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Wearable Haptic Feedback System for Mitigating Motion Sickness in Autonomous Vehicle Users

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Abstract

This paper discusses how an autonomous vehicle environment simulated using a wrist-wearable haptic feedback system enhances the individual's perception of motion and reduces the likelihood of motion sickness. One of the greatest problems with automated driving is motion sickness, as occupants experience a conflict between their senses due to the limited visual and control indicators. The existing countermeasures tend to be pharmacological or visually based, and these countermeasures cannot always be applicable. This paper, therefore, analyzes another intervention, which is a peripheral vibrotactile intervention. The primary goal of this paper is to evaluate the effect of haptic feedback on the sensation of motion sickness and the experience in general. A baseline and haptic group of twelve subjects participated in an instrumented vehicle on-road test, which was a controlled evaluation conducted on the road. Motion sickness was quantified using the Motion Sickness Assessment Questionnaire (MSAQ) as opposed to objective motion exposure, which was read using the Motion Sickness Dosage Value (MSDV). The User Experience Questionnaire (UEQ) was used to assess the user's perception and acceptance. The statistical tests used in the comparison of conditions included the Welch t-test and the Mann-Whitney U test. The results of these indicate that the stimulus of motion is similar in all tests, and lateral motion is a major contributor to motion exposure. The condition based on the haptic was slightly inclined to generate the low scores on motion sickness, but the statistics did not prove to be significant. However, the UEQ scores indicate that the haptic system is positively accepted and perceived to be usable. The outcomes of this research suggest that the principle of wrist-based haptic feedback may be beneficial as an auxiliary support for motion perception. However, further studies employing a larger sample and more sophisticated feedback designs may enhance its performance.

1. Introduction

Autonomous vehicles (AVs) are expected to change the way people travel in the future, as they are anticipated to enhance the comfort and productivity of the journey. Nevertheless, motion sickness among passengers turned out to be a significant issue, in addition to the development of AV technology [1]. Autonomous vehicle sickness (also called motion sickness) was a condition that had symptoms of nausea, dizziness, and discomfort [2]. Past research has also suggested that motion sickness is more likely to occur among passengers than among drivers, especially when passengers are engaged in activities that do not involve driving, such as reading a book or using a cell phone [3]. This was a weakness, as the passengers lacked personal control over the car and had limited visual coverage of the car's impending movements [4].

The sensory conflict theory was the common explanation of motion sickness [5]. This theory posits that motion sickness arises from a discrepancy between sensory inputs, particularly between visual signals and those from the vestibular system, which is responsible for balance and motion perception. In traditional cars, drivers intuitively expected car movement based on visual feedback and input controls, which served to coordinate the visual inputs they received [3]. Conversely, passengers in autonomous vehicles tended to experience a disrupted sensory alignment, particularly when their visual attention was not on the road, resulting in augmented sensory conflict and an increased risk of motion sickness [6]

Several interventions in vehicles to alleviate motion sickness have been explored, including visual, auditory, and environmental approaches. One of these strategies was the use of anticipatory cues, which have been proven effective in alleviating sensory conflict by alerting passengers to the vehicle's impending maneuvers [7]. The cues that warned passengers ahead of time of the impending changes in motion were anticipated cues. Although visual and auditory feedback were typically examined, haptic feedback, which is a form of communication conveyed through the sense of touch, received little attention [8]. The benefit of haptic feedback is the delivery of non-visual information, which is particularly suitable for passengers engaged in tasks or activities that require significant visual attention, or in cases where visibility is restricted [7].

Although the topic of haptic applications has gained popularity, a gap in systematic research persists in wearable haptic feedback systems that continuously relay information about motor vehicle motion [9]. Most available research has focused on discrete alerts or on reducing vibration rather than on continuous motion perception [10]. Thus, this research paper explored a wrist-worn haptic device that provides vibrotactile feedback based on vehicle movement. The goals of the system were to provide better passenger motion awareness and less motion sickness through non-visual anticipatory feedback in real-road driving situations [11].

2. Methodology

In this study, a quantitative experimental design has been employed to assess the effectiveness of wrist-based haptic feedback in mitigating motion sickness in the context of autonomous vehicles. The instrumented vehicle system, haptic system design, experimental protocol, and statistical analysis processes were discussed in the following sections.

