Table 2.2).

Unpleasantness ratings in the center of the scale are however associated with multiple classes of symptoms. One can therefore not unambiguously predict symptom progression from unpleasantness. In any case, my findings indicate that caution is warranted when comparing studies that have employed the different types of scales, as they cannot one-to-one be compared in terms of motion sickness progression. After all, rating how bad someone feels is not the equivalent of rating how close someone is to the point of vomiting.

The implications for mitigating motion sickness

To my knowledge, the study in **Chapter 3** is the first to demonstrate that cognitive cues can induce a systematic percept of passive self-motion in the absence of corresponding sensory stimulation. This finding substantiates the assumption that our brain integrates sensory and cognitive information in percepts of self-motion (Ferrè and Harris 2015, Mast and Ellis 2015). In Chapter 1, I described internal models of the motor and sensory systems that are assumed relevant in sensorimotor control (Wolpert et al. 1998, Popa and Ebner 2019) and motion sickness (Oman 1982, Bos et al. 2008). According to my findings, internal models are not only based on efference copies of motor commands (von Holst 1954) and previous motion exposures (Reason 1978), but can also be influenced by cognitive cues. My study thus supports the assumption that our brain uses a predictive mechanism in self-motion perception. This lends credibility to the idea that cognitive cues could improve estimations of passive self-motion in car passengers; useful for mitigating motion sickness as explored in Chapters 4 to 6 elaborated on below. First, I want to emphasize that studies on self-motion perception should consider the possible influence of cognitive cues in the interpretation of their results. Herein I want to highlight the work of Wertheim et al. (2001), who demonstrated that a priori motion expectations can suppress the somatogravic illusion (Gillingham and Previc 1993). Participants who were kept naive of (the restrictions) of a motion apparatus reported tilting sensations during strong linear horizontal acceleration in darkness – percepts that were not reported in similar studies in which participants had seen the motion apparatus. Studies on self-motion perception should thus provide a detailed description of experimental details that may influence motion expectations such as task instructions, contextual information, and attentional allocation and distraction.

The results of **Chapter 6** indicate that anticipatory vibrotactile cues can mitigate motion sickness in car passengers. Their mitigating effect was larger than the overall reduction in motion sickness generated by anticipatory cues under controlled laboratory conditions. In the laboratory studies of **Chapters 4 and 5**, the motion stimulus was one-dimensional, with motions easier to anticipate than the driving maneuvers used in Chapter 6. The pattern of results across my studies suggests that anticipatory cues generate more effect for more variable (unpredictable) motion stimuli. Motions with multiple degrees of freedom are more difficult to anticipate. Passengers are hence prone to making larger prediction errors, which increases value for an anticipatory cue. Automated vehicles can predict their own motion very well and should be able to respond to unexpected situations quickly. They could thus provide vibrotactile cues to mitigate car sickness in their passengers. When assuming a greater variability in driving maneuvers during real life car driving, the mitigating effect of anticipatory cues might be even larger.

The main motivation behind investigating the effectiveness of vibrotactile cues was their advantages over auditory and visual cues in the context of automated driving. Vibrations presented via the seat 1) can be received passively without any action required from the passenger, 2) do not interfere with audiovisual tasks passengers may want to perform, 3) are hard to ignore and attention capturing, and 4) can be understood by passengers who are visually or hearing impaired (e.g., Scott and Gray 2008; Prewett et al. 2012; Petermeijer et al. 2016; Detjen et al. 2020). In **Chapters 5 and 6**, I compared the user experience of auditory and vibrotactile cues. There was no clear preference for a cue in Chapter 5 (Figure 5.4e), but participants clearly preferred the vibrotactile cue in Chapter 6 (Figure 6.3c). They described it as intuitive and easy to understand whereas the auditory cue, consisting of voice recordings, was described as annoying and intrusive. If research on auditory cues continues, studies may focus on using subtler non-speech cues, such as sounds resembling engine noise (Maculewicz et al. 2021). Nevertheless, in Chapter 6 the vibrotactile cue was more effective than the auditory cue, which did not mitigate motion sickness overall. All aspects considered, it may hold greater value to focus future research on optimizing the effect of vibrotactile cues.

Despite major technological advancements in automated driving functions, a large part of the public is hesitant to use self-driving cars (Schoettle and Sivak 2014, Kyriakidis et al. 2015, Ward et al. 2017). Concerns that are frequently mentioned relate to perceived risks and safety, or in a broader term those aspects relating to trust in the automated driving system (Schoettle and Sivak 2014, Choi and Ji 2015, Kyriakidis et al. 2015, Ward et al. 2017). Automation surprise, occurring when a vehicle performs an unexpected action or fails to perform an expected one, may also degrade trust (Carsten and Martens 2019). Communication of the system's understanding of the environment and its planned driving maneuvers may be a way to increase trust and overcome automation surprise (Koo et al. 2015, Carsten and Martens 2019, Von Sawitzky et al. 2019, Ha et al. 2020). Besides mitigating motion sickness, anticipatory cues may hence serve an alternative purpose in a human-to-automated driving transition.

Motion sickness susceptibility, sensitivity, and the effectiveness of anticipatory cues

In all studies, there were large between-participant differences in the effectiveness (i.e., $\bar{R}_i$) of the anticipatory cues. This could indicate that some participants benefitted from the cues whereas others did not. However, exploratory analyses in Chapter 5 (Figure 5.6) suggested that the observed between-participant variability could be explained by uncontrollable variability (e.g., measurement noise). Theoretically, this implies that cues could be demonstrated effective for all participants if the experiment would be repeated a sufficient number of times. In this interpretation, I assume that the effect of anticipatory cues is not idiosyncratic. Participants who suffer less from motion sickness should benefit as much as participants who suffer more from it. Do they?

An estimate of how much one suffers from motion sickness can be obtained via the Motion Sickness Susceptibility Questionnaire (MSSQ-Short; Golding 2006). The MSSQ asks respondents to indicate the frequency of motion sickness experienced in various contexts (e.g., motorized transport, amusement rides) in the past, during childhood and adulthood. This measure could therefore be interpreted to provide a general impression of motion sickness susceptibility throughout life. I first explored whether MSSQ percentile scores can be used to predict motion sickness reported during the sessions of the studies in Chapters 4 to 6 and Kuiper et al. (2020a). I term this latter response to a specific exposure motion sickness sensitivity, differently from susceptibility that is based on lifetime experience. In my measure of sensitivity, I consider the magnitude of motion sickness as well as its accumulation speed. As proposed by the ISO 2631-1 (1997), I assume that motion sickness accumulates with the square root of exposure duration. Accordingly, I define motion sickness sensitivity as: $MISC_{max} \,/\, \sqrt{t(MISC_{max})}$, indicating the increase rate of the maximum reported MISC score with t in minutes. I calculated this metric for each experimental session in the four studies. For each participant, I subsequently determined their average sensitivity by taking the mean metric across their experimental sessions within a study. For the study in Chapter 6, I only considered the MISC scores rated within the first 15 minutes of each session to match the exposure duration of the sessions in the other three studies. A simple linear regression indicates that the MSSQ only explains 11% of the variance (95% confidence interval [0.02, 0.27]) in motion sickness sensitivity (Figure 7.1a). General motion sickness susceptibility thus seems to be a weak predictor of specific motion sickness sensitivity.

