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Assessing the Effectiveness of iOS Motion Cueing Technologies in Autonomous Vehicles

Kathir Velan Rethnam[1], Abd Fathul Hakim Zulkifli[1]*

[1] *Department of Mechanical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA*

*Corresponding Author: fathul@uthm.edu.my
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Abstract

This study investigated the effectiveness of iOS Motion Cueing technology in reducing motion sickness and improving passenger comfort in autonomous vehicles (AV). Motion sickness is a common problem in autonomous driving, especially when passengers engage in non-driving activities such as reading or using mobile devices. In these situations, conflicts between visual input and vestibular sensations often cause discomfort, nausea, and reduced travel enjoyment, which can limit user acceptance of autonomous vehicle systems. Therefore, the main objective of this research is to evaluate whether the iOS Vehicle Motion Cues feature introduced in iOS 18 can reduce motion sickness symptoms and enhance the overall Malaysian's passenger experience. To achieve this objective, experimental testing was carried out using an instrumented vehicle driven along a real-road route within Universiti Tun Hussein Onn Malaysia. Participants were exposed to two experimental conditions, namely a baseline condition without motion cueing and a condition with iOS Motion Cueing enabled. Motion sickness responses were measured using Motion Sickness Dose Values (MSDV), the Motion Sickness Assessment Questionnaire (MSAQ), and User Experience Questionnaire (UEQ) assessments, followed by statistical analysis to compare both conditions. The results show a clear reduction in motion sickness levels and noticeable improvements in comfort, stimulation, and dependability when motion cueing was applied, as evidenced by the decrease in mean MSAQ score from 3.500 in the baseline condition to 1.500. It is recommended that iOS Motion Cueing be further adopted and optimized as a simple and accessible solution to improve passenger comfort and acceptance in future AV applications.

1. Introduction

Autonomous vehicle technology is advancing rapidly and is expected to reshape future transportation by improving safety, efficiency, and accessibility [1-2]. As vehicles progress toward higher levels of automation, passengers are no longer required to focus on driving tasks and can instead engage in non-driving activities such as reading, using mobile devices, or enjoying entertainment [3]. While this shift increases comfort and productivity, it also brings new challenges related to passenger well-being, particularly motion sickness. Motion sickness arises from a mismatch between what passengers see and what their bodies sense through the vestibular system, and it has become one of the main factors affecting user acceptance of autonomous vehicles [4-5]. This problem is especially noticeable in real-world driving conditions, where frequent acceleration, braking, and turning can significantly increase discomfort [6-7].

Most existing approaches to reducing motion sickness depend on costly hardware systems, complex vehicle motion control strategies, or simulator-based studies, which limit their practicality and widespread adoption [8]. With the introduction of the iOS Vehicle Motion Cues feature in iOS 18, a more affordable and easily accessible solution using everyday mobile devices has emerged [9]. However, the real-world effectiveness of this technology has not yet been adequately validated, particularly in the Malaysian driving environment, where road surface variations and traffic conditions may further contribute to motion sickness. This lack of real-road empirical evidence highlights a clear research gap in determining whether consumer-level motion cueing technologies can genuinely reduce motion sickness and improve passenger comfort in autonomous vehicles [10]. If this gap remains unaddressed, discomfort-related concerns may continue to affect public confidence and slow the adoption of autonomous transportation systems. Therefore, this study aims to examine the effectiveness of iOS Motion Cueing in reducing motion sickness and enhancing Malaysian's user experience during autonomous vehicle travel through real-road experiments and quantitative evaluation methods.

2. Methodology

This section outlines the experimental setup and procedures used to evaluate the effectiveness of iOS Motion Cueing under real-road conditions. An instrumented vehicle was used to collect objective motion data, while participants completed subjective assessments under baseline and motion cueing conditions for comparative analysis.

2.1 Instrumented Vehicle

The Mazda CX-8, a mid-size crossover SUV, was used as the testing vehicle, equipped with instruments to simulate an autonomous driving experience, as shown in Figure 1. The vehicle was driven at a controlled speed of 30 to 35 km/h to ensure consistency, allowing participants to experience rides with and without the iOS Vehicle Motion Cues. This setup enabled the study to evaluate the effects of motion cueing on passenger comfort and motion sickness during simulated autonomous driving conditions.