2.1 Experimental Setup and Instrumentation

The test vehicle was an instrumented Mazda CX-8 Diesel as shown in Figure 1. Data on vehicle dynamics was recorded using a National Instruments compactRIO-9030 (cRIO) system, equipped with an NI-9205 analog input module. Three-axis capacitive accelerometers (ADXL335) were attached to measure longitudinal, lateral, and vertical accelerations. These accelerations were the physical stimuli related to motion sickness [12]. Electrical isolation was performed to minimize signal interference. To ensure signal safety, physiological responses were monitored using AD8232 electrocardiogram (ECG) sensors with optocouplers on the electrodes.

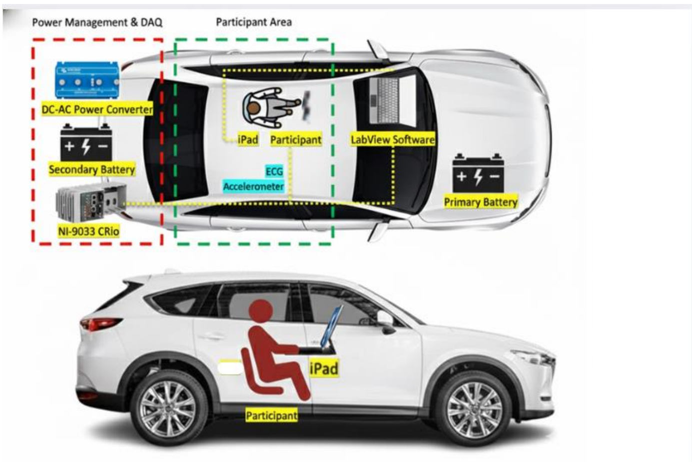

Figure 1: The Instrumented Vehicle

The car interior was set to replicate the autopilot car occupant setting. The participants were in the rear-left seat facing forward. A Wizard-of-Oz strategy was employed [13], in which a human driver was tasked with following a pre-prescribed defensive driving profile to simulate autonomous driving behavior. Lateral acceleration was maintained at 0.3-0.5 m/s^2 and measured in real time via the AUTOACCD interface to ensure consistency across trials.

2.2 Wearable Haptic System Design and Experimental Protocol

The intervention was developed based on the proof-of-concept (POC) wrist-worn haptic feedback device [14]. The machine used Eccentric Rotating Mass (ERS) motors, which produce vibration by having an off-center rotating mass. The vibration frequency was adjusted to 150-200 Hz, which corresponds to the highest sensitivity frequency of Pacinian corpuscles, mechanoreceptors that detect high-frequency vibrations in human skin. The haptics device was activated using a Simple-Release Toggle (SRT) switch and wired with AWG22, as illustrated in Figure 2.

The experiment involved three sessions, which included pre-driving (5 minutes), driving (10 minutes), and post-driving (5 minutes). During the driving stage, the haptic group received vibrotactile feedback on the wrist. Vibration was either 1-2 seconds long and related to either lateral, longitudinal, or vertical vehicle movements [15]. The participants were also engaged in a non-driving-related task (NDRT) at the same time, which involved reading text on a tablet. This was done to minimize visual cues of car movement and to avoid sensory conflict, which is a causative factor of motion sickness.

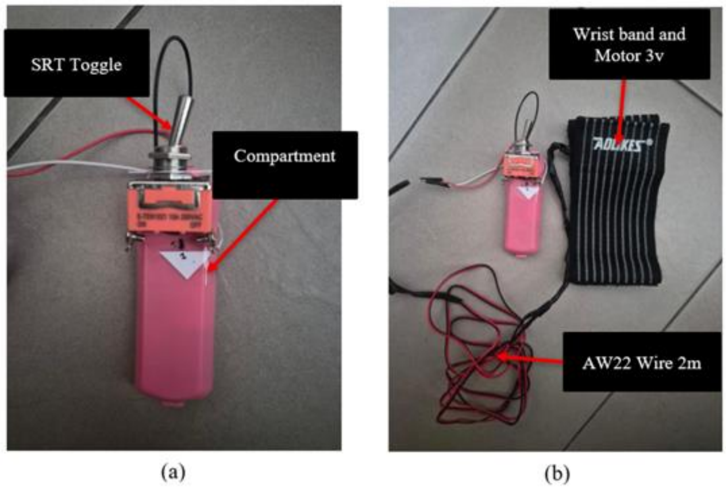

Figure 2 SRT Toggle (b) Wrist Haptic Proof of Concept (POC)

