A Review of Motion Sickness in Automated Vehicles

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ABSTRACT

Automated vehicles (AVs) are the next wave of evolution in the transportation industry, but the progress towards increased levels of automation faces several challenges. One of the major problems, that gets overlooked, is motion sickness. As more drivers become passengers engaging in 'passenger tasks', it will lead to greater occurrences of motion sickness, preventing AVs from providing their true benefit to society. In an attempt to encourage more researchers to solve the problem of motion sickness in AVs, this study conducted a literature review following the PRISMA framework to identify the latest research trends and methodologies. Based on the findings and limitations in the existing literature, this study suggests a bird's-eye-view research framework consisting of causation, induction, measurement, and mitigation techniques, that researchers and early practitioners can utilize to conduct research in this field. Furthermore, the paper highlights future research directions in mitigation techniques to combat motion sickness in AVs.

CCS CONCEPTS

• **Surveys and overviews**; • **Reference works**; • **Evaluation**; • **General literature**;

KEYWORDS

vehicle automation, motion sickness, review, mitigation methods, induction methods, measures of motion sickness, sensory conflict, anticipation

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1 INTRODUCTION

The act of driving is a pleasurable experience for some, and a chore to others. Currently, a massive wave of technological evolution is occurring in the transportation industry, mainly geared towards automated vehicles. According to SAE standards, there are six levels of automated vehicles [44] and as we progress towards higher levels of automation, drivers will begin to take on the role of a passenger. With the drivers freed up to become a passenger, it is expected that they will engage in non-driving related activities or 'passenger activities'. As passengers engage in such activities while being subjected to unexpected movements of the vehicle, they will suffer from motion sickness [40]. This occurrence has a greater impact on the future of automated vehicles. Even with automated vehicles gaining popularity and algorithms making them safer, their adoption will be based on how comfortable passengers feel while using them [35]. Motion sickness in automated vehicles presents an immense issue, and solutions to this problem can be even more challenging given the subjective nature of motion sickness susceptibility, measurements, and mitigation techniques. Rudimentary solutions to car sickness or sea sickness have included medications such as anticholinergics, antihistamines, and other sedatives [56]. The problem has been looked at from a vehicle dynamics perspective to provide smoother ride quality through neural networks to integrate the interaction of lateral acceleration and head tilt concept to minimize lateral accelerations perceived by the passengers [41]. Research has also been done strictly based on mathematical models to minimize motion sickness symptoms with a fixed journey time using optimal control problem algorithms to develop the optimum trajectory and velocity for any road path [15]. However, such studies do not include human subject testing and their modeled measures of motion sickness require further validation with empirical human-subject research [6].

As automated vehicles become more popular, the number of drivers will reduce and the number of passengers will rise. This makes research on this topic crucial to ensure that passengers in automated vehicles have a comfortable experience. Motion sickness is a state of discomfort resulting from exposure to motion. It has physical symptoms such as malaise, dizziness, nausea, and eventually vomiting [23]. Simply put, when there is a mismatch between sensory information and expected bodily sensory state, motion sickness occurs [21]. It has also been shown that exposure to low frequencies such as 0.2 Hz [10, 13] and 0.4 Hz [32] can severely induce motion sickness. Similar theories for the causation of motion sickness are visual-vestibular incongruence and postural instability due to a mismatch between how balance is maintained in the immediate environment [34]. Fixating on an object far away on the horizon, while riding as a passenger, allows the visual-vestibular system to stabilize the eyes as the vehicle turns [30]. This is why when spinning, dancers fixate on one object in front of them as an anchor to prevent motion sickness. However, when the passenger reads from a device or a book whilst inside a moving vehicle, the visual-vestibular system is overridden by the visual pursuit mechanism causing feelings of sickness [5]. Another important theory and the angle of analysis in this survey paper is anticipation [9, 30]. Since passengers are not in control of the vehicle, they are unable to predict how the vehicle will react; this contrasts the driver's perspective because (1) the driver has a clear view of the road through the windshield directly in front of them, and (2) the driver is in

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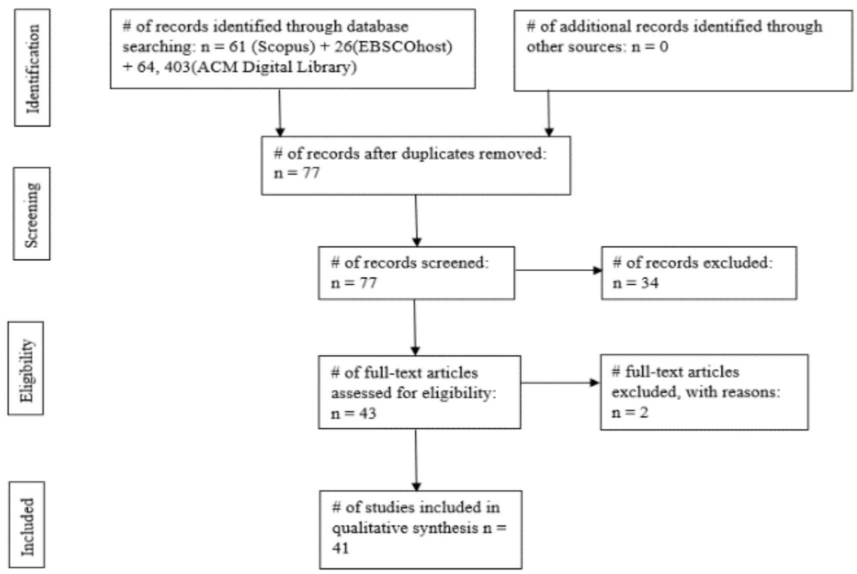