The instrumented vehicle was organised into four main sections, as shown in Figure 1. The rear housed the power management and DAQ system with a secondary battery and power converter, while the NI cRIO 9030 in the centre processed sensor signals. Participants completed tasks on an iPad in the front passenger seat, and an accelerometer measured vehicle motion. A laptop at the front running LabVIEW enabled real-time monitoring and data logging. This setup allowed controlled and consistent passive riding experiments to assess the effects of iOS motion cues on passenger comfort.

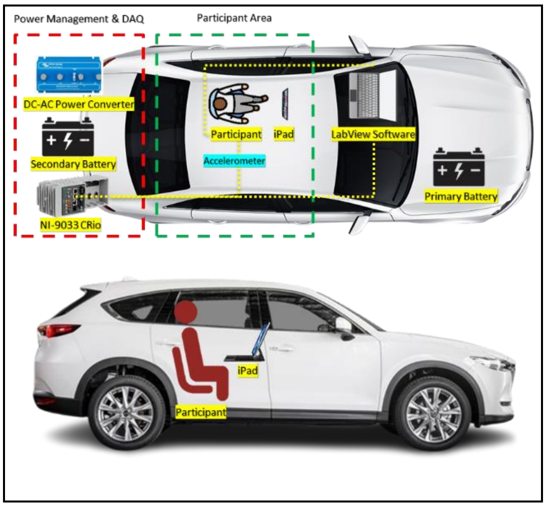

Fig. 1 *The arrangement of the instrumented vehicle*

2.2 Test Route

The study was conducted under real-road conditions on the Universiti Tun Hussein Onn Malaysia campus road, where Malaysian traffic regulations were applied. During the experiment, participants experienced a realistic driving environment, as the route was shared with other road users, including cars, motorcycles, bicycles, buses, and pedestrians. The designated test route had a total length of approximately 4.00 km and included 17 turns, with turning radius ranging from 10.95 m to 49.97 m, as well as one roundabout with an approximate circumference of 264 m, as shown in Figure 2.

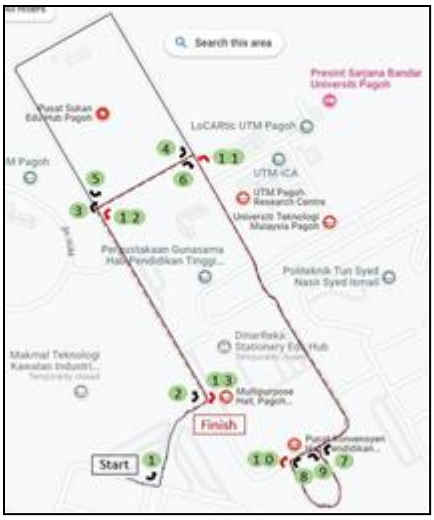

Fig. 2 *The designated route for the road-testing session*

2.3 Procedure

The experiment involved three stages, pre-driven, driven, and post-driven, with durations of approximately 5, 10, and 5 minutes, as shown in Figure 3. Stage 1 was conducted while the vehicle was stationary, Stage 2 during driving, and Stage 3 after stopping. The Interactive Wizard guided participants throughout, providing instructions for each stage. Participants first signed the informed consent form and completed the pre-MSAQ, then entered the instrumented vehicle, fastened seatbelts, and adjusted seats for comfort, with the option to stop at any time.