2.3 Subjective and Objective Measurement Instruments

The Motion Sickness Susceptibility Questionnaire (MSSQ) was administered prior to experimental trials to assess each participant's predisposition to motion sickness. The MSSQ is a standardized self-report scale that measures a person's historical predisposition to experience motion sickness in various transport and motion-related events. This questionnaire was administered to ensure that the participants were not overly susceptible, thereby preventing it from interfering with the experiment's results. The MSSQ scores were used as a screening and descriptive measure rather than an outcome variable to provide contextual information about participants' variability prior to exposure to the driving task [16].

Post-processing of vehicle acceleration data was performed on a laptop after it was recorded in real-time. NI DIAdem 2019 was used to filter the raw signals using a 5th-order Savitzky-Golay filter, which removed high-frequency noise while preserving the waveform attributes. Exposure to motion sickness was measured by the Motion Sickness Dose Value (MSDV) [17], which is an aggregate of frequency-weighted acceleration with time as illustrated in Figure 3.

A total of 12 subjects were selected and divided into two groups: a haptic group ($n = 6$) and a control group ($n = 6$). Statistical tests were performed using JASP (version 0.19.1). The normality of the data was tested using the Shapiro-Wilk test. Since the variances were unequal (Levene test, $p = 0.021$), parametric comparisons of Motion Sickness Assessment Questionnaire (MSAQ) change scores were made using the Welch t-test, and the Mann-Whitney U test was used to perform non-parametric tests. The level of significance was determined to be $p < 0.05$, and Cohen's d effect size was computed to measure the effect. The User Experience Questionnaire

(UEQ) was used to evaluate user experience [20]. The analysis of the responses was performed using the UEQ Data Analysis Tool, which transforms the Likert-scale ratings into six dimensions: attractiveness, perspicuity (ease of understanding), efficiency, dependability, stimulation, and novelty.

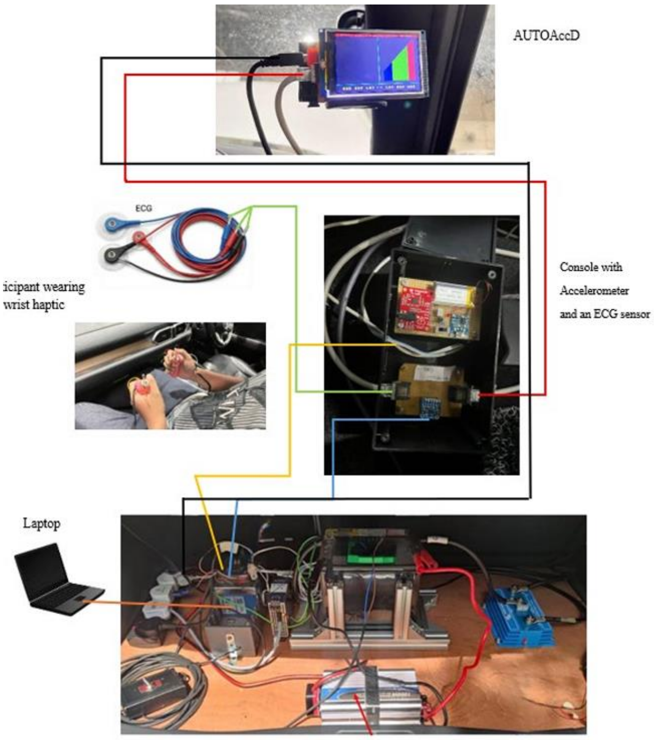

Figure 3: The connection of the AUTOAccD, console, accelerometers, electrocardiogram, data acquisition system, and portable laptop

3. Results and Discussion

The discussion and presentation of the results were done in three components in this section. The initial section assessed subjective motion sickness using the MSAQ. The latter section examined objective motion exposure with MSDV. The third one tested the user acceptance and experience using UEQ. The discussion of these results was done to elaborate on the effectiveness and viability of the wrist-based haptic feedback system.

