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The Potential of Haptic Motion Cueing to Mitigate Motion Sickness in Highly Automated Passenger Cars

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ABSTRACT

The evolution of road vehicles towards high levels of automation is forecasted along with a higher prevalence of motion sickness on board such transportation systems. Experiencing such situations may precipitate concerns related to comfort, safety and trust, potentially compromising the overall acceptability of these vehicles among users. While prevalent in various modes of transportation, motion sickness is an intricate physiological reaction of the human body, likely to be caused by inconsistent perception of the motion forces, and a lack of postural stability. The use of haptic stimuli as sensory motion cues ("haptic cues") should be underscored as an effective countermeasure. This approach offers the advantage of seamless integration with other mitigation techniques. Haptic cues also have virtues for helping in the estimation of self-motion in space and anticipation. Through a concise analysis of the prior research, this paper surveys the potential strategies and systems for the effective delivery of haptic cues to alleviate motion sickness in cars while considering the prerequisites associated with passenger comfort. The results show that vibrotactile and arthrokinetic signals can act as force-based haptic cues to mitigate motion sickness in cars. The provision of airflow, concurrently serving as a thermal cue, shows potential for motion sickness mitigation, but the exact underlying mechanisms remain unclear. Studies conducted in cars suggest that haptic stimulations can only be effective when congruent visual cues are provided. The different types of haptic systems are proffered for potential in-car integration, along with their respective operating principles to enhance perceptibility.

Keywords: Motion sickness, Haptic systems, Vehicle automation, Human factors, Passenger comfort, Human-machine interaction

INTRODUCTION

Experiencing kinetosis, better known as "motion sickness", is a common phenomenon. Individuals feel its associated symptoms in many forms of transportation where they travel as passengers, with car journeys being the most frequent case (Turner and Griffin, 1999). Its most plausible cause is described by sensory rearrangements in response to a neural discrepancy between the expected and the real motion forces to be perceived (Reason, 1978). This conflicting situation may result into impaired strategies to stabilize the body, which have been shown to precede the onset of sickness symptoms (Riccio and Stoffregen, 1991; Stoffregen and Smart, 1998).

Human physical perception of motion is made by sensory integration of visual, vestibular and somatosensory signals, each transmitted to the brain by specific sensory receptors (Ernst and Banks, 2002). Other non-physical sensory cues such as auditory signals can help in better estimating spatial orientation. In one motion environment, all these sensory information help individuals to estimate self-motion and anticipate external forces from a moving environment (Table 1).

In car transportation, motion sickness is primarily caused by unpredictable and rough driving behaviour (Turner and Griffin, 1999), which passengers have difficulty anticipating and stabilizing their bodies against. With the increasing automation of vehicles, where drivers transition to the role of passengers, the likelihood of motion sickness is expected to rise, especially among habitual drivers (Diels, 2014; Sivak and Schoettle, 2015). This poses concerns for comfort, trust, and safety, leading to increased research efforts to find effective solutions for an application in highly automated vehicles (HAVs) (Diels et al., 2016).

Table 1. Sensory channels crucial for car passengers in perceiving self-motion and spatial orientation while experiencing vehicle dynamics (Bohrmann, 2022, p. 11).

Vehicle dynamics	Sensory channels for motion perception				
	Visual	Auditory	Vestibular	Kinaesthetic	Tactile
Position	X				
Velocity	X	(X)			(X)
Acceleration		(X)	X	(X)	X
Angle	X				
Angular velocity	X		X		

BACKGROUND

Overview of Motion Sickness Mitigation in Cars

Motion sickness remains a challenge without a universally proven countermeasure. While habituation is the most reliable solution, it may not be effective for everyone (Reason and Brand, 1975). To address this, ongoing research focuses on designing motion planning algorithms in HAVs to minimize the risk of motion sickness, aiming for trajectories that are both comfortable and predictable (Bellem et al., 2016; Elbanhawi et al., 2015). However, unpredictable vehicle movements and unavoidable low-frequency motions pose challenges, necessitating the integration of multiple mitigation techniques to enhance anticipation and postural stability for optimal motion sickness mitigation in cars.

Sensory motion cueing is a method used to alleviate motion sickness in cars by providing sensory signals that enhance an individual's perception of their position and self-motion in relation to their surroundings. By improving these abilities, individuals can more accurately estimate present and future motion forces, reducing the chances of a sensory mismatch that could lead to motion sickness symptoms. According to the multiple resource theory, the brain has the capacity to process various sensory motion cueing techniques simultaneously, given sufficient cognitive resources (Ernst and Banks, 2002; Wickens, 2008).