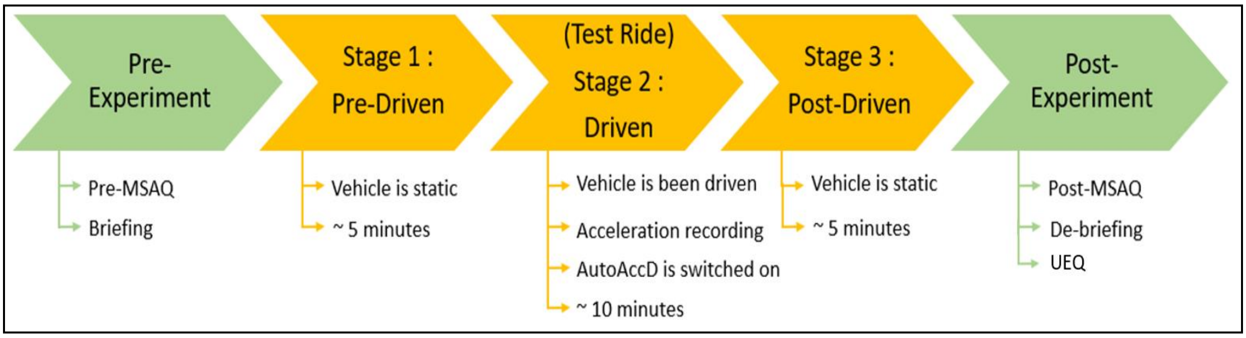

Fig. 3 *Stages of the experiment*

During Stage 1, the vehicle remained in a parking area. In Stage 2, the vehicle followed the designated route under the Driving Wizard's guidance, with participants experiencing normal driving conditions, including acceleration, deceleration, braking, and cornering, while acceleration data were recorded. Stage 3 involved post-driven measurements while stationary. After the session, participants completed the post-MSAQ and a user experience questionnaire to prevent washout effects, followed by a debriefing and RM20 compensation.

3. Results and Discussions

This section presents the analysis of objective vehicle motion data and subjective participant responses to determine the effectiveness of iOS Motion Cueing. The findings are discussed based on Motion Sickness Dose Value (MSDV), Motion Sickness Assessment Questionnaire (MSAQ), and User Experience Questionnaire (UEQ) results, followed by statistical evaluation to compare the baseline and motion cueing conditions.

3.1 Motion Sickness Dose Value (MSDV)

The Motion Sickness Dose Value (MSDV) results derived from the experimental vehicle motion data are summarized in Table 1, while the corresponding MSDV distributions for each motion axis are presented in Figures 5, 6, and 7. The MSDV was computed using frequency-weighted acceleration in accordance with ISO 2631-1, providing an objective measure of the potential motion sickness experienced by participants.

Table 1: The mean, standard deviation (SD), and coefficient of variation (CoV) of MSDV were analysed for 12 test rides across the three axes captured by the instrumented vehicle's accelerometer

Axis	Mean ($ms^{-1.5}$)	Standard Deviation	Coefficient of Variance (%)
MSDVx	9.98	11.52	1.15
MSDVy	3.73	4.30	1.15
MSDVz	0.590	2.86	4.85

Based on Table 1, the longitudinal direction (MSDVx) showed the highest mean value of 9.98 m $s^{-1.5}$ with a coefficient of variance of approximately 115 percent, indicating considerable variability in longitudinal motion. The MSDVx signal exhibits noticeable fluctuations which are associated with intermittent acceleration and deceleration, as shown in Figure 5. These variations suggest that certain periods during the test contributed more strongly to the development of motion sickness.

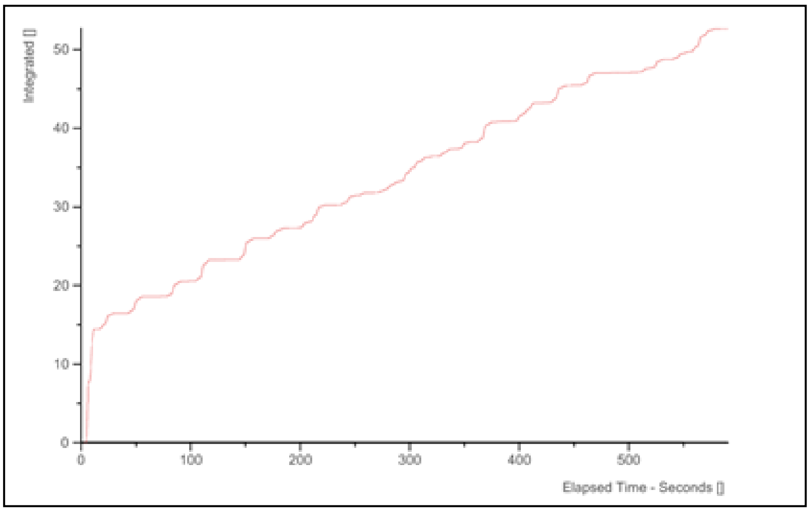

Fig. 4 *Longitudinal Motion (MSDV) Measured Along the X-Axis During 12 Test Rides*

The lateral motion results show a mean MSDVy of 3.73 m $s^{-1.5}$ with a coefficient of variation of approximately 115 percent, as shown in Table 1. The lower mean compared to MSDVx indicates lateral motion contributed less to overall motion sickness, but high variability suggests irregular accelerations. These peaks are likely caused by steering or lane change events, as illustrated in Figure 6. Although smaller than longitudinal motion, such intermittent lateral events can still cause discomfort, particularly for passengers engaged in non-driving activities.

