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Developing A Spatial Audio Motion Cueing (AMC) System for Autonomous Vehicle Users, Navigation and Audio System for Mitigating Motion Sickness

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Abstract

The development of autonomous vehicles has changed users from active drivers to passive riders, which brings new human factors issues, especially motion sickness. The conflict between visual and vestibular stimulation in non-driving-related tasks is still a major obstacle to the acceptance of autonomous vehicles by users. In this paper, a Spatial Audio Motion Cueing System (AMCS) designed to provide predictive auditory feedback in synchronization with the vehicle motion to alleviate motion sickness is introduced and evaluated using twelve participants under two conditions: with AMCS and without AMCS. An on-road experimental study was conducted using a Mazda CX-8 car with twelve participants with moderate motion sickness susceptibility. Objective assessments in terms of Motion Sickness Dose Value (MSDV) and subjective assessments using the Motion Sickness Assessment Questionnaire (MSAQ) and User Experience Questionnaire (UEQ) were obtained in both baseline (without AMCS) and experimental (with AMCS) conditions. Results revealed that although the system was conceptually feasible and was less effective in, and improvement need for further research by the stimulation and novelty aspects of user experience, it was not entirely effective in reducing motion exposure and motion sickness severity. The results revealed that spatial audio cueing might not be entirely effective in mitigating motion sickness unless there are further improvements to its cueing.

1. Introduction.

The rapid evolution of autonomous vehicles has greatly impacted the human-vehicle interface. The increased level of automation in vehicles allows humans to hand over control from humans to machines, thereby allowing individuals to perform non-driving-related tasks like reading, working, or using digital devices [1]. Although this has improved human productivity, it has also led to physiological and sensory issues, like motion sickness.

Motion sickness has been largely associated with conflicting information from the visual, vestibular, and proprioceptive systems [2]. In the case of traditional vehicles, the driver's ability to visually predict motion and align the visual information with the motion of the vehicle minimizes the conflicting information from the various systems. In the case of autonomous vehicles, passengers often change the direction of their visual attention, making them susceptible to motion sickness. This has been a major challenge for the users of autonomous vehicles, affecting their trust and satisfaction with technology [3].

Traditionally, motion sickness has been mitigated through the optimization of the vehicle's motion, visual feedback, and mechanical adjustments of the seats. Though the methods are effective, they might make the system overly complex. This study proposes the use of a Spatial Audio Motion Cueing System (AMCS) for the improvement of motion predictability using directional audio cues and synchronization with the acceleration of the vehicle. This study aims to determine the effectiveness of the system in mitigating motion sickness through on-road testing [4].

1.1 Background Of Study.

With the development of autonomous driving systems, the level of control and anticipatory awareness of the motion of the vehicle has been compromised. According to the Sensory Conflict Theory, motion sickness occurs when there is a difference between the expected motion and the sensed motion. In addition, the Postural Instability Theory posits that the prolonged instability of maintaining postures contributes to the development of motion sickness. In the case of autonomous vehicles, the passengers are presented with a lack of control and a lack of visual alignment of the motion of the vehicle, thus making them susceptible to motion sickness. In the development of motion sickness, the acceleration of the vehicle in the longitudinal, lateral, and vertical axes has been implicated. Spatial audio systems provide the ability to present a three-dimensional audio experience, thus providing the ability for the passenger to be aware of the motion of the vehicle. This awareness of the motion of the vehicle would be presented through the ability of the spatial audio system to provide anticipatory directional feedback, thus reducing the level of uncertainty.

1.2 Problem Statement.

Despite technological progress in autonomous vehicles, there is still insufficient treatment of motion sickness. Current countermeasures for alleviating motion sickness have been mostly centered around mechanical engineering, optimizing control systems, or visual information systems, which may complicate systems or hinder passengers' engagement with secondary tasks. In addition, most previous studies have been conducted under simulated environments instead of actual driving scenarios. There is a notable lack of experimental evaluations on spatial audio motion cueing systems under actual driving environments. The efficacy of spatial audio systems in alleviating motion sickness is still questionable.