Figure 1: PRISMA framework of paper selection

control of the vehicle and thus, can predict how exactly the vehicle will move. This lack of awareness for passengers is what leads to increased susceptibility to motion sickness [51]. The 'anticipation' theory is of much interest; multiple papers have identified the use of anticipatory cues to mitigate motion sickness as is described in the Section 3.3. Understanding the various ways motion sickness can occur enabled us to focus on studies that utilized such theories to induce motion sickness and develop mitigation strategies.

This survey paper provides a qualitative analysis of the existing challenges to conduct research on motion sickness in automated vehicles. We analyzed 41 papers to identify the common themes found in the current literature. We discuss the findings, provide a bird's-eye-view of a framework highlighting key areas that require focus, and suggest directions for future research in this field. Three key areas are identified as, induction methods, measures, and mitigation methods of motion sickness in automated vehicles. This paper contributes to providing a legitimate framework for research on motions sickness and practical guidelines for designing multimodal mitigation strategies.

2 METHOD

A relatively limited number of search keywords were used to find as many papers involving motion sickness identification, motion sickness causation, and methods of mitigation for passengers in regular and automated vehicles. Popular human factors studies databases were searched including Scopus, EBSCOhost, IEEE Xplore, and ACM Digital Library using the following combinations of keywords, '(autonomous vehicles AND motion sickness)' OR '(motion sickness AND mitigation AND autonomous vehicles)' OR '(motion sickness AND situation awareness AND autonomous vehicles)'.

We examined the abstracts of the papers to include those that approached the issue from a human factors perspective, and made use of driving scenarios to test a solution. Papers originally published in the English language, and those to which we had full text access were then selected for full review. Papers that studied motion sickness from other engineering or a strictly medical perspective were excluded for the most part. Data were extracted based on the experimental methods reported in the studies. Our focus was to identify experimental environments that were used, causation theories being reported, the measures of motion sickness that were utilized, and any modalities of solutions that were tested to mitigate motion sickness.

For this review, we followed the PRISMA framework (Figure 1) [26]. The results from ACM Digital Library were overarching and tended to include many unrelated papers, and as a result that source was not included in the final iteration. IEEE Xplore database was used mainly to get access to certain papers that were identified on Scopus and EBSCOhost.

A total of 41 papers from 2006-2021 were included for the purposes of this survey paper. This period was not predefined but seemed to contain the most relevant papers. This survey paper aims to study motion sickness mitigation methods from a human factors standpoint. As a result, the majority of the papers are from human factors and related journals; while most papers from core engineering fields were excluded, certain papers relating to vehicle dynamics and control algorithms were included to learn about additional approaches that are being researched to solve the problem of motion sickness in automated vehicles.

3 RESULTS

Analysis of the selected papers led us to find three common key areas of research, namely, induction methods, measures of motion sickness, and mitigation methods. Each of these areas is discussed in detail in the sections 3.1, 3.2, and 3.3.

These areas seemed to fit into a temporal order in each paper, starting with induction methods, followed by the measures, and lastly the mitigation methods. All assumptions, however, were based on the causation theory initially reported in the paper. These findings led us to generate a bird's-eye-view research framework that is discussed in Section 4.

3.1 Induction Methods and Environment

Real-world scenarios provide a multitude of conditions under which motion sickness can occur. As a passenger engaged in non-driving related tasks or 'passenger tasks' such as reading, watching a movie, attending an online meeting, or simply being a passenger in a vehicle making sharp turns, braking and accelerating harshly will provide conflicting cues to the passenger's sensory systems causing motion sickness.

Table 1 shows the various methods of induction and the environment of research. Two methods seemed to be most popular – the combination of using a driving simulator with the use of a virtual reality (VR) headset for a fully immersive experience of being a passenger in a highly automated vehicle, and real-world driving where the participant was driven in a vehicle and asked to engage in non-driving related tasks. Both deployed driving routes and styles that were designed to induce motion sickness. Another method of induction is from studies that did not have human subjects, but rather had mathematical models for motion sickness and vehicle performance, which were used to improve vehicles' dynamics in order to provide a more comfortable ride.

Studies related to the 'anticipation' theory used simple fore and aft motion to induce motion sickness [23, 34]. This was done in the real world on a set of rails, with the participant seated in a closed box that travelled along the rails. This was a fairly basic motion trajectory mimicking mildly harsh braking and acceleration in unexpected or unanticipated directions. This method cannot be considered comprehensive or representative of real-world driving. However, they showed that the provision of anticipatory cues through auditory messages before the motion significantly lowered motion sickness ratings.