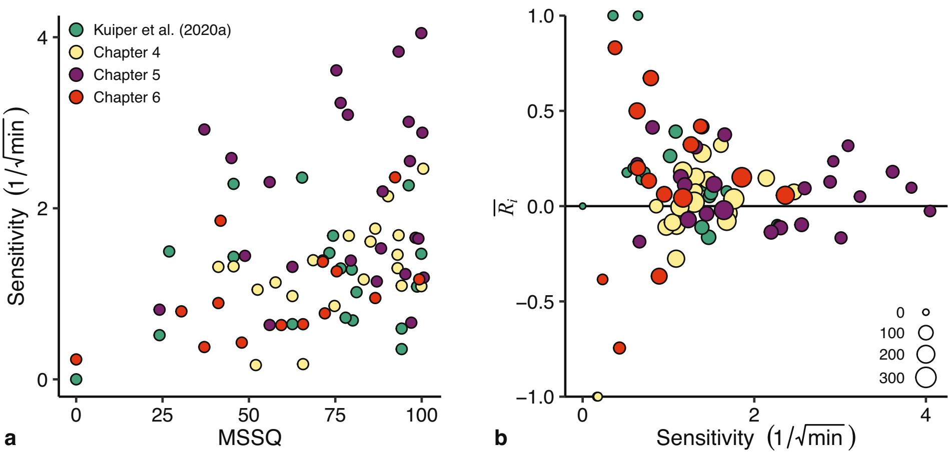


Figure 7.1 Exploratory analyses on the relationship between motion sickness susceptibility, sensitivity, and the effectiveness of the anticipatory cues. **a.** MSSQ percentile scores explain only 11% of the variance in motion sickness sensitivity, defined as the increase rate of maximum MISC score during a provocative exposure. General motion sickness susceptibility thus seems a weak predictor of specific motion sickness sensitivity. **b.** The reduction in motion sickness generated by anticipatory cues ($\bar{R}_i$) seems independent of motion sickness sensitivity. $\bar{R}_i$ is more variable across participants with a lower sensitivity, indicating that studies with more sensitive participants have higher statistical power. The size of a data point reflects its weight, corresponding to the sum of MISC scores underlying the data.

Instead of investigating whether the effectiveness of the cues depends on susceptibility, I explored whether it depends on sensitivity (Figure 7.1b). For the studies in Chapters 4–6 which included multiple anticipatory sessions, I first determined a weighted reduction across the anticipatory sessions per participant. The results provide no evidence that the cues' effectiveness depends on motion sickness sensitivity: sensitivity only explains 0.6% of the variance in $\bar{R}_i$ ($r = -0.08$, 95% confidence interval [−0.24, 0.08]). This suggests that the cues generate a reduction in motion sickness symptoms that is independent of how much one suffers from motion sickness. Given the one step increments of the MISC, the resolution of R is low when it is calculated on low MISC scores. Therefore, $\bar{R}_i$ is more variable across participants with a lower sensitivity. This implies that the effectiveness of the cues cannot be reliably estimated from few observations and that studies with more sensitive participants have higher statistical power.

Directions for future research

On the measurement of motion sickness

A question that cannot be answered by the study in **Chapter 2** is how to explain the observed unpleasantness reduction at nausea onset. The simplest interpretation is that when individuals start feeling nauseated, pre-nausea symptoms diminish. I observed some indirect evidence for this interpretation as participants who reached a maximum score of MISC 6 during a session afterwards rated feeling less unpleasant compared to participants who had reached a maximum score of MISC 5 (Figure 2.5). Furthermore, magnitude estimations on the associated unpleasantness with each MISC class were not different before and after exposure to a session with provocative motion (Figure 2.2a). This interpretation is counterintuitive, and some authors present results they interpret as indicating that unpleasantness does increase monotonically with symptom progression. De Winkel et al. (2022) asked participants to provide a MISC score every 30 s during a ≤90 min session of provocative motion. After the session, participants rated the unpleasantness corresponding to each MISC class they had scored as it was experienced during the session. The results indicated incremental unpleasantness with each MISC class, without a reduction at nausea onset. The difficulty in determining the relationship between symptomatology and unpleasantness is that semantic and retrospective ratings both have limitations in validity. Measuring symptomatology and unpleasantness simultaneously without interaction may however be impossible. A suggestion for future studies is to ask participants to provide MISC and FMS ratings alternately to investigate if the onset of nausea is correlated with a reduction in unpleasantness.

On the role of internal models

Besides investigating the influence of cognitive cues on the perception of self-motion, I was interested in answering another question in **Chapter 3**. If participants perceive self-motion in the absence of corresponding sensory stimulation, will they feel motion sick? Although participants did report a larger peak-to-peak displacement in the session with cues suggesting continuing swing motion, this increase was not reflected in motion sickness. The reported symptoms of motion sickness were minimal and comparable between the two sessions (Figure 3.5b). The average reported peak-to-peak displacement of 29 cm may have been too small to elicit motion sickness. A sinusoidal displacement of this size at 0.2 Hz can be estimated to result in a sickness incidence of only 1% for an exposure duration of 30 minutes (ISO 2631-1 1997). This prevented me from answering this research question. It could be worthwhile to investigate if participants do report motion sickness when they perceive larger displacements in the absence of corresponding sensory input. Following Wertheim et al. (2001), a suggestion is to introduce participants to the experimental set-up blindfolded.

On the mitigation of motion sickness

My findings indicate that it is worthwhile for future studies to elaborate on the optimization of anticipatory, particularly vibrotactile, cues in real car driving. Several topics of interest are outlined in the next paragraphs.

In **Chapter 4**, I investigated whether the effectiveness of anticipatory vibrotactile cues depended on their timing. The results indicated there was no significant difference in the effectiveness of a cue presented 0.33, 1, or 3 s in advance of a forward displacement (Figure 4.5b). However, the statistical power of this study was limited, indicating that the absence of evidence should not be interpreted as evidence of absence. It may be worthwhile to evaluate the effect of anticipatory intervals for motion stimuli comparable to those used in Chapter 6, in which vibrotactile cues did mitigate motion sickness. As the prediction accuracy of automated driving systems is highest for accelerations in the near future, the anticipatory intervals of interest can be limited to those of a few seconds.