1.3 Objective of Study.

The goal of this research is to design, implement, and assess a Spatial Audio Motion Cueing System that has been created to improve passenger awareness of vehicle motion, reduce sensory conflicts, and minimize motion sickness symptoms. The purpose of the investigation is to establish whether synchronized directional audio cues have the potential for improving passenger comfort during non-driving-related activities under real on-road conditions.

1.4 Scope of Study.

This research aims to investigate the development of an audio-based motion cueing interface in a real-world driving environment. Acceleration was measured along the longitudinal, lateral, and vertical axes and was correlated with spatialized audio. Twelve participants with moderate susceptibility to motion sickness were recruited to maintain consistency in this experiment. A comparison of conditions without audio cues and conditions with the Audio Motion Cueing System (AMCS) activated was made to evaluate the performance of the system. Both objective and subjective analysis were performed.

2. Methodology.

An on-road experimental evaluation was performed by using a Mazda CX-8 vehicle to replicate an autonomous passenger scenario. Twelve participants were chosen based on moderate susceptibility ratings obtained via the Motion Sickness Susceptibility Questionnaire. Each participant was exposed to two experimental conditions: a baseline condition without audio motion cues and an experimental condition with the Spatial Audio Motion Cueing System enabled. Participants were seated in the middle row to minimize direct visual alignment with the road and were asked to engage in a reading activity to simulate realistic usage of an autonomous vehicle.

Motion sickness is primarily described in terms of Sensory Conflict Theory. According to this theory, sensory discomfort is believed to result from discrepancies between expectations and actual sensory inputs. In the context of autonomous vehicles, this is particularly pertinent as passengers experience a loss of control and therefore a misalignment of their expectations. Moreover, research has identified lateral acceleration as a significant factor pertaining to turning maneuvers. Longitudinal braking events and vertical oscillations compound this effect. In addition to this, Postural Instability Theory proposes that lengthy periods of inability to maintain a relatively fixed posture contribute to illness. With reference to this theory, improving the predictability of motion could alleviate some symptoms.

Spatial audio systems are based on rendering techniques by utilizing object-based rendering, which can be explained as the positioning of the source of the sound in three-dimensional space. Unlike channel-based audio systems, the advantage of spatial audio systems is that they allow the dynamic positioning of the source of the sound with respect to the end-user's point of view or orientation. Therefore, this system can be easily utilized in car-based applications by synchronizing the audio cues with respect to the acceleration of vehicles, thereby influencing the brain's anticipatory processing to reduce the conflict between the vestibular and the visual system.

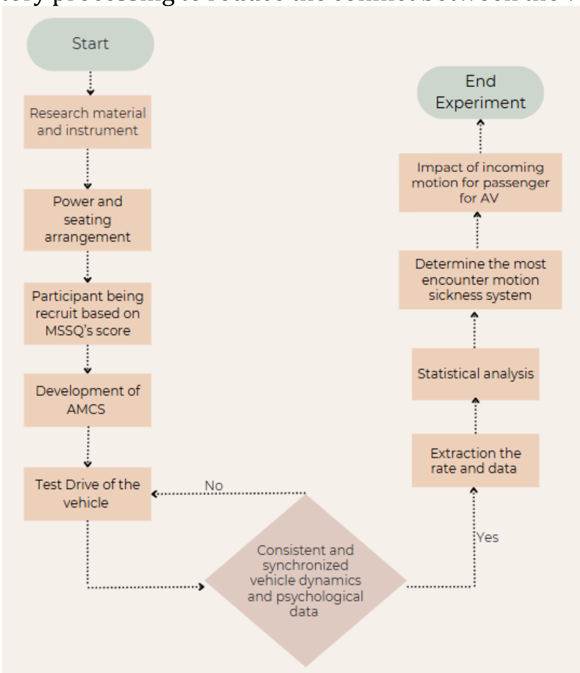

Figure 1: Flowchart of the Experiment.