A popular method of induction was through the use of a driving simulator combined with a VR headset. Combining automated driving scenarios from a driving simulator with a VR headset to expose participants to driving conditions such as countryside with many turns, has been shown to successfully induce motion sickness, especially with more dynamic driving conditions [14]. The driving simulator required at least four degrees-of-freedom (roll, pitch, yaw, heave) to successfully immerse the participant in the scenario as body movements were crucial to producing the required changes in the visual-vestibular system. The same settings were augmented for a rear facing seat position [8]. This is another point of interest as a more non-conventional seating configuration is being considered with the increase in automated vehicles, to support passenger tasks [50].

Compared to the use of driving simulators and VR headsets, real-world driving has better ecological validity. Motion sickness was successfully induced with vehicles driven in an urban setting in a defensive manner with lateral accelerations reaching up to 2.84 m/s2, with participants sitting inside viewing content on a screen [1]. Driving was also done on a test track along a predefined route, during which participants were asked to perform non-driving related tasks such as picking out pattern of "b q" in a random series of "b", "d", "p", and "q" [3]. It is of the opinion that the term, "non-driving related tasks", will evolve to become "passenger tasks" (PTs), since the tasks under consideration in research are being performed by passengers in an automated vehicle, and not by a driver. Another real-world motion sickness induction method was where the vehicle was driven by the researcher at speeds of up to 100 kmph or 62 mph on a preselected curvy road with multiple serpentines, while the participants were asked to read and reply to texts on a smartphone. This was a classic example of how limited peripheral vision and sharp driving maneuvers lead to motion sickness [30]. It is entirely reasonable to assume that vehicle owners will want to be driven around a curvy, scenic cliff while they take pictures and edit them on the go. Motion sickness remains a barrier for such use cases, where the entire purpose of an automated vehicle could be rendered useless.

3.2 Motion Sickness Measures

Over the years, multiple measurements have been used, most of which are subjective rating scales. Physiological measures are also utilized but they do not always reach statistical significance. Motion sickness is a fairly subjective experience; two individuals who have had different exposures to different motions in life might not feel the same susceptibility to motion sickness on the same winding road. To that extent, it is first necessary to pick participants who have similar motion sickness susceptibility, in order to have an equivalent group. Table 2 shows the commonly used motion sickness measures.

Figure 2 shows the frequency of occurrences of the major motion sickness measures as identified from the papers for the purposes of this research. Golding [18] developed a shorter version of the original susceptibility questionnaire, called Motion Sickness Susceptibility Questionnaire – Short (MSSQ-Short). This has been a widely accepted questionnaire administered before exposure to any treatment to assess participants' susceptibility to motion sickness in general [3, 8, 18, 19, 22, 28, 29, 32, 34, 36, 52]. MSSQ-Short is a simpler, faster version of the original questionnaire by Reason and Brand from 1975 and has a strong correlation to the original ($r = 0.94$) [18]. It requires participants to score their experiences with different forms of motions experienced as a child (under 12 years of age) and as an adult. According to one study, participants aged 21-56 years were found to have a MSSQ score of 12.8 ± 8.21 [3]. Another study with a population aged 21-60 years reported MSSQ scores ranging from 28.6 to 100, with a median of 77.85 [30]. The wide range of values confirms the need to administer a MSSQ before any treatments to understand the general susceptibility of the participants. This affects the final conclusions and the extent of generalizing the results.

Another measurement is MSAQ, or the Motion Sickness Assessment Questionnaire, which treats motion sickness as a multidimensional problem rather than unidimensional, having four dimensions: gastrointestinal (sickness to the stomach, nausea), central (fainting, lightheadedness), peripheral (cold sweats, hot/warm), and sopite-related (drowsiness, fatigue). MSAQ is strongly correlated with scores from two other widely used indexes, Pensacola Diagnostic