The anticipatory vibrotactile cues in Chapter 6 mitigated motion sickness even though some part of the motion was unannounced due to variability in human driving behavior. Which motions and nuances therein should cues convey during real-life car driving? Providing passengers information about the sharpness of a curve or the intensity of braking might enhance the effect of anticipatory cues. However, providing cues for unprovocative motions should be avoided as this could lower user acceptance resulting in passengers disabling the cueing system (Reagan et al. 2018). If found beneficial, nuances in motion parameters may be conveyed by varying the temporal and spatial aspects of a cue. For example, individuals associate shorter intervals between vibration pulses or auditory beeps with a greater sense of urgency (Edworthy et al. 1991, Meng and Spence 2015, Van Erp et al. 2015). Needless to say, human limitations in the ability to detect, distinguish, and understand different cues should be taken into consideration (Jones and Sarter 2008; Fitch et al. 2011; Nees and Walker 2011; Petermeijer et al. 2016; Duthoit et al. 2018). Differentiating between cues is more difficult when passengers are distracted by other tasks (Chan et al. 2005, Feng et al. 2021), when additional vibrations are introduced by uneven road surfaces (Krausman and White 2008), or when additional sounds are coming from inside or outside the vehicle (Šabić et al. 2021).

Lastly, anticipatory cues are not the only possible solution to mitigate motion sickness. Alternative mitigation methods include adapting vehicles dynamics for comfort (e.g., Saruchi et al. 2020), pharmacological (e.g., Zhang et al. 2016) or nutritional (e.g., Rahimzadeh et al. 2023) intervention, habituation training (e.g., Golding and Gresty 2005), and manipulating passengers' upper body into the direction of centripetal force during cornering (Wada and Yoshida 2016, Karjanto et al. 2021). However, these alternatives have limitations. For example, drugs may cause drowsiness and degrade performance (Leung and Hon 2019), and habituation is known to generalize poorly across contexts (Reason and Brand 1975). It would be valuable to gain a better understanding of how anticipatory cues compare to other interventions in terms of effect, advantages, and disadvantages. Combining mitigation methods might offer the greatest benefit (Bos 2015) but should be tailored to context and personal preference. Moreover, the obtained 40% reduction in motion sickness symptoms by the vibrotactile cue in Chapter 6 is substantial by itself.

Conclusion

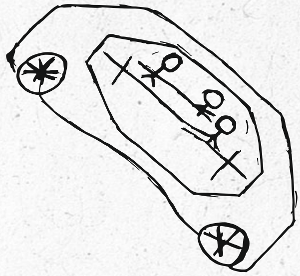
How to resolve motion sickness in automated driving is a (too) big question. But throughout my dissertation, together with my co-authors, I have made some significant steps forward into answering the question how to mitigate it. I will close this chapter by listing the three key findings of my work, using the preferred style of my supervisors: "<=>", or in words, "less is more".

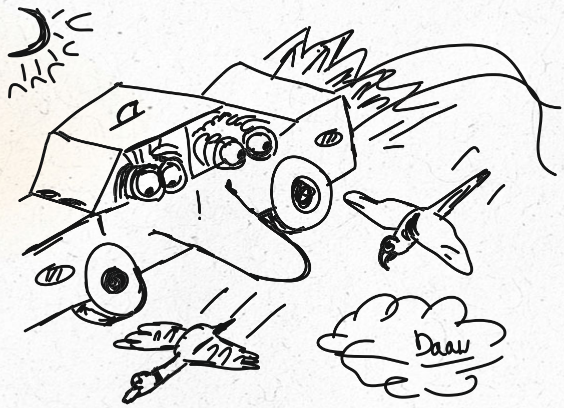
1. Motion sickness is a syndrome of discomfort, which progresses with exposure duration to a provocative motion stimulus. When interested in capturing this progression, it is better to use a scale that focuses on measuring symptomatology rather than on unpleasantness, for instance the Motion Illness Symptoms Classification (MISC).

2. Our perception of passive self-motion is strongly influenced by a priori motion expectations that are shaped by cognitive cues such as task instructions, contextual information, and attentional allocation. In fact, such cues can elicit a percept of oscillatory self-motion in the absence of corresponding sensory stimulation: one can perceive self-motion without motion.

3. Car passengers suffer much more from motion sickness compared to car drivers, presumably because drivers can better anticipate the car’s motions. Anticipatory vibrotactile cues that inform passengers of upcoming motions can mitigate motion sickness symptoms during a real car drive by 40%. They are more effective than auditory cues, and anticipatory cues tested in a laboratory.

All studies considered, I have strived for writing a dissertation of scientific value, the conclusions of which can be translated into those having value for society.

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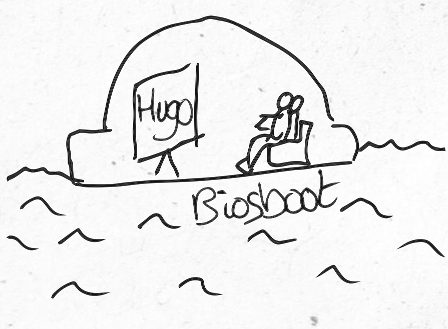
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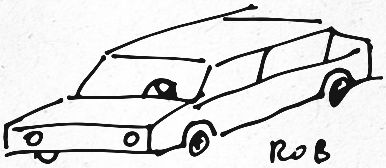
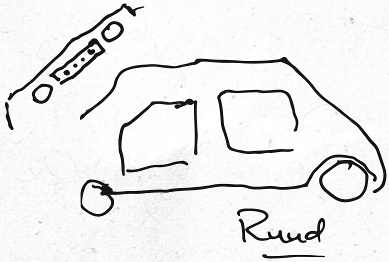
R. The robot driver that is also a radio.





CHAPTER 8

Data and code
Bibliography
List of publications

DATA AND CODE

All data and code from Chapters 2 to 5 has been made publicly available on the Open Science Framework. Preregistrations of Chapters 4 and 5 are also available.

CHAPTER 2

How feelings of unpleasantness develop during the progression of motion sickness symptoms

https://osf.io/ybw7d

CHAPTER 3

Self-motion perception without sensory motion

https://osf.io/q7wux

CHAPTER 4

The (in)effectiveness of anticipatory vibrotactile cues in mitigating motion sickness