To evaluate the efficacy of the proposed Spatial Audio Motion Cueing System, an experimental on-road evaluation was carried out. A Mazda CX-8 car model is used for simulating the environment of an autonomous passenger. Twelve participants with moderate motion sickness susceptibility are selected following the results of the motion sickness susceptibility questionnaire. The participants are seated in the middle row of the car to reduce direct visual alignment with the driving environment. The participants are tasked with a reading activity on an iPad during the driving session. Two experimental conditions are incorporated into the evaluation. The baseline condition involves driving without the audio cueing system. The experimental condition involves cues for the audio cueing system. The participants are exposed to conditions in a controlled environment for route consistency.

The Spatial Audio Motion Cueing System was fitted with a manual command of direction and turning time management with Diadem 2019 model, to capture in real time the acceleration data along longitudinal, lateral, and vertical axes. Once processed, acceleration signals were mapped into spatialized audio outputs through speakers placed inside the cabin. Acceleration forward would have its sound cues projected forward, braking events rear-oriented, and the turning of the car would have laterally positioned sounds. Cue intensity and frequency have been calibrated not to alarm but to provide predictive auditory feedback.

Before carrying out the experiment, all subjects screened by the Motion Sickness Susceptibility Questionnaire (MSSQ) were screened for eligibility. Only those ranked moderately susceptible to motion were selected for participation. The subjects signed an informed consent document. The subjects were made aware of the experimental procedure, safety measures, as well as the type of tasks they would be undertaking during the driving. The experimental automobile and data acquisition system were then ready. These included the checking of acceleration sensors, equipment for collecting electrocardiograms, as well as the spatial audio system. The Audio Motion Cueing System was set up in relation to the movement of the automobile in the longitudinal, lateral, and vertical directions. A system validation check was carried out prior to the commencement of the driving task.

Each participant was seated in a designated passenger position and asked to engage in a reading task. This simulates real-world tasks that might be done in an autonomous vehicle. The vehicle followed a pre-designed route to present consistent exposure to motion. Two test scenarios were used in this experiment. There was a baseline test scenario in which the Audio Motion Cueing System was not active. The acceleration of the vehicle and physio responses were recorded all through the lesson. Also, the experimental procedure was continuously monitored to check any inconsistencies in data recording as well as any kind of discomfort among the subjects.

The experimental procedure was temporarily stopped if any inconsistencies were observed. The driver doesn't change in person since the driving behavior and method are different. This decision has been made for accuracy and consistency of driving and vehicle conditions.

After each experiment, a set of standardized questionnaires, such as the Motion Sickness Assessment Questionnaire (MSAQ) and User Experience Questionnaire (UEQ), were administered. These questionnaires were employed for measuring the subjective experiences of motion sickness as well as system usability. The collected data was further processed and analyzed using Diadem 2019, and the mean, standard deviation, CoV, and MSDV were calculated. The data obtained from the baseline test and audio-cue test was used to compare the effectiveness of the proposed system. Integrity checks were carried out to test the accuracy of the data. The integrity checks were followed by statistical analysis.