Table 1: Method of Induction and Environment

Reference	Participants	Method of Induction	Environment
[Kuiper a et al., 2018]	N = 20 [12 M, 8 F], avg. age of 39.5 years]	Real-world fore and aft motion on a rail track with varying pauses and direction	Real-world motion and cues
[Gruden et al., 2021]	N = 22 [20 M, 2 F], aged 19-40, avg. BMI 24.6±4.9	Driving simulator with VR headset for L5 automated vehicle. Highway vs. countryside driving scenarios.	Virtual environment while seated in a driving simulator
[de Winkel et al., 2021]	N = 19 [7 M, 12 F], avg. age of 27.7 years	VR headset in rear facing seat, with AR cues and NDRT	Virtual environment with AR cues.
[Le et al., 2020]	N = 50 [23 M, 27 F], avg. age of 40	Real-world NDRT	Real-world environment
[Jurisch et al., 2020]	N = 50 [25 M, 25 F], age of 20-60	Driving simulator scenarios	Simulator driving
[Wang et al., 2020]	N = 36 [17 M, 19 F], avg. age of 24.3 years	Real-world driving	Real-world driving
[Saruchi et al., 2020]	N = 10 [Age not reported]	Simulator driving	Simulator driving
[Paddeu et al., 2020]	N = 56 [39 M, 17 F], avg. age of 51 years.	Real-world automated driving	Real-world automated vehicle
[Yeo et al., 2020]	N = 20 [16 M, 4 F], avg. age of 24	Automated driving scenarios	Real-world, virtual environment driving
[Perrin et al., 2013]	N = 85 [64 M, 21 W] avg. age of 31.5 years. Competitive driving experience of 4.5 years	Scenario based driving, competitive driving	Real-world driving
[Kuiper et al., 2018]	N = 18 [8 M, 10 F], avg. age of 26 years	Slalom driving, visual tracking NDRT	Real-world driving
[Salter a, et al., 2019]	N = 20 [11 M, 9 F], avg. age of 36 years	Seating orientation, NDRT	Automated real-world driving
[Karjanto et al., 2017]	N = 10 [6 M, 4 F], avg. age of 25 years	Automated defensive urban driving, NDRT	Real-world driving
[Sakai et al., 2019]	N = 10 [8 M, 2 F], avg. age of 25 years.	VR immersion with movement speed variation	Electric wheelchair, VR immersion
[Schartmüller & Riener, 2020]	N = 24 [8 M, 16 F], avg. age of 22.83 years	Various driving maneuvers	Test track driving
[Nakajima et al., 2009]	N = 2 [2 M, 0 F], avg. age of 24.5 years	HUD, vibrations induced at varying frequencies	Driving simulator
[Bohrmann & Bengler, 2020]	N = 50 [21 M, 29 F] avg. age of 42.46 years; N = 16 [14 M, 2 F], avg. age of 36.6 years	Backrest angle, seating direction, NDRT; multi-sine waves, shaking stimuli, NDRT	Real-world automated driving; ride simulator
[Smyth et al., 2018]	N = 51 [27 M, 24 F], avg. age of 31 years	Simulator driving route, Visual, Physical, Cognitive performance tasks	Driving simulator

Index (PDI, r = 0.81) and Nausea Profile (NP, r = 0.92), indicating its validity [12]. MSAQ consists of 16 questions that can be rated from 1 (not at all) to 9 (severely). It can be administered before and after an exposure to assess the validity of the treatment effects. MSAQ scores are mainly used as the difference between pretest and posttest. This nature of scoring has a disadvantage in that there are no measurements for the exposure period itself. While it is true that motion sickness symptoms generally increase over time, there may be non-linear variations during the treatment, which are not recorded by MSAQ.

MISC, or Misery SCale has an advantage. It measures motion sickness symptoms on an 11-point scale, allowing variable temporal readings over the period of exposure [4]. The different severity ratings provide a more sensitive scale than MSAQ, although it is comparable only to the overall MSAQ score. Once a participant reaches a rating of 6, induction or the condition is usually halted [32].

Yet another similar scale is Fast MS Scale (FMS). FMS is shown to be highly correlated (r = 0.785) with a total Simulator Sickness Questionnaire (SSQ) scores, which measures sickness from using a simulator such as driving simulators or virtual reality headsets