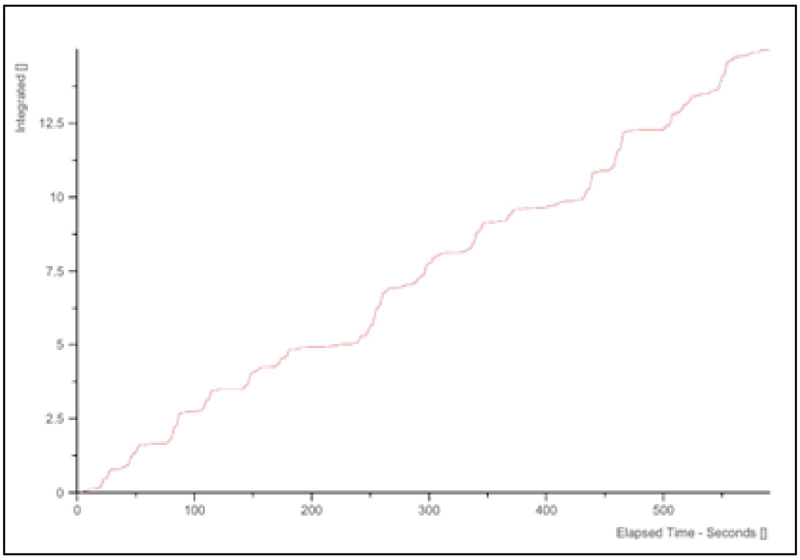

Fig. 5 *Lateral Motion (MSDV) Measured Along the Y-Axis During 12 Test Rides*

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The vertical direction showed a mean MSDVz of 0.59 m $s^{-1.5}$ with a standard deviation of 2.86 m $s^{-1.5}$. This resulted in a notably high coefficient of variance of approximately 485 percent, as shown in Table 1. The exceptionally high variability is largely due to the low mean value, which amplifies the relative variation. The vertical MSDV signal shows a low average magnitude with occasional sharp peaks caused by road surface irregularities such as bumps or uneven pavement, as shown in Figure 7.

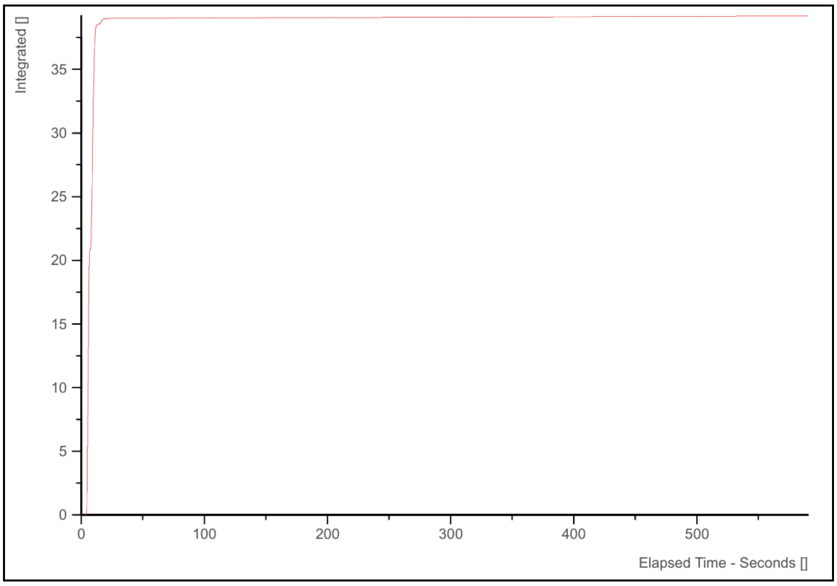

Fig. 6 *Vertical Motion (MSDV) Measured Along the Z-Axis During 12 Test Rides.*

3.2 Motion Sickness Assessment Questionnaire (MSAQ)

This section provides a detailed discussion of the subjective motion sickness responses measured using the Motion Sickness Assessment Questionnaire (MSAQ). The experiment was conducted with 12 participants, 6 assigned to the baseline condition and 6 assigned to the iOS vehicle motion cueing condition. The effectiveness of iOS vehicle motion cueing was evaluated through descriptive analysis, between-group comparisons, and within-group statistical testing using JASP software.