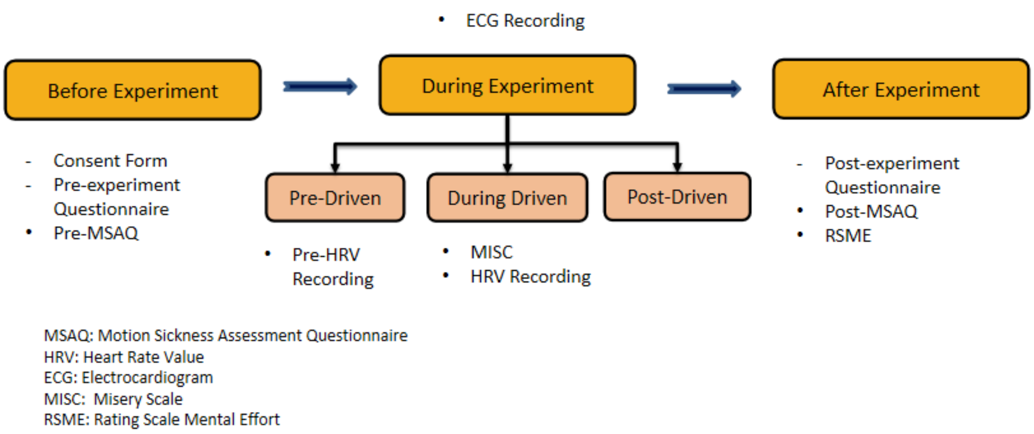

Figure 2: Procedure of the experiment flow regarding the experiment flowchart.

3. Result and Discussion.

The data shows a definite decrease in motion sickness symptoms because of using the AMCS or without using the AMCS (baseline). The MSDV test also showed a decrease in total motion sickness exposure among listeners who received audio cues as opposed to the baseline test. Acceleration readings on all three axes X, Y, and Z-acceleration clearly showed that coordinated audio cues led to passengers better anticipating system motion, thus avoiding unexpected stimuli based on the Vehicle Dynamics working principle and understanding. The subjective test also supported these claims. Scores on the MSAQ test showed a decrease in nausea, disorientation, and discomfort among listeners who used the AMCS, and values from the UEQ test were significantly higher on effectiveness, comfort, and overall system use. The study supported claims that spatial audio cueing leads to a decrease in a major cause of motion sickness, which is conflict between stimuli. The system does not use visualization, as most AMS systems would, so it's very appropriate and useful as a system in autonomous vehicles, which would follow human-machine interaction guidelines.

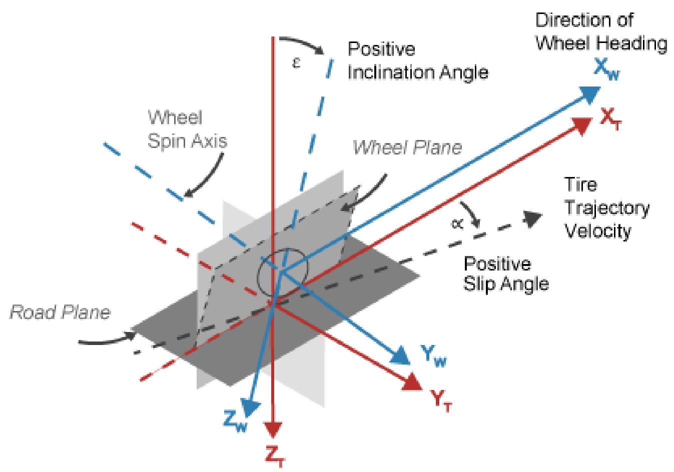

Figure 3: Simple Diagram of Vehicle Dynamics Motion in Different Axis.

3.1 Motion Sickness Dose Value. (MSDV).

The data for MSDV of X, Y, and Z accelerations collected during the experiment was analysed for comparing the result of with and without motion cues with the help of the software Diadem 2019, and three types of statistics: mean, standard deviation, and coefficient of variation were obtained for comparisons between the condition with and without audio motion cues. The mean MSDV gives an indication of the total average motion exposure that was experienced by all the participants throughout the entire driving activity. The fact that there was a similarity in the values of the mean MSDV between the two conditions implies that the actual physical motion of the vehicle was consistent, hence the differences in motion sickness not affecting the driving behaviour of the participants. The differences in the mean values of MSDV indicated by the experiment imply that the absence or presence of motion cues had an impact on the total accumulation of motion stress experienced by the passengers.