Table 2: Measures of Motion Sickness

Reference	Participants	Measure
[Kuiper et al., 2018]	N =20 [12 M, 8 F], avg. age of 39.5 years]	MSSQ [Motion Sickness Susceptibility Questionnaire], MISC [MIsery Scale
[Kuiper et al., 2020]	N = 17 [5 M, 12 F], avg. age of 39.6 years]	MSSQ [Motion Sickness Susceptibility Questionnaire], MISC
[Gruden et al., 2021]	N = 22 [20 M, 2 F], aged 19-40, avg. BMI 24.6±4.9	EGG [electrogastrography], GSR [galvanic skin response], HR [heart rate], Subjective assessment [#nausea onsets, SSQ - Simulator Sickness Questionnaire]
[de Winkel et al., 2021]	N = 19 [7 M, 12 F], avg. age of 27.7 years	MSSQ, FMS [Fast Motion Sickness Scale], SSQ, Evaluation Questionnaire
[Ittner et al., 2020]	N = 119 [48 M, 71 F], avg. age = 41.3 years; N = 24 [11 M, 13 F], avg. age of 46.96 years	Questionnaire, Interview
[Le et al., 2020]	N = 50 [23 M, 27 F], avg. age of 40	Standing balance exercise, IMU [inertial measurement unit] to measure postural sway, RMS of angular positions and velocity in A/P and M/L.
[Jurisch et al., 2020]	N = 50 [25 M, 25 F], age of 20-60	MSSQ, MSQ, IL, PES, HRV, Cabin temperature
[Wang et al., 2020]	N = 36 [17 M, 19 F], avg. age of 24.3 years	Vehicle motion parameters, passenger comfort evaluation
[Saruchi et al., 2020]	N = 10 [Age not reported]	MSI Quantification [head roll, lateral acceleration]
[Yeo et al., 2020]	N = 20 [16 M, 4 F], avg. age of 24	SSQ, visual, motion, presence questionnaire
[Salter et al., 2020]	N/A	Mathematically derived sickness equation, visual performance, MISC
[Perrin et al., 2013]	N = 85 [64 M, 21 W] avg. age of 31.5 years. Competitive driving experience of 4.5 years	MSSQ, MSSQ Short
[Kuiper et al., 2018]	N = 18 [8 M, 10 F], avg. age of 26 years	MISC, accelerometer data
[Levine et al., 2014]	N = 80 [37 M, 43 F], avg. age of 20.28 years	Subjective rating scale, SSMS [Subjective Symptoms of Motion Sickness], EGG
[Salter et al., 2019]	N = 20 [11 M, 9 F], avg. age of 36 years	MSSQ Short, SSQ, Temperature, Accelerometer
[Zhang et al., 2020]	N = 52 [42 M, 10 F], avg. age of 28.5 years	MSQ, fNIRS
[Karjanto et al., 2017]	N = 10 [6 M, 4 F], avg. age of 25 years	MSAQ [Motion Sickness Assessment
[Mu et al., 2020]	N = 3 [0 M, 3 F], avg. age of 39 years	Questionnaire], SART [Situation Awareness Rating Technique]
[Md. Yusof et al., 2020]	N = 20 [12 M, 8 F], avg. age of 26	MISC
[Kuiper et al., 2019]	N = 16 [14 M, 2 F], avg. age of 37.31 years	MSSQ, MSAQ [Motion Sickness Assessment Questionnaire], SART, RSME [Rating Scale Mental Effort], ride quality Likert scale.
[Meschtscherjakov et al., 2019]	N = 10 [4 M, 6 F], avg. age of 40.5	MSSQ, MISC
[McGill et al., 2017]	N = 18 [18 M, 0 F], avg. age of 25.1 years	MSSQ Short, MSAQ, post questionnaire, interview
[Bohrmann & Bengler, 2020]	N = 50 [21 M, 29 F] avg. age of 42.46 years; N = 16 [14 M, 2 F], avg. age of 36.6 years	SSQ, EGG, ECG, UX Curve
[Smyth et al., 2018]	N = 51 [27 M, 24 F], avg. age of 31 years	Illness rating scale, SSQ, IPQ [iGroup Presence Questionnaire], VR Immersion preference rating
[Sawabe et al., 2016]	N = 1	User's CG [Center of gravity] movement

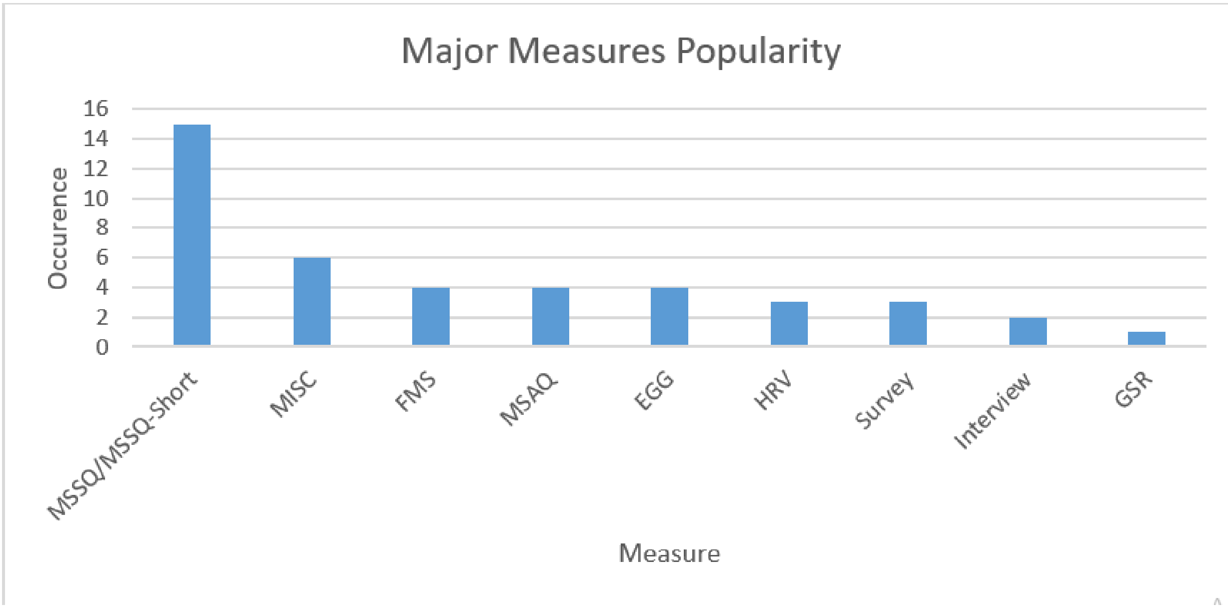

Figure 2: Occurrences of major measures identified

[20]. The FMS is administered verbally throughout the exposure period providing real time feedback, instead of requiring any recall. It is rated on a single dimension from 0 (not nauseas) to 20 (about to vomit).