3.2.1 Descriptive Statistics with the Shapiro–Wilk Test

The Descriptive statistics provide an initial indication of the effectiveness of iOS vehicle motion cueing in reducing subjective motion sickness compared to the baseline condition, as shown in Table 2. Under the baseline condition, the mean MSAQ score increased from 2.833 (SD = 2.229) pre-exposure to 3.500 (SD = 2.739) post-exposure, while the median rose from 2.000 to 3.000. This upward shift indicates that motion exposure without motion cue assistance consistently worsened participant comfort. The maximum post-exposure score reached 8.000, showing that some participants experienced relatively severe motion sickness symptoms.

Table 2: Descriptive Statistics with the Shapiro–Wilk Test

Descriptive Statistics				
	BASELINE		IOS VEHICLE MOTION CUES	
	PRE_MSAQ	POST_MSAQ	PRE_MSAQ	POST_MSAQ
Valid	6	6	6	6
Median	2.000	3.000	1.000	1.000
Mean	2.833	3.500	1.833	1.500
Std. Error of Mean	0.910	1.118	0.654	0.342
Std. Deviation	2.229	2.739	1.602	0.837
Coefficient of variation	0.787	0.782	0.874	0.558
Shapiro-Wilk	0.821	0.897	0.634	0.701
P-value of Shapiro-Wilk	.089	.357	.001	.006
Minimum	1.000	1.000	1.000	1.000
Maximum	6.000	8.000	5.000	3.000

In contrast, the iOS vehicle motion cue condition exhibited a markedly different pattern. The mean MSAQ score decreased from 1.833 (SD = 1.602) pre-exposure to 1.500 (SD = 0.837) post-exposure, while the median remained constant at 1.000. This stability in the median and together with the reduction in mean value. This indicates that iOS motion cueing prevented the escalation of motion sickness symptoms and reduced them. The maximum post-exposure MSAQ score under the iOS condition was 3.000, which is substantially lower than the baseline maximum of 8.000 and demonstrates that motion cueing effectively limited severe symptoms. Overall, the descriptive statistics suggest that iOS vehicle motion cueing effectively reduces and stabilizes motion sickness compared to the baseline condition.

3.2.2 Paired Samples T-Test

A paired samples t-test was conducted to evaluate the overall effect of motion exposure on MSAQ scores by comparing pre- and post-exposure measurements, as shown in Table 3. The analysis showed a statistically significant difference with $t = 4.547$, $df = 191$, $p < 0.001$. This indicates that motion exposure significantly increases motion sickness symptoms.

Table 3: Paired Samples T-Test

Paired Samples T-Test					
Measure 1		Measure 2	t	df	p
POST_MSAQ	-	PRE_MSAQ	4.547	191	< .001

Note. Student's t-test.

This result confirms that vehicle motion alone contributes to motion sickness, particularly in the absence of any mitigating intervention. Integration of descriptive and independent samples analyses reveals that motion exposure heightens symptoms under the baseline condition, whereas iOS vehicle motion cueing effectively moderates this effect. Overall, the paired samples t-test confirms that motion exposure is a key factor in motion sickness, while the descriptive findings illustrate that the increase is mostly observed under baseline conditions. Participants under the iOS vehicle motion cueing condition exhibited stable or mildly reduced MSAQ scores during identical driving exposures.

3.3 User Experience Questionnaire (UEQ)

The User Experience Questionnaire (UEQ) was utilized in this study to assess participants' subjective perceptions of the iOS vehicle motion cueing system. It evaluates key dimensions of user experience, including attractiveness, clarity, efficiency, reliability, stimulation, and novelty. Through the UEQ, this study examined how the motion cueing feature influenced participants' comfort, satisfaction, and perceived usability during the autonomous vehicle test rides. This assessment compares the baseline and iOS vehicle motion cue conditions and shows the effectiveness and acceptance of the iOS vehicle motion cue.