The ocular system's crucial role in perceiving self-motion (Table I) underscores the significance of visual motion cueing as an effective mitigation approach (Diels and Bos, 2021). However, the possible engagement of vehicle passengers in NDRAs may restrain their cognitive abilities to process these cues, and visual signals may not fully compensate for deficiencies in self-motion perception (Costes and Lécuyer, 2023). Auditory motion cueing is another sensory cueing method to enhance predictability on the future motion. Despite studies reporting encouraging results, auditory signals may be felt as intrusive while working, listening to music or chatting with other vehicle occupants (Diels and Bos, 2021). Conversely, some sensory cues, such as haptics, do not present the disadvantage of interference, making them a specific area of interest.

Haptic motion cueing, which involves delivering tactile, kinesthetic, or vestibular information, recently gained interest for its potential in enhancing perception and conveying anticipatory signals. Haptic signals have already been successfully used to provide car users with information about the vehicle's states (Asif and Boll, 2010; van Erp and van Veen, 2001), and their integration with other sensory cues could greatly improve motion perception. Such signals are processed faster than visual (Jordan, 1972) or auditory stimuli (Chang et al., 2011) and can cover a wider bandwidth of cueing information (Li and Chen, 2022). They can also be more emotional and personal while being delivered in a silent and private way (Yusof, 2019, p. 141). Up to date, haptics have been poorly investigated as sensory motion cueing techniques to alleviate motion sickness in cars, leaving significant room for exploration (Dam and Jeon, 2021). In this perspective, the present paper aims to address this potential and explore the possibilities of integrating such techniques in HAVs.

The Potential of Haptic Motion Cueing

Definition and Types of a Haptic Feedback

The term "haptic" relates to the senses of tactile and kinesthetic perception (Costes and Lécuyer, 2023). Tactile senses are elicited by cutaneous stimulations to innervate the mechanoreceptors of the skin (e.g. vibrations or pulses applied on the skin) whereas kinesthetic senses encompass information on the velocity, acceleration and direction of motion from the sensory receptors of muscles, joint, limbs and tendons (McCloskey, 1978). Three different feedback mechanisms of haptic can be distinguished: nerve-based, thermal-based and force-based (Huang et al., 2022).

Nerve-based feedback and thermal-based feedback are two types of haptic cueing strategies that have not been specifically studied for mitigating motion sickness in cars. While nerve-based feedback relies on electrical transcutaneous stimulations to induce tactile sensations (D'Anna et al., 2017), thermal-based feedback uses liquid circulation or thermoelectric stimulations to generate heat transfers on the skin (Lee et al., 2020). The applicability of these cueing methods in vehicular contexts is yet to be tested, but it is worth noting that thermal feedback may help regulate body temperature, which is known to be affected by motion sickness (Nobel et al., 2012). On the other hand, a force-based feedback, such as tactile/vibrotactile stimuli and arthrokinetic stimuli (moving a body limb), has shown potential in enhancing both tactile and kinesthetic perception, with the advantage of being non-invasive and comfortable (Bos, 2015). Each force-based feedback system offers distinct advantages in alleviating motion sickness in cars.

Haptic Cueing Strategies

Among the different types of haptic feedback, the authors distinguished four haptic cueing strategies that show potential to reduce motion sickness for car passengers. It is to notice that these strategies can apply for other sensory modalities as well.

- Disrupt the physical perception of self-motion;
- Enhance the physical perception of self-motion;
- Increase predictability on the upcoming motion forces;
- Minimize involuntary movement.

Disrupt the physical perception of self-motion: In this strategy, haptic cues are utilized to reduce the sensory discrepancy and introduce non-disturbing vibrations as ambient noise. Although the scientific explanation for its effectiveness is still lacking, it is hypothesized that this approach decreases the sensory mismatch, reduces the reliability of vestibular and proprioceptive modalities, and affects the overall perception of motion. Studies have shown that comfortable low-frequency vibrations on the head can significantly alleviate sickness induced by rotations, and applying Bone Conducted Vibrations (BCV) to the head can delay symptom onset and mitigate sickness severity (Bos, 2015; Lucas et al., 2020; Salter et al., 2019; Weech et al., 2018). The effectiveness of this strategy may be enhanced by combining vibrations with sound signals, and the location of vibration plays a crucial role, considering the varying sensitivity of different body limbs to such stimuli.