https://osf.io/bsznv

CHAPTER 5

Mitigating motion sickness by anticipatory cues

https://osf.io/tz7ca

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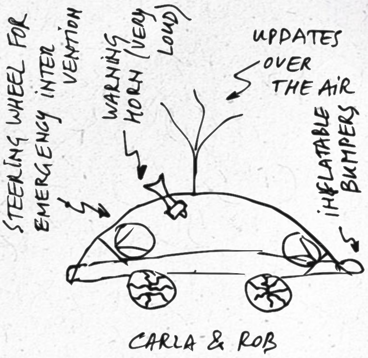
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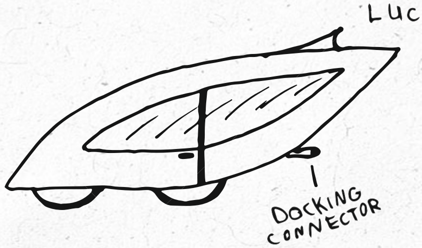
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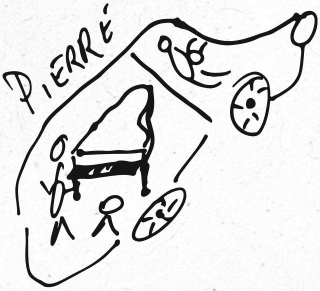
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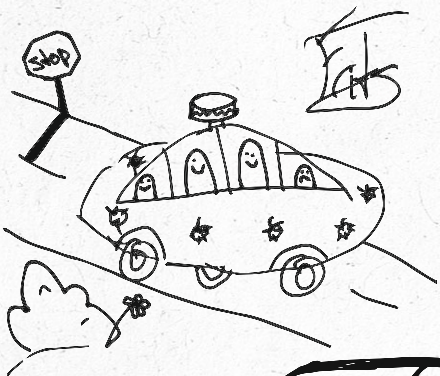
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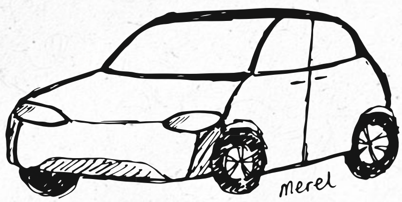
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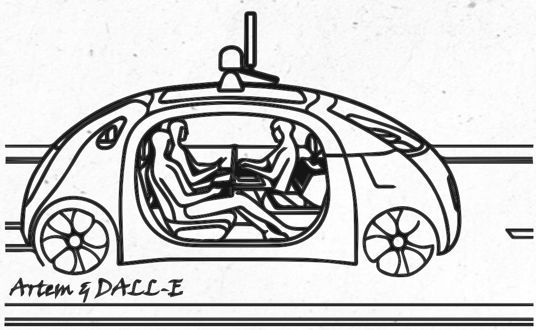
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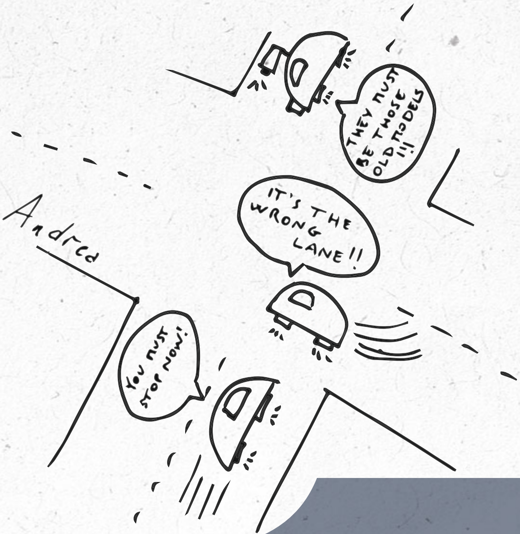
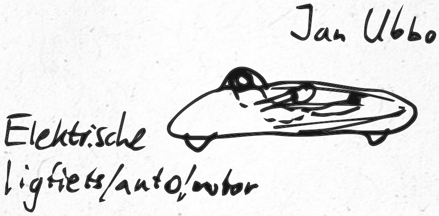
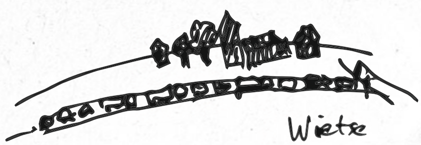




CHAPTER 9

Summary
Samenvatting
Dankwoord
About the author



SUMMARY

Self-driving cars are no longer science fiction: in several cities around the globe, fully automated taxis have been launched since 2020. Automated driving is expected to offer various societal, environmental, and economic benefits. Despite such advantages, a negative consequence is an expected increase in motion sickness. The lifetime incidence of motion sickness during car travel has been reported as high as 58%, and predominantly concerns car passengers rather than drivers. As the majority of car occupants are currently drivers, the number of car travelers who may experience motion sickness will multiply following a human-to-automated driving transition. Therefore, the overall aim of my dissertation is to contribute to research on the mitigation of motion sickness, particularly in the context of automated driving. To that end, I started by investigating how motion sickness can best be measured when using a self-report rating scale. A plethora of available rating scales indicates that a standard on the measurement of motion sickness is currently lacking. To measure motion sickness reliably, a scale should capture its progression unambiguously. The results of **Chapter 2** indicate that a scale focusing on the symptomatology of motion sickness does so better than a scale focusing on general feelings of unpleasantness. This motivated my decision to use the Motion Illness Symptoms Classification (MISC) throughout the remaining studies within my dissertation. In **Chapter 3**, I explored to which extent cognitive cues influence the perception of self-motion. The results indicated: profoundly. Cognitive cues that manipulated a priori motion expectations elicited a percept of oscillatory self-motion in the absence of corresponding sensory stimulation. To clarify, when receiving cues that suggested self-motion, blindfolded participants reported that they were swinging on a parallel swing which was motionless in reality. This finding supports the assumption that our brain uses a predictive mechanism in self-motion perception, such as internal models. The possibility to influence percepts of self-motion via cognition provided some support for a motion sickness mitigation method which I elaborated on in Chapters 4 to 6. The increased motion sickness prevalence in car passengers relative to drivers may be explained by the advantage of drivers to anticipate self-motion. A possible solution to mitigate motion sickness could therefore be to improve the anticipation of passive self-motion in passengers. *Anticipatory cues* that alert passengers of changes in the motion trajectory via vision or sound have indeed been demonstrated to mitigate motion sickness. In automated vehicles, providing anticipatory cues via the tactile modality may be more desirable. Vibrations presented via the seat 1) can be received passively without any action required from the passenger, 2) do not interfere with audiovisual tasks passengers may want to perform, 3) are hard to ignore and attention capturing, and 4) can be understood by passengers who are visually or hearing impaired. In **Chapter 4**, I investigated whether anticipatory vibrotactile cues that announced the onset of a forward displacement mitigated motion sickness, and if the timing of the cue was of influence. To determine their effectiveness, I developed a new pre-registered measure: R. With R, it becomes possible to quantify the reduction in motion sickness symptomatology between a session with anticipatory cues and a control

session in a single value. Using this measure, in **Chapter 5** I compared the effectiveness of anticipatory auditory and vibrotactile cues for a more unpredictable motion stimulus with motions varying in onset and direction (forward or backward). In both studies, the anticipatory cues generated some reduction in motion sickness, but large variability between participants resulted in a lack of statistical power. To increase power, I performed an internal meta-analysis in which I combined the data of Chapters 4 and 5, and of a comparable study conducted by Kuiper et al. (2020a). Based on this analysis, I concluded that anticipatory cues are overall effective in mitigating motion sickness. The studies in Chapters 4 and 5 were performed in the laboratory on a linear sled with motions limited to one dimension. In **Chapter 6**, I performed a test track study in which I compared the effectiveness of anticipatory auditory and vibrotactile cues during a real car ride. A trained driver performed lateral and longitudinal driving maneuvers that resembled those of everyday car driving. The same analysis using the measure R indicated that the vibrotactile cue mitigated motion sickness in car passengers. The auditory cue was significantly less effective and generated no significant mitigation overall. Remarkably, the mitigating effect of the vibrotactile cue was larger than the overall effect of anticipatory cues found in the meta-analysis based on laboratory studies. This increased effect may be interpreted as higher value for anticipatory cues when motions consist of multiple degrees of freedom, causing passengers to make larger prediction errors. Overall, my findings indicate that anticipatory vibrotactile cues could be an effective solution to mitigate motion sickness. Automated vehicles can predict their own motion very well. They could thus provide vibrotactile cues to mitigate car sickness in their passengers. In conclusion, I hope that my work contributes to a better understanding of the measurement and mitigation of motion sickness, so that we can drive comfortably in the future.