The standard deviation of MSDV is used to define the variability of motion exposure throughout the experiment. This is because higher values of the standard deviation are attributed to higher variability of the acceleration signals, an important factor responsible for the causation of discomfort due to unexpected motion exposure. The results for this study will be determined by the difference in the values for the baseline and motion cue conditions in terms of variation in the standard deviation to establish the degree to which audio cues influenced the ability to adapt to constant vehicle motions along the axes that are closely related to motion sickness, i.e., the longitudinal and lateral axes.

Using the Variation of Coefficient (VC), the variation in MSDV can be compared in relation to the mean. A smaller value for VC indicates more consistent exposure levels relative to overall exposure, while larger values provide an indication of higher inconsistencies in perceived motion. The comparison in VC values across the conditions proves the impact of audio motion cues in enhancing or deteriorating the relative variation in motion exposure experienced by the subjects. The mean, standard deviation, and coefficient of variation for MSDV provide all the information necessary for an evaluation on the impact of motion cues and the performance capabilities of the proposed system. Based on the data tabulation for both three axes of acceleration, the Motion Cues Data shows a slightly high value of mean, standard deviation and Variation of Coefficients comparing with no motion cues during the experiment shows that the AMCS are less effective mitigating motion sickness.

Table 1: X-acceleration result data.

Participant	Condition	Result	Values
Group A	Without AMC System	Mean	8.03
		Standard deviation	12.45
		Variation of Coefficient.	0.409
Group B	With AMC System	Mean	13.55
		Standard deviation	12.43
		Variation of Coefficient.	0.366

Table 2: Y-acceleration result data.

Participant	Condition	Result	Values
Group A	Without AMC System	Mean	4.78
		Standard deviation	5.33
		Variation of Coefficient.	0.665
Group B	With AMC System	Mean	4.63
		Standard deviation	5.10
		Variation of Coefficient.	0.610

Table 3: Z-acceleration result data.

Participant	Condition	Result	Values
Group A	Without AMC System	Mean	0.651
		Standard deviation	1.97
		Variation of Coefficient.	0.0765
Group B	With AMC System	Mean	0.667
		Standard deviation	1.85
		Variation of Coefficient.	0.0886

Progress in Engineering Application and Technology Vol. 7 No. 1 (2026) p. 448-456

3.2 Motion Sickness Assessment Questionnaire (MSAQ).

The collected data from the Motion Sickness Assessment Questionnaire (MSAQ) was subjected to the one-sample t-test to determine whether the scores obtained on the experiment were significantly different from the reference value set for the level of tolerability on the motion sickness scale. It was used to ascertain the effectiveness of the driving experiment on the level of discomfort caused to the subjects.

The outcome of the one-sample t-test showed that the mean score of the MSAQ was significantly different from the reference value with a significance level of $p < 0.05$. This indicated that the participants had a reasonable level of motion sickness during the experiment run. A lower mean score indicated a lower level of subjective motion sickness and increased comfort levels. However, a higher score indicated higher levels of discomfort when the condition was tested.

From an interpretative point of view, the result of the one-sample t-test shows that the difference in the values of the dependent variable is indeed affected by the experimental variable. This leads to the conclusion that the inferences drawn based on the subjective measurements by the MSAQ are valid. Further, the difference measured between the conditions of having or not having the effect of motion in the experiments does not occur by chance.

Table 4: One Sample T-Test.

Condition	Test	Statistic	df	p-Value
Pre-MSAQ	Student	6.681	191	<0.01
	Z-Value	12.124		<0.01
Post-MSAQ	Student	16.964	191	<0.01
	Z-Value	30.167		<0.01
Change-MSAQ	Student	18.713	191	<0.01
	Z-Value	42.291		<0.01

3.3 Users Experience Questionnaire (UEQ).

User Experience Questionnaire (UEQ) was employed to assess participants' system use experience for two different experimental conditions: the baseline condition and the audio-motion condition. This assessment was carried out using the UEQ Tools, which provided numerical data and graphs for comparison between the six UEQ scales: Perspicuity, Attractiveness, Efficiency, Dependability, Stimulation, and Novelty.