3.3.1 Evaluation of Baseline Condition

The Baseline condition showed generally positive but moderate UEQ results across all six dimensions, as presented in Figure 8. Attractiveness had a mean of 1.44, suggesting that participants generally viewed the system in a positive light, while Perspicuity scored 1.29, indicating that it was reasonably easy to understand. Efficiency scored 1.79, showing that participants could complete tasks effectively even without motion cueing support. Dependability had a mean of 1.17, Stimulation 1.29, and Novelty 1.25, reflecting moderate confidence in the system, varied levels of engagement, and a somewhat innovative experience. Overall, the combination of moderate dependability, inconsistent stimulation, and limited predictability contributed to sensory conflict and made it harder for users to anticipate vehicle motion under the Baseline condition.

Scale	Mean	Standard Deviation
Attractiveness	1.44	0.94
Perspicuity	1.29	0.71
Efficiency	1.79	0.68
Dependability	1.17	0.58
Stimulation	1.29	1.07
Novelty	1.25	0.69

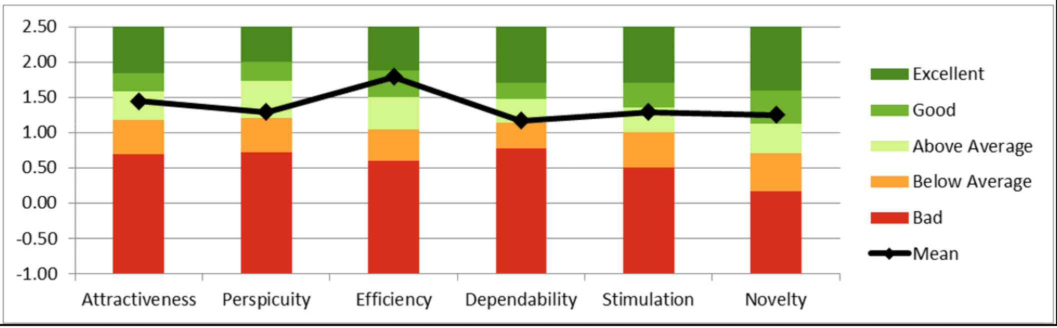

Fig. 7 *The UEQ results for the baseline condition*

3.3.2 Evaluation of iOS Motion Cue Condition

The implementation of the iOS Vehicle Motion Cue resulted in a clear improvement in participants' overall user experience, as shown in Figure 9. Attractiveness reached a mean of 1.97, indicating stronger positive emotional responses and greater comfort. Perspicuity scored a mean of 2.00, showing that the system was very clear and easy to understand, with little variation among users. Efficiency remained high at 1.88, suggesting that using the system did not require extra effort. Dependability also improved to 1.88, reflecting increased predictability and trust in the system. Stimulation recorded the highest mean of 2.21, demonstrating that the system effectively engaged users in a consistent way, while Novelty increased to 1.63, providing a sense of innovation that was still easy to adapt to. Overall, the iOS Vehicle Motion Cue contributed to better alignment of visual and vestibular cues, reducing sensory mismatch and supporting the reduction of motion sickness.

Scale	Mean	Standard Deviation
Attractiveness	1.97	0.61
Perspicuity	2.00	0.32
Efficiency	1.88	0.61
Dependability	1.88	0.59
Stimulation	2.21	0.37
Novelty	1.63	0.34