Enhance the perception of self-motion: the startegy consists in using sensory signals to enhance one's perception of self-motion. While not specifically tested in cars, numerous studies have shown the benefits of haptic feedback in virtual environments, where it facilitates the sensory illusion of self-motion (Amemiya et al., 2013; D'Amour et al., 2017; Weech and Troje, 2017). This illusion, known as vection, is considered a prerequisite for visually induced motion sickness. Vibrotactile devices are identified as suitable tools for implementing this strategy, as they can effectively stimulate the senses and contribute to alleviating symptoms of motion sickness (Kooijman et al., 2022).

Increase predictability on the upcoming motion forces: This strategy involves using haptic feedback to enhance anticipation of present and future motion. Studies have shown that anticipatory haptic cues, experienced in both static and dynamic simulators, can lead to slightly lower sickness scores and feelings of controllability (Li and Chen, 2022; van Veelen, 2022). However, anticipation haptic signals did not significantly alleviate motion sickness in real-vehicle experiments (Tomzig et al., 2023; Yusof et al., 2020), suggesting that the effectiveness of this strategy may vary depending on the type of motion being cued.

Minimize involuntary movement: Postural instability has been theorized as a preceding condition to motion sickness (Stoffregen and Smart, 1998). In cars, stabilizing the head and better controlling body movements has been reported as an effective countermeasure (Bertolini and Straumann, 2016; Wada et al., 2012). To obtain such effects, some studies proposed limiting involuntary movements that are caused by the acceleration forces while exploring the use of arthrokinetic haptic cues, such as inflatable air bags in seat pans or moving plates in seat rests, to decrease head tilt and induce sickness reduction (Karjanto et al., 2021; Konno et al., 2011). Additionally, experiments in involving seat belt retractions before braking maneuvers found that despite inconclusive effects on motion sickness, such haptic signals could enhance feelings of safety and trust in vehicle automation (Kremer et al., 2022; Tomzig et al., 2023).

These different possibilities of application demonstrate the potential of haptic motion cueing to elicit various perceptual phenomena (Costes and Lécuyer, 2023). This paper suggests that the wide application spectrum of haptic stimulations may be suitable to human's complex perception mechanism, where other types of sensory cues may be limited in efficiency. Since the reviewed literature only mentions the use of force-based haptic signals or airflow to mitigate motion sickness, the next subsections aim to identify the structures of a vehicle cockpits where such haptic systems could be implemented.

Structures for a Hardware Integration of Force-Based Haptic Motion Cueing Devices Inside Passenger Cars

To successfully incorporate force-based haptic cues in cars, it is important to have continuous physical contact with the passenger's body, regardless of their seating position or activity. This ensures accurate perception of the haptic cues. It is to notice that within the reviewed literature, tactile innervations were exclusively executed through a vibrotactile feedback. The influence of purely tactile stimulations remains an area yet to be thoroughly investigated.

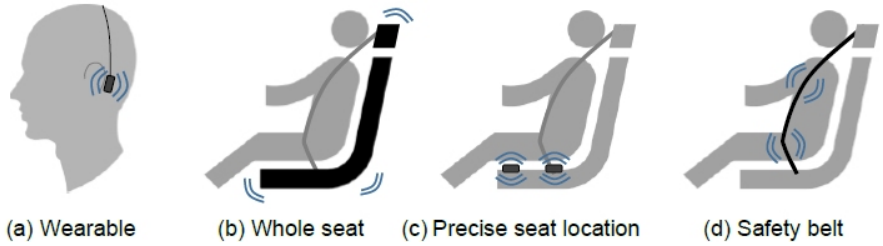
(a) Wearable (b) Whole seat (c) Precise seat location (d) Safety belt

Figure 1: Different implementation possibilities of a force-based haptic system to mitigate motion sickness in cars.

The delivery of haptic motion cues through a wearable device could offer convenience by providing vibrations around the ear (Figure 1a) to disrupt the physical perception of motion (Bos, 2015). Another conceivable implementation involves positioning such devices on inferior or superior body extremities to indicate directions of motion (Yusof et al., 2020). Nevertheless, it is crucial to acknowledge that wearable devices may be felt as invasive and exhausting unless they are integrated into a display that the user desires to wear (e.g. a VR-HMD[1] for entertainment purposes).

Integrating haptic cues within the vehicle cockpit, such as the seat structure, seat cushion, or seat belt, offers potential for enhancing the perception of self-motion and increasing predictability of upcoming motion forces. While vibrating the whole seat (Figure 1b) can stimulate abdominal sensory cells (Lucas et al., 2020), it may affect overall comfort and psychological factors. A more localized approach, focusing on the seat pan (Figure 1c) or seat-belt (Figure 1d), can provide less intrusive haptic feedback, while respectively targeting to improve the physical perception of motion and minimize involuntary movement. The seat rest and headrest are also viable options, given their frequent contact with the passenger's body, allowing for the replication of various aforementioned haptic cueing strategies. However, it is essential to note that the cues transmitted within these areas may be interpreted as more urgent than in other seat locations (Chang et al., 2011).