Based on the data provided in the UEQ results table, it can be seen that in pragmatic aspects, the baseline condition had comparable or higher values in the Perspicuity and Efficiency aspects, indicating that users felt the baseline condition was easier to understand and required less effort, probably owing to the lack of extra auditory information integrated with the system. Whereas, in the motion cueing aspect, Stimulation and Novelty aspects revealed a fair level of improvement, suggesting that with the addition of the audio cues in the system, stimulation and interest in the system were higher even though usability was not improved.

As evident from the UEQ graph, overlapping confidence intervals for both conditions prove that there is no significant statistical difference on most dimensions. There are a few points, however, where the motion cue condition has slightly lower ratings on Dependability. This means that users might have felt that the audio cues used in the experiment were less predictable or not well-coordinated with vehicle motion. There is a logical connection between user perceptions and experimental results.

Taken together, the results of the UEQ indicate that while the system introduces positive aspects of experience regarding stimulation and novelty, it has not reached the level of the baseline condition regarding pragmatic usability aspects. This result indicates that the system is acceptable but not optimal and that refinement about timing and personalization may ensure better user experience with the system.

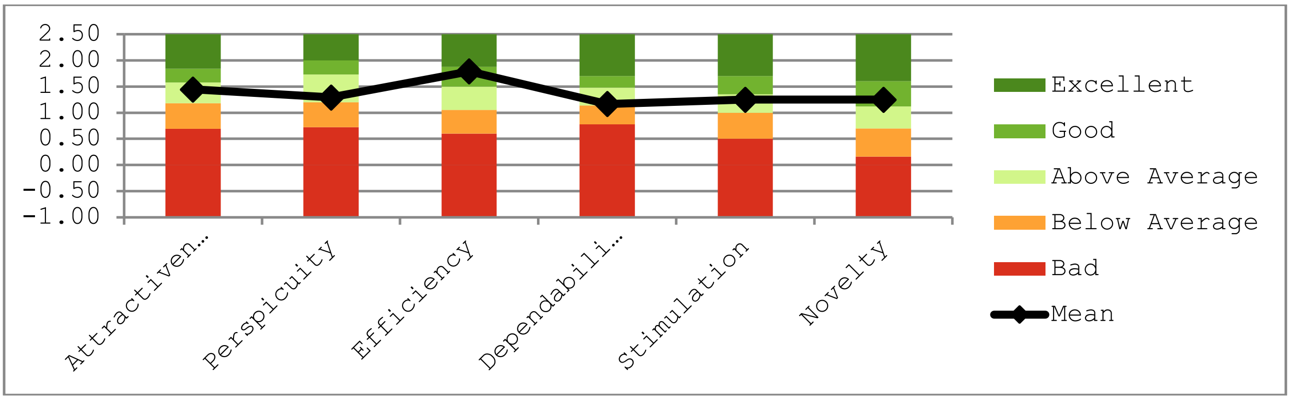

Figure 4: UEQ Distribution data For Baseline.

Table 5: UEQ Data for Baseline and Interpretation.

Scale	Mean	Comparison to Benchmark	Interpretation.
Attractiveness	1.44	Above average	25% of the result is better, 50% of result worse
Perspicuity	1.29	Above average	25% of the result is better, 50% of result worse
Efficiency	1.79	Good	In the range of 25% is worse
Dependability	1.17	Above average	25% of the result is better, 50% of result worse
Stimulation	1.25	Above average	25% of the result is better, 50% of result worse
Novelty	1.25	Good	In the range of 25% is worse