3.1 Motion Sickness Assessment Questionnaire (MSAQ)

The Motion Sickness Assessment Questionnaire (MSAQ) was used to assess the subjective response to motion sickness. By comparing pre- and post-exposure scores, a change score (ΔMSAQ) was computed to evaluate the effect of the driving task on the intensity of motion sickness symptoms. The positive values indicate that pre-exposure scores were larger than the post-exposure scores. Descriptive analysis revealed that symptoms of motion sickness were observed under both experimental conditions. The Haptic group had a better mean score of change (M = 1.167, SD = 0.753) than the Baseline group (M = 0.667, SD = 2.503), as shown in Table 1. The Baseline group, however, was much more varied, with a variance of 6.267 as opposed to 0.567 in the Haptic group. The difference in dispersion was statistically significant using Levene's test for equality of variances, which indicated that the homogeneity assumption was not met ($F(1, 10) = 7.528$, $p = .021$). The reduced variability in the Haptic group indicates that participants' subjective responses were more consistent with vibrotactile feedback.

Table 1: Descriptive Statistics of motion sickness scores for baseline and haptic feedback conditions

Condition	N	Mean	Std. Deviation	Std. Error	Minimum	Maximum	Variance
Baseline	6	0.667	2.503	1.022	-2.000	5.000	6.267
Haptic	6	1.167	0.753	0.307	0.000	2.000	0.567

Unequal variances between the groups necessitated the use of a Welch t-test to compare ΔMSAQ scores. The statistical analysis revealed no significant difference between the Baseline and Haptic conditions, t(5.897) = -

0.469, p = .656. To confirm the strength of this finding, a non-parametric Mann-Whitney U test was also conducted. In line with the parametric test, the results showed no significant difference between the groups (U = 15.0, p = .682) as illustrated in Table 2. The analysis with the effect size also supported the finding that the difference was minor (Cohen's d = -0.271; rank-biserial correlation r = 0.167), indicating that the practical impact of the haptic intervention on the general MSAQ scores is minimal.

Table 2: Welch's T-test

Test	Statistic	df	p-value	Effect Size
T-test	t = −0.469	10.000	0.649	d = −0.271
Welch's t-test	t = −0.469	5.897	0.656	d = −0.271
Mann–Whitney U test	U = 15.0	–	0.682	r = 0.167

Table 3 Normality test results for MSAQ change scores

			W	p
MSAQ_Post	-	MSAQ_Pre	0.955	< .001

Table 4 Paired T-Test

Test	Statistic	z	df	p	VS-MPR	Location Parameter	SE Difference	Effect Size	SE Effect Size
Student	8794		191	<.001	$1.261 x 10^{+13}$	1.234	0.14	0.635	0.09
Wilcoxon	8706.00	7.391		<.001	$1.469 x 10^{+11}$	1.5		0.715	0.096

Table 3 shows that, because the data did not meet the normality assumption (p < .001), nonparametric tests were also conducted to strengthen the results. As shown in Table 4, a paired-samples analysis was performed to confirm that the driving task induced motion sickness. Between-group comparisons were used to evaluate the effectiveness of the haptic intervention, but the results did not reach statistical significance.

3.2 Interpretation of MSAQ Findings

The subjective motion sickness responses were interpreted as follows. The results indicate that wrist-based vibrotactile feedback did not significantly alter participants' overall perception of motion sickness, as no statistically significant reduction in MSAQ scores was observed. Despite the trend being descriptive, the parametric and nonparametric tests all led to the same conclusion: the null hypothesis would not be rejected. This result suggests that, with its existing implementation, the haptic system did not provide stimulus-response levels or response times that significantly counteracted the sensory discordance experienced during vehicle motion.

A small sample size (N = 12) is a significant limitation for detecting statistically significant effects. The level of motion sickness vulnerability is highly person-specific, and in this case, only 6 people per category were involved, resulting in insufficient statistical power to detect small to moderate effects. Additionally, the significant difference in the Baseline group (SD = 2.503) suggests that participants had varied responses to the 17 turning maneuvers. This fluctuation may have obscured possible mitigation action output from the haptic feedback, especially when compared to the steadier distribution of reactions observed in the Haptic group. The absence of a matching significant decrease in MSAQ scores indicates a decoupling of objective exposure to motion and the mitigation of the symptoms. Although the haptic stimuli probably presented anticipatory sensation to the user, it is possible that the vibration on the wrist was not salient enough to overcome the intensive vestibular-visual conflict that occurs during prolonged cornering in actual driving situations.