Physiological measures or biological effects have also been considered as measures for motion sickness. The problem, however, is that there is no single valid parameter that can represent motion sickness accurately [47]. As a result, any study utilizing physiological measures should include at least a combination of EGG (electrogastrography), GSR (galvanic skin response), and HRV (heart rate variability). A recent study from 2021 investigated the use of above parameters to reliably measure motion sickness onset from the use of a driving simulator with a condition to induce motion sickness utilizing a VR head mounted device [14]. EGG analyzes myoelectrical stomach activity. The collected EGG signals showed the root mean square (RMS) value increased with the simulated drive session, but did not reach statistical significance. GSR, which is a variation of electrical characteristics of the skin due to sweat gland activity, also increased with the simulated drive and reached statistical significance. The same trend was seen with HRV although the difference was not significant compared to the control. HRV has also been used to confirm the efficacy of treatment effects across different conditions [29]. According to the previous paper, RMS values over a period of time and detected EGG signal amplitude increase can be used as accurate short-time indicators. Pretest and posttest EGG and HRV readings showed differences, but did not reach significance [46]. However, these measures require careful interpretation since the signals are subject to noise and inter participant contamination.

Finally, surveys and interviews are also an option, especially for pilot studies. Surveys allow to reach a large audience which can be used to identify common problems or themes, such as co-driver discomfort [17, 48]. Following up with interviews is beneficial to gain a deeper understanding of the problems allowing to pinpoint areas of research directions, and further identify niche problems for developing a cognitive co-driver discomfort model [17].

3.3 Mitigation Methods

Mitigating motion sickness requires knowledge of the causes of motion sickness. As seen, two major theories of motion sickness have been identified – sensory conflict theory and anticipation theory. Based on these theories, multiple techniques have been tested for their effectiveness. The following sections discuss visual, auditory, haptic cues as well as interior design, and non-driving related activities that have been researched.

3.3.1 Visual Cues. Visual cues and vision-based methods have been the most popular. The location of visual displays is an important element when discussing vision-based solutions. Head movement has been known to lead to motion sickness, and its minimization can help to improve stabilization since it reduces the degree of inputs to the vestibular system [24, 37]. Head movement minimization can be achieved by fixating one's gaze on a distant point for reference while experiencing motion in a vehicle. This is helpful as it reduces involuntary head motion and avoids incongruent sensory inputs [2]. Based on that, they tested two display heights – (1) at eye height of the passenger in front of the windscreen to provide considerable peripheral view of the outside environment, and (2) at the height of the glove box that required the participant to look down. It was found that the first position caused lesser motion sickness symptoms [32]. Increased focal vision on displays showing content inconsistent with the vehicle's motion has also been shown to lead to sensory conflict in the visual-vestibular system [4]. Recommendations have also been made to locate displays near the line of sight out of the window, and to limit the size of the display to allow for sufficient peripheral visual information [9].

It is expected that in the future of automated vehicles, passengers will want to perform a myriad of activities, some of which might not leave any room for peripheral view of the real-world such as using VR headsets to attend meetings, or playing games to relax. In such cases, anticipation theory comes into play. By providing cues of future motions, such as turns, acceleration, or decelerations, the passenger can be informed of the upcoming motion. Various studies have researched providing such cues visually with different prediction time ranging from 3 seconds to 500 milliseconds. One study showed that by providing visual cues through the use of LED strips on the sides of a display inside the vehicle, three seconds before the upcoming turn, with the light moving along the strip four times within those three seconds, they were able to reduce motion sickness symptoms significantly [1]. A similar concept utilized a single reading device which was modified to show floating bubbles along the perimeter of the screen, and these bubbles would react according to the acceleration forces picked up the device's gyroscope, informing the user of the vehicle's motion [30]. This afforded the user to focus their vision onto the reading device, and not have to maintain vision of the outside view for peripheral information. These two studies, however, did not use predictive information but only live cues. Predictive visual cues were provided in a study that utilized a VR environment with a rear facing passenger engaged in a non-driving related task of playing a visual game in the virtual environment. The cues in this case were multiple small balls of light that were superimposed on the interior surfaces of the vehicle, and provided inertial cues 500ms ahead of the actual motion [8].

3.3.2 Auditory Cues. Compared to visual cues, auditory cues have a greater promise of mitigating motion sickness effects given hearing's omnidirectional characteristic. Two specific advantages exist for auditory cues compared to visual cues: hearing is omnidirectional allowing designers to take advantage of spatial audio to provide auditory cues about turns, accelerations, and decelerations; and auditory cues allow for better dual-task performance. The second advantage is based on the multiple resources theory [53]. According to this theory, different modalities require separate mental resources to process information. Since most non-driving related tasks are expected to primarily use vision (e.g., VR headsets, book reading, attending meetings online, watching a movie), providing the anticipatory cues through the auditory modality has a big advantage. It is a subtler form of continuous information probe that allows for parallel processing with lower mental workload. It is considered that the best technology is the kind that manifests itself only when it is required and is otherwise indistinguishable from the environment. Auditory cues can fit this description, by subtly providing spatial cues just when they are required to mitigate motion sickness symptoms, if implemented correctly. Not very many related papers were found towards this issue. It has been demonstrated that predictable motion generates lower motion sickness scores compared to conditions when the motion is directionally and temporally unknown [23]. However, in this study they only tested a motion profile that allowed for fore and aft motion, which is not representative of real-world driving scenarios. Knowing this, another study was conducted on the same fore and aft motion profile but this time auditory cues were provided one second prior to the motion occurrence, communicating either "forward" or "backward" in the participant's native language. The cues led to a 17% reduction in motion sickness scores after an exposure period of 15 minutes [34].