SAMENVATTING

Zelfrijdende auto's zijn niet langer een toekomstfantasie: in meerdere steden wereldwijd rijden sinds 2020 volledig geautomatiseerde taxi's. Naar verwachting zal geautomatiseerd rijden diverse maatschappelijke, ecologische en economische voordelen bieden. Ondanks dergelijke voordelen is een negatief gevolg een verwachte toename in wagenziekte. Tot wel 58% van de bevolking ervaart wagenziekte, waarbij dit voornamelijk passagiers en niet bestuurders betreft. Aangezien het merendeel van alle auto inzittenden bestuurder is, zal de prevalentie van wagenziekte sterk toenemen als geautomatiseerd rijden standaard wordt. Het doel van mijn proefschrift is om bij te dragen aan onderzoek hoe we wagenziekte kunnen mitigeren. Daartoe begon ik met het onderzoeken hoe wagenziekte het beste gemeten kan worden middels een zelfbeoordelingsschaal. Schalen om wagenziekte te meten zijn in overvloed beschikbaar, wat impliceert dat een standaard mist. Om wagenziekte betrouwbaar te meten, zou een schaal de progressie ervan eenduidig in kaart moeten brengen. De resultaten van **Hoofdstuk 2** geven aan dat een schaal die focust op de symptomen van wagenziekte dit beter doet dan een schaal die focust op gevoelens van ongemak. Dit motiveerde mijn besluit om de *Motion Illness Symptoms Classification (MISC)* in de resterende studies van mijn proefschrift te gebruiken. In **Hoofdstuk 3** exploreerde ik in hoeverre cognitieve signalen de perceptie van zelfbeweging beïnvloeden. Uit de resultaten bleek: in zeer grote mate. Cognitieve signalen die a priori verwachtingen over zelfbeweging manipuleerden, resulteerden in een waarneming van zelfbeweging die niet correspondeerden met sensorische input. Ter verduidelijking, na het ontvangen van cognitieve signalen die zelfbeweging suggereerden, gaven geblinddoekte proefpersonen aan dat ze schommelden op een parallelschommel die in werkelijkheid stilstond. Deze bevinding ondersteunt de aanname dat ons brein een predictief mechanisme gebruikt voor zelfbewegingswaarneming, zoals bijvoorbeeld interne modellen. De mogelijkheid om middels cognitie zelfbewegingswaarneming te beïnvloeden, gaf enige onderbouwing voor de effectiviteit van een methode om wagenziekte te mitigeren. Deze methode onderzocht ik verder in Hoofdstukken 4 tot 6. Mogelijk hebben passagiers meer last van wagenziekte dan bestuurders omdat bestuurders hun zelfbeweging beter kunnen anticiperen. Een potentiële oplossing om wagenziekte te mitigeren is daarom het verbeteren van de anticipatie van passieve zelfbeweging bij passagiers. En inderdaad, signalen die passagiers waarschuwen voor autobewegingen middels zicht of geluid, resulteren in aantoonbaar minder wagenziekte. Bij geautomatiseerd rijden is het aanbieden van dergelijke *anticiperende signalen* middels tactiele informatie wellicht wenselijker. Vibraties die middels het zitvlak van de stoel worden gecommuniceerd 1) kunnen passief door de passagier worden ontvangen, 2) interfereren niet met audiovisuele taken die passagiers mogelijk uitvoeren, 3) zijn aandachttrekkend en moeilijk om te negeren, en 4) kunnen ook worden begrepen door passagiers met hoor- en zichtproblemen. In **Hoofdstuk 4** onderzocht ik of anticiperende vibrotactiele signalen die een vooruitgaande verplaatsing aankondigden, wagenziekte mitigeerde, en of hun timing van invloed was. Om hun effectiviteit te bepalen, ontwikkelde ik een nieuwe gepreregistreerde maat: R. Middels R is het mogelijk om een reductie in wagenziekte tussen een sessie met anticiperende signalen en een controle sessie in één getal uit te drukken. Deze maat gebruikte ik ook om in **Hoofdstuk 5** de effectiviteit van anticiperende auditieve en vibrotactiele signalen te vergelijken. Dit deed ik bij een onvoorspelbaardere bewegingsstimulus, welke bestond uit bewegingen variërend in zowel aanvang als richting (voor- of achteruit). In beide studies genereerde de anticiperende signalen een reductie in wagenziekte, maar grote variabiliteit tussen proefpersonen resulteerde in een tekort aan statische power. Om de power te verhogen, voerde ik een interne meta-analyse uit waarbij ik de data uit Hoofdstukken 4 en 5, en van een vergelijkbare studie uitgevoerd door Kuiper et al. (2020a) combineerde. Uit deze analyse concludeerde ik dat anticiperende signalen over het geheel genomen effectief zijn in het mitigeren van wagenziekte. De studies in Hoofdstukken 4 en 5 werden in een laboratorium uitgevoerd op een lineaire slede, waarbij de bewegingen beperkt bleven tot variabiliteit in één richting. In **Hoofdstuk 6** voerde ik een studie op een testcircuit uit waarbij ik de effectiviteit van anticiperende auditieve en vibrotactiele signalen kon vergelijken tijdens een echte autorit. Een getrainde chauffeur voerde laterale en longitudinale manouevers uit welke leken op die van alledaags autorijden. Dezelfde analyse met de maat R liet zien dat de vibrotactiele signalen wagenziekte bij passagiers mitigeerden. De auditieve signalen waren significant minder effectief en genereerden geen significante reductie. Opvallend is dat het mitigerende effect van de vibrotactiele signalen groter was dan het effect van anticiperende signalen gevonden in de meta-analyse uitgevoerd op de data van laboratorium studies. Een mogelijke interpretatie voor deze bevinding is dat anticiperende signalen grotere meerwaarde hebben wanneer bewegingen uit meer vrijheidsgraden bestaan, waardoor passagiers grotere voorspellingsfouten maken. Al met al wijzen mijn bevindingen erop dat anticiperende vibrotactiele signalen een effectieve oplossing kunnen zijn om wagenziekte te verminderen. Aangezien geautomatiseerde voertuigen hun bewegingen goed kunnen voorspellen, zouden zij vibrotactiele signalen kunnen communiceren om zo wagenziekte bij hun passagiers te mitigeren. Concluderend hoop ik dat ik mijn werk bijdraagt aan een beter begrip hoe we wagenziekte kunnen meten en mitigeren, zodat we in de toekomst comfortabeler kunnen rijden.