Although the MSAQ scores showed no significant decrease, the haptic device was feasible as a demonstration of a proof-of-concept intervention. The lower variability and similar response patterns in the Haptic group suggest that vibrotactile feedback can be used to stabilize subjective perceptions of motion, even when the magnitude of the symptoms does not decrease significantly. These results, along with the positive user experience achieved during the UEQ analysis, suggest that wearable haptic feedback is a promising technology.

How to optimize the intensity, timing, and spatial encoding of vibration, augment sample size, and improve future work to better generalize anticipatory cues into measurable anti-motion sickness responses.

3.3 Motion Sickness Dosage Value (MSDV) analysis

The exposure to physical motion of the subjects was measured based on the Motion Sickness Dosage Value (MSDV) on three orthogonal planes, which are longitudinal (x), lateral (y), and vertical (z). MSDV is the frequency-weighted cumulative acceleration, which has been shown to be associated with motion sickness, especially in low frequencies below 0.5 Hz. Tables 5 and 6 provide an overview of the mean value of MSDV, standard deviation (SD), and coefficient of variation (CoV) for the Baseline and Haptic conditions. These measures were adopted to evaluate the magnitude, consistency, and repeatability of the vehicle motion in all the test runs. In general, the findings validated the participants' exposure to meaningful motion stimulus that could produce motion sickness and had acceptable consistency across each of the experimental conditions.

The objective analysis of Motion Sickness Dosage Value (MSDV) showed that the subjects were subjected to significant lateral motion stimuli, with a mean MSDV(Y) of 7.21 ms (-1.5). In the Baseline state, the longitudinal axis (MSDV Y) contributed most to the exposure of motion, with a high mean of 51.6 ms-1. This implies that the participants experienced high acceleration and braking forces during the driving task. Additionally, the highest individual MSDVx value (approximately 64.0), as indicated on the x-axis of the figure, suggests the presence of aggressive longitudinal dynamics within the driving profile as illustrated in Figure 5. Single peaks were approximately 64.0 ms-1 and indicated sudden longitudinal maneuvers in the baseline. The lateral axis (MSDV Y) had a smaller mean (14.9 ms-1, five times), although with high variability (CoV = 42.08%), indicating that the cornering forces were not consistent among the participants.

Table 5 Mean, Standard Deviation (SD), and Coefficient of Variation (CoV) for MSDV baseline [19]

MSDV	Mean (ms−1.5)	Standard Deviation (SD)	Coefficient of Variation (CoV) (%)
MSDVx	51.6	10.99	21.30
MSDVy	14.9	6.27	42.08
MSDVz	0.90	0.23	25.56

The Haptic condition, in their turn, was dominated by a lateral motion stimulus. The mean value of the lateral MSDV Y is 7.21 ms-5 with a CoV of very low (8.34%), which is evidence of a very high degree of consistency in the cornering maneuvers in all haptic trials. This consistency demonstrates that the predetermined turning events were executed in a consistent manner, and the haptic intervention assessed the presence of a consistent physical stimulus. The vertical axis (MSDV Z) was the least contributing element in both conditions, as illustrated in Figure 6, particularly in the case of road-induced vibrations.

Table 6 Mean, standard deviation (SD), and coefficient of variation (CoV) for MSDV for Haptic [19]

MSDV	Mean (ms (^ {-1.5}))	Standard Deviation (SD)	Coefficient of Variation (CoV%)
MSDV X	3.05	0.74	24.19
MSDV Y	7.21	0.60	8.34
MSDV Z	1.36	0.83	61.20

The outcome of the MSDV demonstrated that the Baseline condition had always had a higher accumulated motion dosage along the longitudinal (x), lateral (y), and vertical (z) axes than the Haptic condition. The steeper Baseline curve gradients reflected increased exposure to acceleration that causes motion sickness, especially on the lateral axis, which is considered the most influential factor in causing motion sickness. On the contrary, the Haptic condition exhibited reduced and less fluctuating MSDV growth, indicating that coordinated vibrotactile feedback aided in regulating the dosage of motion by enhancing motion anticipation. This result aligns with ISO 2631-1, which states that frequency-weighted accelerations in low-frequency lateral motion have a significant impact on the severity of motion sickness [19].