3.3.3 Haptic Cues. Haptic cues also have not been explored as much as visual cues. Haptic cues have the advantage of being a separate modality compared to vision allowing for better dual-task performance, following the multiple resources theory. One study deployed wearable sleeves on each wrist that had motors producing vibrations at 183 Hz with a temporal pattern of ON and OFF for 0.6 seconds each for a period of three seconds, and depending on a left or a right turn, the corresponding sleeve would provide haptic feedback to inform the user of the vehicle's intention [29]. The vibrotactile display provided participants with the correct sense of the vehicle's movements as they were engaged in a visual tracking task.

3.3.4 Olfactory Cues. Another interesting modality of perception is scent. While scents have been known to increase motion sickness [36], scents have also been investigated to reduce motion sickness using lavender scents to calm the central nervous system, and ginger for its positive effects on the gastric system [46]. However, they did not find any significant differences in motion sickness scores between their scented and unscented groups, even though lavender showed increased non-driving task engagement duration, its effects did not reach the statistical significance level.

4 DISCUSSION

The focus of this study was to systematically review the existing papers on motion sickness in AVs, identify limitations in the research, develop a bird's-eye-view framework (Figure 3) that can guide future researchers and practitioners, and suggest future directions of research on mitigation methods for passengers in AVs. As vehicles reach increased levels of automation, it will free up the driver to become a passenger, and consequently engage in a variety of 'passenger tasks' to increase productivity [43]. This is supposed to be automated vehicles' biggest unique selling point.

Current research has investigated the issue of motion sickness, but has not been enough to provide a complete solution. A number of challenges remain to truly solve the problem of motion sickness in AVs from engagement in 'passenger tasks'. These challenges include effectiveness of motion sickness induction, accurate measurement, but most importantly the effectiveness of the mitigation techniques. Based on the existing studies, and in an effort to encourage more research towards this field, we suggest a framework to conduct effective research on motion sickness in automated vehicles. Figure 3 shows a bird's eye view of a framework that can be utilized to structure a research plan for the different stages of motion sickness research. It starts with a causation theory, based on which an induction and/or mitigation method may be selected. For example, based on anticipation theory, the induction method could be a real-world driving route with all peripheral vision blocked out and a display in front of the participant to perform a passenger task; the mitigation method could be providing cues of upcoming motion using a single or multimodal display. Irrespective of the induction

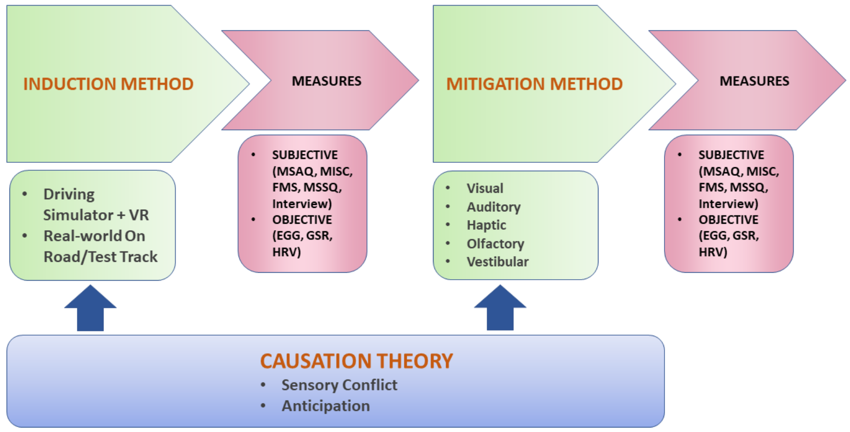

Figure 3: Bird's-eye-view Research Framework

or mitigation method, both require validation. A pilot study to perform a manipulation check ought to be done using appropriate measures to test the effectiveness of the induction method. The same goes for the mitigation method. Furthermore, the modalities themselves require investigation to identify the most appropriate modality, and duration of application. Each block with the same lightness contrast can also become areas of focused research as described in sections 4.1, 4.2, and 4.3, and together they represent the entire research structure.