DANKWOORD

Op 1 december 2019 begon ik met mijn PhD project. Een voor mij nieuw onderwerp, waar ik vrijwel niets vanaf wist. Nu, ongeveer vier jaar later, eindig ik mijn project met meer kennis, maar ook met meer vragen. Ik heb de afgelopen jaren als bijzonder leerzaam, motiverend en inspirerend ervaren. Dat had niet alleen te maken met het onderwerp van mijn project, maar ook zeker door de personen om mij heen, die ik graag wil bedanken.

Ten eerste de drie personen van wie ik de afgelopen jaren het meeste mocht leren: mijn drie (co-)promotoren.

Jelte, al in de eerste gesprekken die ik met je voerde, vielen jouw passie en open houding onmiskenbaar op. De kennis die je over het onderwerp (in brede zin) hebt is werkelijk reusachtig, en je enthousiasme in het vertellen daarover is aanstekelijk. Ik ben je dankbaar dat je altijd tijd voor mij vrijmaakte, ondanks je vaak propvolle agenda. De vele uren waarin je mij allerlei theoretische concepten, modellen en (tot meermaals toe) kinematica probeerde uit te leggen zijn daar getuige van. Zeker voor je engelengeduld in dat laatste aspect wil ik je bedanken. Maar niet alleen inhoudelijk heb ik van onze samenwerking genoten, want het is gewoonweg leuk om met jou samen te werken. Ik kon allerlei twijfels en gedachtes met je delen, wat resulteerde in leuke discussies. Onze gezamenlijke uitstapjes naar meerdere conferenties, Ford in Aken en Volvo in Zweden, vormden daarbij de kers op de taart! Ik ben onwijs blij dat ik nog een tijdje met je mag samenwerken!

Jeroen, in het begin was het nog niet bekend dat ook jij een van mijn promotoren zou worden. Maar wat ben ik blij met hoe dit uiteindelijk is gelopen! Ik vroeg je tijdens de analyse van de resultaten van onze eerste studie naar je ideeën over de aanpak daarvan. Je liet mij inzien dat dit niet alleen met statistiek zou moeten, maar dat visuele interpretaties en (soms) data normalisaties een beter inzicht kunnen bieden. Waardevolle opvattingen die aanvulling boden op wat ik had geleerd tijdens mijn studie psychologie. Ik deel veel van jouw opvattingen over schrijfstijl, dataverwerking, en data visualisatie, en ben dankbaar dat je me de mogelijkheid bood om in deze vaardigheden te groeien. Ook jouw open houding in het altijd mogen stellen van vragen, zelfs vragen waarvan ik eigenlijk dacht het antwoord ondertussen zelf te moeten weten, maakte jouw bijdrage onmisbaar. Naar mijn idee bezit je een hele waardevolle eigenschap: je kunt begrijpen waarom iemand iets niet begrijpt en het zo uitleggen totdat diegene het wel begrijpt, zonder dat diegene [ik] zich dom voelt.

Marieke, jij bood waardevolle hulp vanaf grotere afstand. Bijzonder is dat wij elkaar tijdens mijn project maar 2x in het echt hebben ontmoet: tijdens mijn sollicitatiegesprek en tijdens de oratie van Riender. Ondanks je drukke baan wist je tijd vrij te maken om mijn project via online meetings en mailwisselingen te begeleiden. Tijdens onze maandelijkse overleggen dacht je mee over de planning en voortgang van mijn project, en over oplossingen voor onverwachtse problemen. Jouw achtergrond en dagelijkse werkzaamheden boden een andere invalshoek op de inhoud dan ik van Jelte en Jeroen meekreeg, waardoor jouw input een welkome aanvulling was. Je gaf kritische suggesties op mijn teksten en bood soms het nodige tegenwoord op de plannetjes die ik tijdens mijn dagelijkse supervisie met Jelte en Jeroen had bedacht. Daarbij was het fijn om een mede-psycholoog in een begeleidersteam met natuurkundigen te hebben!

Concluderend, jullie vormden een geweldig team waarin jullie kennis, vaardigheden en persoonlijkheden een mooie aanvulling op elkaar vormden. Ik vind dat ik ontzettend geboft heb! Jullie open houding gaf dat we vele leuke discussies hadden, met (volgens mij) een best mooi eindresultaat zoals beschreven in dit boek!

Verder onmisbaar waren de drie technici die het uitvoeren van mijn experimenten überhaupt mogelijk maakte.

Frans-Jozef, als eerste jouw betrokkenheid bij het experiment met de parallelschommel op de VU. Toen we daarnaar vroegen, haalde je deze binnen enkele dagen weer onder het stof vandaan. En de aanpassingen voor de ventilator en voetensteun maakte je binnen een mum van tijd, waarna je zelfs wel even voor proefpersoon wilde spelen. Vandaar dat je als participant model bent vereeuwigd in Figuur 3.2 (dankzij de designvaardigheden van *Tjitske*, de dochter van Jelte). Het vinden van proefpersonen was lastig tijdens het Corona tijdperk waarin dit experiment werd uitgevoerd en keer op keer moest ik je vragen of je de schommel wilde ophangen om deze daarna weer tijdelijk op te bergen. Dat deed je zonder enig klagen, en ik leerde je snel beter kennen. Het was altijd gezellig om je in de wandelgangen of koffie corner tegen te komen om 'even' bij te kletsen!

Rein en Frank, jullie wil ik bedanken voor de andere grote onderzoeksopstelling waar ik tijdens mijn project gebruik van maakte: de Limosine (lineaire slede) bij TNO. *Rein*, het duurde enige tijd voordat ik jou beter leerde kennen. Dat kwam voornamelijk omdat jij je – in tegenstelling tot andere collega's – niet bovengronds bevond, maar vele uren in de kelder spendeerde om de Limosine in gereedheid te brengen. Ik leerde je pas goed kennen toen we samen de metingen uitvoerde voor het experiment beschreven in Hoofdstuk 4. Verbazingwekkend genoeg ontpopte je je in korte tijd tot een ware kletskous! Bedankt voor alle enthousiasme en energie die je stak in het verbeteren van de Limosine, en voor het maken van het matje voor de vibrotactiele signalen. Helaas konden we de verdere experimenten niet samen ondernemen, maar gelukkig was *Frank* bereidt om verder aan de Limosine te klussen. De Limosine had zo zijn kuren, en ik ben dankbaar voor jouw doorzettingsvermogen om deze op te lossen. Er waren dagen waarbij de oplossingen zoek leken. Met enige regelmaat werden we gedwongen om het gebouw pas tegen sluitingstijd te verlaten. Vaak waren we te laat, en moest ik alvast tussen de automatisch sluitende poort gaan staan zodat deze open bleef. Dan ging jij snel je vouwfiets halen om daarna te beginnen aan je terugreis naar het verre Helmond. Ook voor de door jouw gemaakte aanpassingen in de software voor het geven van de vibrotactiele en auditieve signalen en daarnaast gezelligheid, dank!