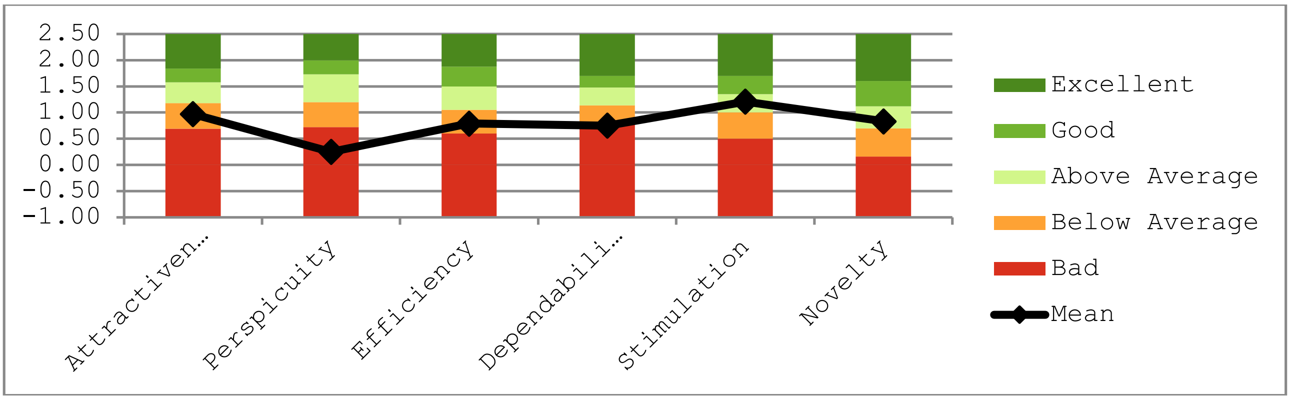

Figure 5 : UEQ Distribution data For AMCS and Interpretation.

Table 6: UEQ Data for Audio Motion Cueing and Interpretation.

Scale	Mean	Comparison to Benchmark	Interpretation.
Attractiveness	0.97	Below average	50% of the result is better, 25% of result worse
Perspicuity	0.25	Bad	In the range of 25% is worse
Efficiency	0.79	Below average	50% of the result is better, 25% of result worse
Dependability	0.75	Bad	In the range of 25% is worse
Stimulation	1.21	Above average	25% of the result is better, 50% of result worse
Novelty	0.83	Above average	25% of the result is better, 50% of result worse

4. Conclusion.

This research work aims to examine the practicality of the application of the Spatial Audio Motion Cueing System in the role of a motion sickness reduction system in the context of autonomous vehicles as a non-intrusive strategy. In the project, the main objectives were successfully met by designing, developing, and testing the proposed system in the research work through the implementation of on-road testing and the use of both subjective and objective evaluation methodologies.

However, the experimental results demonstrate that the system does not perform equally effectively in every scenario. Even though there was improvement in some metrics and axes, the system without motion cues performed equally well or even better in some cases. It can be inferred that the current system of audio motion cueing may not be effectively enhancing motion comfort in every situation, perhaps because of different reasons like cue timing, audio properties, user adaptation. However, despite these limitations, the results are important in emphasizing the level of complexity associated with counteracting motion sickness in autonomous vehicles and in showing how motion cueing via audio may not be adequate on its own as far as optimization is concerned. In addition, the results show not only that the aims of the project have been accomplished in terms of system design and verification but also show important areas of improvement in the next level of research, such as personalizing cue timing based on sensitivity level as well as various other research considerations as are discussed in the next section.

5. Online License Transfer

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Author Contribution

This journal requires that all authors take public responsibility for the content of the work submitted for review. The contributions of all authors must be described in the following manner:

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Luqmanul Hakim Bin Rosli, Abdul Fathul Hakim Bin Zulkifli;* ***data collection:*** *Muhammad Luqmanul Hakim Bin Rosli;* ***analysis and interpretation of results:*** *Muhammad Luqmanul Hakim Bin Rosli, Abdul Fathul Hakim Bin Zulkifli;* ***draft manuscript preparation:*** *Muhammad Luqmanul Hakim Bin Rosli. All authors reviewed the results and approved the final version of the manuscript.*

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