4.1 Induction Methods

An important consideration when designing induction techniques is the effectiveness of the method. This is more important when using a driving simulator and VR headset as a method of motion sickness induction. Simply, the use of a driving simulator has been known to induce motion sickness, measured with the Simulator Sickness Questionnaire [7, 33, 37]. Adding further induction techniques through the use of specifically designed routes, confusing cues, and non-driving related tasks or passenger tasks will add on to motion sickness. It is therefore, important to understand which is the true cause of induction – is it just the use of the simulator and VR headset, or is it the treatment condition within the simulator and VR headset? It is recommended to test the effectiveness of the induction method to verify that the motion sickness is truly coming from the induction method and not simply from the use of the simulator. This relates to internal and external validity of the study. This confounding variable will make it hard to generalize the results and offer reliable design guidelines. It is also seen that speed of movement in VR simulation with respect to actual speed in the real-world has an effect of perceived 'strangeness' [38]. This is further evidence that induction methods need to be tested for their true effectiveness through pilot studies before progressing to later stages of the research.

4.2 Measures

Another challenge is the measures of motion sickness. Several subjective scales have been developed to record motion sickness scores for experimental purposes. While some of them have been verified against pre-existed standards such as the Pensacola Index and Nausea Profile [12], other measures (MISC, FMS) have been verified against other subjective measures using the Simulator Sickness Questionnaire [37]. Interestingly, all of these measures have been developed or verified by themselves with no cross verification. If we add physiological measures such as EGG, HRV, or GSR to this, there exists a multitude of independent measures that have no relationships to each other even though they are all measuring the same quality (or construct). There has been little investigation to verify these measures with each other. Physiological measures require further consideration given their susceptibility to noise, and the experimental design's construct validity before conclusions can be drawn. Thus, future research should consider conducting a pilot study to verify and select an accurate measure of motion sickness through a thorough evaluation of different scales and/or physiological measures. This can become an extensive area of research in itself. Developing a model that relates these scales with one another to generate coefficients for easy conversion between them can be an entire research area by itself. Categorizations can also be made depending on age groups, gender, and geographical location of subjects to generate a table that future researchers can refer to for verifying their recorded scores.

4.3 Mitigation Methods

Lastly, regarding modalities of mitigation techniques, there exists substantial room for improvements with auditory, haptic, as well as visual feedback. Special interest lies with the auditory modality, given its two advantages, as discussed earlier in Section 3.4.2. Current issues with this mitigation technique include its effectiveness compared to visual cues which can provide continuous low level sensory information [11], and the limited degrees-of-motion pattern used in the study [34]. An additional concern is the time period for prediction (one second) which was chosen arbitrarily in the study, while visual cues have been tested from 3 seconds to 500 milliseconds. Most of these considerations can be summed together into design guidelines such as speech vs. non-speech sounds, length of cues, temporal pattern, prediction time period, sound pressure levels, and effectiveness of spatial audio. It also remains to be tested whether a single modality is the answer to this, or a multimodal approach would be more beneficial.

Haptic feedback is another modality that deserves attention. Currently, haptic seats have been deployed as a safety warning feature in the driver's seat to warn for lane departures, collision alerts, and parking assists [45]. Further considerations would include the pattern of such haptic feedback, location preference, frequency and amplitude.

5 LIMITATIONS

The current study conducted a review of the existing literature, and utilized a PRISMA framework to identify relevant papers. The analysis was mostly limited to a qualitative analysis, and did not consider performing a quantitative meta-analysis. No requirements were set by the author to consider only "high quality" papers since we wanted to include as many related studies as possible. Also, there were also only two authors who were part of the screening process. It is possible that by including more authors, the screening the eligibility of papers could be validated further. It was not possible to provide assessment of risk of bias of each study given the limited number of researchers and resources at the time of conducting this study. Despite the use of a PRISMA framework, because of the above limitations, this study may not be considered a complete systematic analysis, but rather a comprehensive review of related literature.

Lastly, we would also like to address the fact that no health related or medical databases were included in the identification process. One paper reporting the use of clinical drugs however, was included and has been reported in the Introduction. Our objective was to look at the problem from a human factors perspective only. We did include studies on vehicle dynamics as an additional perspective but human factors papers formed the basis of this study. To that extent, we believe that the system design should be human centered. The system should adapt to encompass user needs, and therefore, solutions should focus on improving passenger experiences irrespective of external factors such as road infrastructure, or weather conditions.

6 CONCLUSION

The goal of this paper was to investigate the problem of passengers suffering from motion sickness in automated vehicles. The advent of automated vehicles will transform drivers into passengers. Additionally, passengers will engage in non-driving related tasks to take advantage of the time gained by not driving. Considerable research is still required to provide solutions to the issue. Our paper, following a PRISMA review, investigated 41 papers related to identify barriers in conducting research on this topic. We were able to identify induction methods, measures, and mitigation methods as the three major areas that require future investigation

It is hoped that this survey paper will serve as a starting point for research in the field of motion sickness in automated vehicles. It sheds light on the key aspects of this field that require attention, and will inform students, early researchers, and practitioners to generate new ideas towards a potentially unified solution. It is entirely possible that a 'single solution' will not be appropriate for all circumstances and individuals, and there might be a need to develop 'individualized solutions' that cater to specific circumstances and demographics. The discussed limitations surrounding mitigation techniques should open up possibilities for future research in the human factors field to tackle motion sickness in automated vehicles.

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