Table 2 shows the many different possibilities of providing vehicle occupants with permanent haptic feedback as a physical cue to decrease motion sickness while summarizing the different possibilities of force-based haptic stimulation, distinguished by the type of haptic system.

Table 2. Different types of haptic devices and signals studied for mitigating motion sickness.

Type of haptic system	Force-based haptic motion cueing	
	Vibrotactile	**Arthrokinetic**
Wearable additional device	Karjanto et al., 2021; Salter et al., 2019; Yusof et al., 2020	
Actuators in the seat pan	Li and Chen, 2022; Reuten et al., 2023; Sawada et al., 2020; van Veelen, 2022	Konno et al., 2011
Actuators in the seat rest or in the head rest	Bos, 2015	Karjanto et al., 2021
The whole seat	D'Amour et al., 2017; Lucas et al., 2020	
Seat belt actuators		Kremer et al., 2022; Tomzig et al., 2023

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[1] Virtual Reality Head-Mounted Display

Airflow as a Tactile or Thermal Haptic Feedback

Although commonly reported as effective, the effectiveness of airflow on reducing motion sickness in cars has not been scientifically verified. Studies have shown that airflow can have positive effects on reducing simulator sickness (D'Amour et al., 2017; Harrington et al., 2019; Paroz and Potter, 2021), regardless of whether the airflow is direct or indirect (Igoshina et al., 2022). However, there is no specific location requirement for implementing ventilation systems, as the influence of airflow is primarily related to how vehicle passengers perceive the stimuli on uncovered skin surfaces, such as the face and hands.

There is also uncertainty on which haptic cueing strategy can be attributed to airflow for mitigating motion sickness, as its exact influence on the alleviation of symptoms is yet unclear. While airflow can stimulate tactile sensors on the skin, it also serves as a thermal cue and can regulate body temperature. Airflow may not alleviate sickness by facilitating illusory self-motion on its own (Seno et al., 2011), and the study of Igoshina et al. (2022) suggests that the alleviation of symptoms is rather due to thermal than tactile stimulations. Yet, further evidence is needed to validate this hypothesis.

DISCUSSION

While some studies conducted in simulators show promising results, further research is needed to be conducted in real vehicles considering the limited transferability of findings from virtual to real motion environments (Talsma et al., 2023). It is also to notice that in the studies reporting positive outcomes, haptic signals were associated to visual effects within a motion simulation. This observation does not necessarily imply that the haptic signals would solely work for reducing motion sickness in cars. Examining the limited studies carried out into real cars simulated as HAVs, we can notice that positive results were found when a forward view was available (Karjanto et al., 2021; Salter et al., 2019). Some simulator studies also reported haptic cues to be effective when supporting visual cues (Amemiya et al., 2013; Churan et al., 2017). Conversely, no effect was found when the subjects focused on NDRAs without visual cues on the vehicle's motion (Tomzig et al., 2023; Yusof et al., 2020). These findings raise concerns about applicability of haptic cues in HAVs, where passengers would not necessarily focus on the road (Sivak and Schoettle, 2015).

The effectiveness of different strategies for mitigating motion sickness in real cars remains unclear. Studies investigating vibrotactile cues in real motion environments suggest their relative effectiveness, but the authors argue that their efficiency may vary under specific motion conditions (Reuten et al., 2023; Yusof et al., 2020). Further research is needed to explore the influence of varying parameters of haptic feedback, such as location, pattern, frequency, amplitude, and signal timing, on human perception.

Apart from investigating which strategy is optimal, studying the best tradeoff between comfort and perceptibility should be also considered to ensure designing both efficient and user-friendly haptic cues. Additionally, it is imperative to understand the psychological impacts of such haptic signals since individual feelings have great influence on the development of symptoms (McIntosh, 1998). Studying the learning and exhaustion effects of haptic cues is also a necessary requirement for determining the long-term benefits of haptic cues during extended travel times and frequent usage.

CONCLUSION

The investigation of haptic motion cueing for mitigating motion sickness in cars has been insufficient, leaving uncertainty on its potential. This domain presents ample opportunities for research to explore the efficacy of integrating haptic systems that maintain continuous contact, thereby reducing the risk of a sensory mismatch. Further research should focus on validating the effectiveness of each related cueing strategy and studying their subjective impact before considering their industrial application.

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