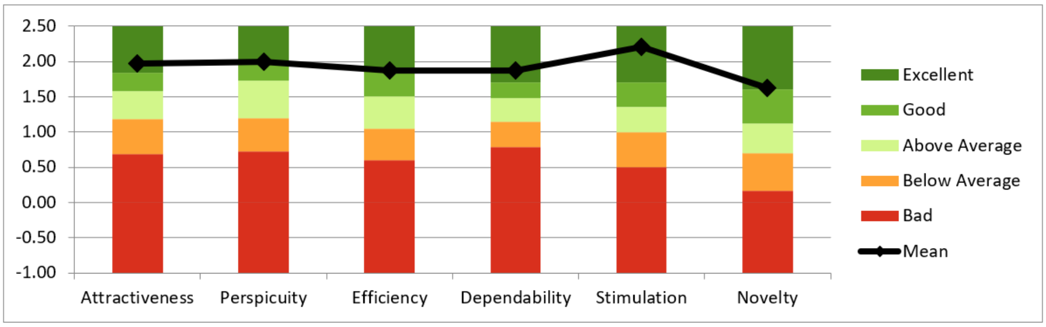

Fig. 8 *The UEQ Results for the iOS vehicle motion cue condition*

3.3.3 Evaluation of Comparison between Conditions

The comparison indicates that the iOS Vehicle Motion Cue outperformed the Baseline across all UEQ dimensions, as shown in Figure 10. Attractiveness improved from 1.44 to 1.97, Perspicuity from 1.29 to 2.00, and Dependability from 1.17 to 1.88, highlighting enhanced comfort, clarity, and predictability. The most significant improvement was in Stimulation, which increased from 1.29 to 2.21 with reduced variability, reflecting more consistent user engagement. Overall, the higher scores and greater consistency demonstrate a more stable and reliable user experience, confirming that motion cueing effectively reduces sensory conflict and enhances passenger comfort in autonomous vehicles.

Scale	BASELINE						IOS VEHICLE MOTION CUE					
	Mean	STD	N	Confidence	Confidence Interval		Mean	STD	N	Confidence	Confidence Interval	
Attractiveness	1.44	0.94	6	0.75	0.69	2.20	1.97	0.61	6	0.49	1.48	2.46
Perspicuity	1.29	0.71	6	0.57	0.72	1.86	2.00	0.32	6	0.25	1.75	2.25
Efficiency	1.79	0.68	6	0.54	1.25	2.33	1.88	0.61	6	0.49	1.39	2.36
Dependability	1.17	0.58	6	0.47	0.70	1.63	1.88	0.59	6	0.47	1.41	2.34
Stimulation	1.29	1.07	6	0.85	0.44	2.14	2.21	0.37	6	0.29	1.91	2.50
Novelty	1.25	0.69	6	0.55	0.70	1.80	1.63	0.34	6	0.28	1.35	1.90

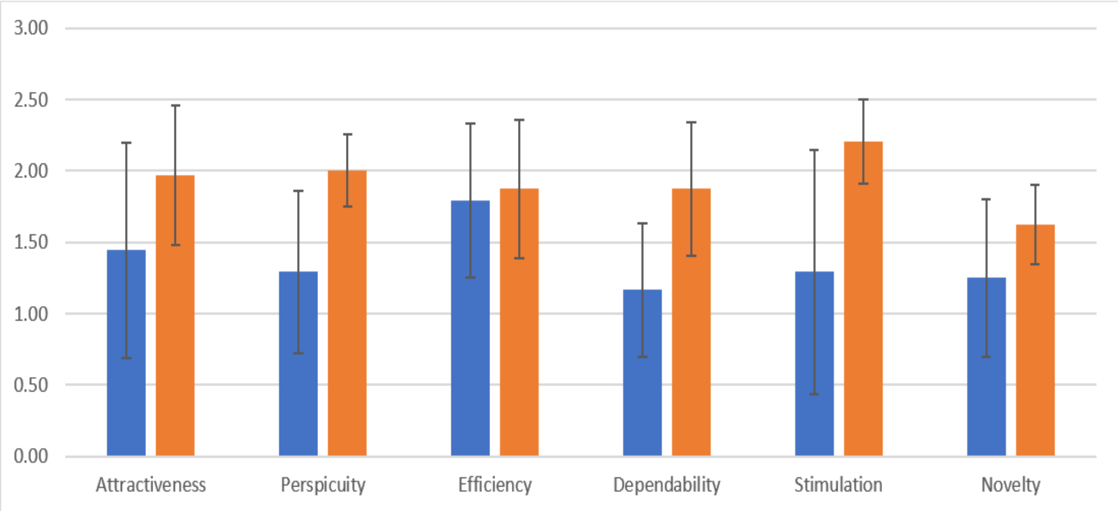

Fig. 9 *The comparison of the baseline and iOS vehicle motion cue*

4. Conclusion

This study examined the effectiveness of iOS Motion Cueing in reducing motion sickness and improving passenger comfort during autonomous vehicle travel in real-road conditions. The results demonstrated that iOS Motion Cueing effectively reduced motion sickness severity, as evidenced by the decrease in mean MSAQ score from 3.500 in the baseline condition to 1.500, confirming its capability to prevent severe symptoms in autonomous vehicle passengers. Participants also reported a more positive overall experience, particularly in terms of comfort and reliability. These findings suggest that a simple, consumer-level solution like iOS Motion Cueing can play a meaningful role in addressing motion sickness in autonomous vehicles, offering a practical and affordable approach that supports greater user acceptance and comfort.

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