Next to the people mentioned above, there are many others who have contributed to my project.

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To the members of my doctoral committee: dr. Donker, prof.dr.ir. Happee, prof.dr. Hecht, prof.dr. Slagter and dr. Souman, thank you for reading my dissertation. I am not sure that many others will do so. I am curious (and a bit scared) to hearing your questions on my defense!

Mijn paranimfen Nina en Ruud, jullie hadden in de afgelopen paar jaar een speciale betekenis voor mij.

Nina, wat heb ik veel gelachen met jou, en jij om mij! Je maakte het voor mij nog leuker om op de VU te werken en ik miste je dan ook zeker tijdens jouw avontuur in Amerika en het mijne in Zweden. Ondanks dat we op een aantal vlakken tegenpolen van elkaar zijn (ja, ik tel wandelen ook als sporten), zijn er genoeg dingen die ons binden. Tijdens onze mini-vakantie naar Gent struinde we allerlei winkeltjes af voor mooie prullaria en tweedehands kleding, aten we de duurste wafels van ons leven, en zagen we hoe machtig mooi de haven van Antwerpen is. Je bent grappig, eerlijk, lief, creatief, zorgzaam, trouw en onwijs slim. Bij de vele twijfels die ik met jou kon delen hielpen jouw motiverende woorden me om te kalmeren en relativeren, en ik ben dankbaar voor jou als vriendin!

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Ik heb de mogelijkheid gekregen om op drie plekken experimenten voor mijn PhD project uit te voeren. Dat betekende vele leuke gesprekken en inzichten verkregen door de personen die ik nog niet eerder in mijn dankwoord heb genoemd.

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Dan mijn tweede (ondertussen eerste) thuishaven: TNO! Om te beginnen wil ik het oude team AHEAD bedanken: *Annemarie*, *Charelle*, *Eric*, *Fred*, *Heleen*, *Karin*, *Lotte*, *Mark*, *Olaf*, *Pierre*, *Rico*, *Suzanne* en *Wietse*. Jullie lieten mij als eerste welkom voelen op TNO, ondanks dat ik niet in projecten meewerkte. Het vaste uurtje op de dinsdagochtend, met de "Taart!" momentjes en zeldzame kroketten-lunchen zal ik koesteren. Graag wil ik *Suzanne* explicieter bedanken. Helaas konden we maar een korte tijd samen werken, maar jouw kritische blik en waardevolle suggesties voor onze studie beschreven in Hoofdstuk 2 waardeer ik onwijs. Je hielp om de ideeën van Jelte en Jeroen op scherp te zetten en mij daarover kritisch te laten nadenken. Naarmate de tijd verstreek, leerde ik ook de anderen van onze afdeling steeds beter kennen. *Aafke*, *Andre*, *Anne*, *Anne-Marie*, *Boris*, *Bram*, *Corny*, *Dave*, *Douwe*, *Erik*, *Ester*, *Frank*, *Hilvert*, *Irene*, *Ivo*, *Jan Ubbo*, *Jikke*, *Juliette*, *Kaj*, *2x Koen*, *Laura*, *Leanne*, *Leon*, *Linsey*, *Lisa*, *Maarten*, *Mariëlle*, *Marc*, *Martin*, *Matthijs*, *Milène*, *Minke*, *Nick*, *Paola*, *Piet*, *Rob*, *Ruth*, *Salem*, *Sam*, *Sanne*, *Wendy*, *Willeke* en *Wouda*: bedankt voor jullie gezelligheid tijdens lunches, afdelingsdiners en -uitjes & input op mijn kleine experimentjes bij de koffie corner! En niet te vergeten, *Geert*, jou wil ik graag bedanken voor de gestelde mogelijkheid om de Limosine voor mijn experimenten in te zetten. Tot slot is er nog een team vanuit TNO Helmond om niet te vergeten, met wie ik een aantal leuke studies buiten mijn PhD project heb mogen uitvoeren: bedankt *Marika*, *Jan* en *Milad*!

In the last year of my PhD, with support from a travel grant of the *Amsterdam Movement Sciences*, I received the opportunity to conduct one last study abroad, at Volvo Cars in Gothenburg. *Ilhan*, I want to thank you first. Because thanks to your efforts in convincing your colleagues of the importance of this study, we could make it happen in the first place! Even though it was difficult, with the help of your friend *Hediye*, we could eventually find sufficient participants. I am afraid my direct Dutch personality drove you crazy at times, so please forgive me and thank you for sticking up with it. You were a great host, taking me to all of your favorite restaurants and cafés. I am wishing you the very best, and with your hard-working personality I am confident that you will finish your PhD soon! *Willy*, thank you for all your efforts in the preparations for our study, your help was essential! And I will not forget the exciting demonstration of driving maneuvers you gave on the snowy test track. You made a subset of our participants feel car sick, for which I also should thank our other two *test drivers*. Lastly: dear *participants*, thank you for enduring these provocative rides.

Tot slot zijn er een paar lieve vrienden en familieleden die ik graag wil benoemen.

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Clichés zijn er om clichés te zijn, dus eindig ik maar bij waar het ooit begon: mijn lieve *papa* en *mama*. Bedankt voor de ondersteuning die jullie in allerlei opzichten boden, zowel in de afgelopen paar jaar, maar ook zeker in die daarvoor. Jullie gaven me de mogelijkheid om zonder zorgen te studeren, dachten mee over lastige keuzes en deelden de waarden die mij tot mij vormde. Ik vrees dat de langdradige verhalen die ik jullie vertelde niet altijd te volgen waren; toch bedankt voor het luisterend oor en de adviezen die jullie als antwoord boden. Maar het allermeest dankbaar ben ik voor het gevoel dat ik altijd op jullie mag terugvallen.

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Anne (voor de meesten) aka Anna (for some)

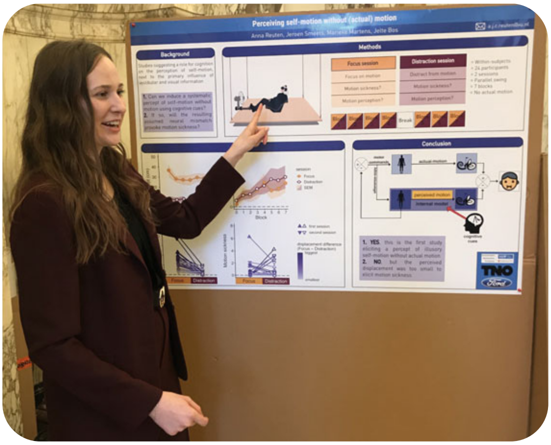
24/03/24

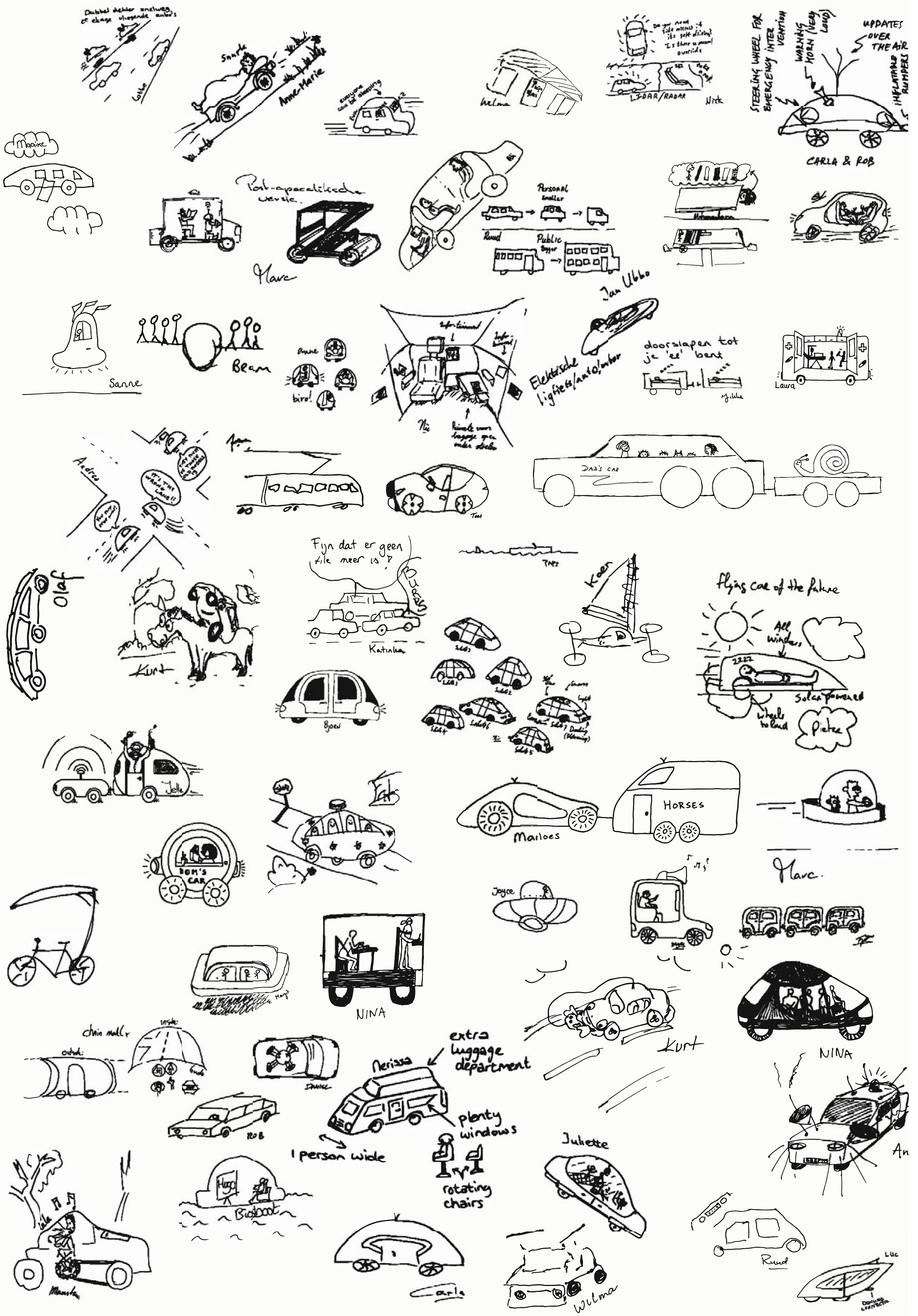
ABOUT THE AUTHOR

I am motivated to learn new things, aiming to understand what I do not yet understand. Having more knowledge generally leads to having more questions, which I usually enjoy, but sometimes lead to skepticism. I like to listen and talk to others, to collaborate and to learn from their perspectives, knowledge, and skills.

Because of a general interest in human behavior, I chose to study Psychology (Utrecht University, 2017, cum laude). During my bachelor's, I focused mainly on neuropsychology in order to better understand how our brain works. Later I refocused my interest to Clinical Psychology (Utrecht University, 2018, cum laude). As conducting research had always drawn my interest, I decided to pursue another master's degree in Applied Cognitive Psychology (Utrecht University, 2019, cum laude). For this study, I completed my internship at TNO in Soesterberg. After obtaining my degree, to my surprise and luck, a PhD position opened up at the Vrije Universiteit in consortium with TNO Soesterberg and Ford Motor Company.

The topic of my PhD project was not without a personal connection. I had always been scared to start car driving, for which reason I only obtained my driver's license at the age of 26. I still dislike car driving; familiar routes I find extremely boring and new routes stress me out. Automated vehicles therefore seem an attractive alternative. They would even provide additional free time which I could spend on all kinds of tasks. However, I do suffer from car sickness so finding a solution to mitigate it lies within my personal interest. I do wonder if I would not find travelling in an automated car scarier than driving a real one..?





Dubbel dekker snelweg of etage vliegende auto's
Snurk
Anne-Marie
Lotte
Maaike
everyone can be sleeping
Post-apocalyptische versie
Marc
Wilma
Do you need side mirrors if it's self driving? Is there a manual override
LIDAR/RADAR
Nick
STEERING WHEEL FOR EMERGENCY INTERVENTION
WARNING HORN (VERY LOUD)
UPDATES OVER THE AIR
INFLATABLE BUMPERS
CARLA & ROB
Personal
Smaller
Ruud
Public
Bigger
Sanne
Bram
Anne
biro!
Info-tainment
Niec
Jan Ubbo
Elektrische ligfiets/auto/motor
doorslapen tot je er bent
Laura
Andres
IT'S THE WRONG LANE!!
DAD'S CAR
Toos
Fijn dat er geen file meer is!
Katinka
Olaf
Kurt
Koen
flying car of the future
All windows
Solar powered
wheels to land
Pieter
Bjorn
Jelle
HORSES
Marloes
MOM'S CAR
Marc.
Joyce
NINA
chain maker
outside:
inside:
extra luggage department
Nerissa
plenty windows
1 person wide
rotating chairs
ROB
Juliette
Hugo
Bioboot
Carla
Wilma
Ruud
Luc

Amsterdam Movement Sciences

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Amsterdam Movement Sciences conducts scientific research to optimize physical performance in health and disease based on a fundamental understanding of human movement in order to contribute to the fulfillment of a meaningful life.