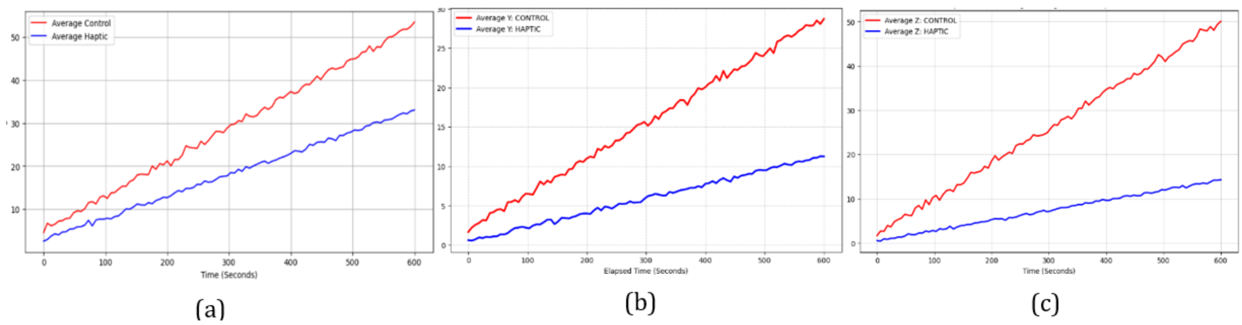

Figure 4 Comparison of average Motion Sickness Dosage Value (MSDV) when in Baseline and Haptic conditions in longitudinal (x), lateral (y), and vertical (z) directions.

The MSDV experimental outcomes revealed that the motion stimuli, both in experimental conditions, were provocative and realistic to a certain extent. The internal validity of the experiment was supported by the low standard deviations in the Haptic condition (SD < 1.0), indicating that the vehicle dynamics were well controlled. Although the dosage of lateral motion is always high, the proportional severity of the subjective symptoms did not increase in the MSAQ results. It was found that there was a partial decoupling between objective motion exposure and perceived discomfort. The haptic feedback at the wrist was presumably used as anticipatory feedback, enabling the subjects to better anticipate the vehicle's future movement and even to stabilize their sensory expectations. In general, the MSDV analysis provided a solid physical foundation for interpreting the subjective MSAQ and UEQ results.

3.4 User Experience Evaluation (UEQ Results)

User experience of the wrist-based vibrotactile haptic feedback system was evaluated using the User Experience Questionnaire (UEQ). The UEQ measures six dimensions of user experience: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. A total of 12 participants were included in the UEQ analysis, comprising 6 in the Haptic condition and 6 in the Baseline condition, using the official UEQ analysis tool [20].

The UEQ scores are presented in Table 7 as the average in the Haptic condition. The UEQ means are all positive (more than 0.8), indicating a generally favourable user experience. Stimulation, Efficiency, and Attractiveness were the highest-rated dimensions, with means of 1.75, 1.54, and 1.58, respectively. Perspicuity (Mean = 1.21) and Dependability (Mean = 1.25) were slightly lower but also fell in the above-average and good scale. Novelty (Mean = 1.46) indicates that the wrist-based haptic system was seen as moderate in terms of innovation by the participants. Table 6 shows that the comparison scores achieved in the two experimental conditions were positive on the UEQ scale, with all means above zero, indicating a reasonably positive user experience. The haptic condition had better mean scores in Attractiveness, Stimulation, and Novelty, whereas the baseline condition had somewhat high mean scores in Perspicuity and Efficiency. In both conditions, the scores for dependability were similar.

Table 7 Descriptive Comparison of UEQ Scale Means

Scale	Haptic Mean	Baseline Mean
Attractiveness	1.58	1.44
Perspicuity	1.21	1.38
Efficiency	1.54	1.79
Dependability	1.25	1.21
Stimulation	1.75	1.25
Novelty	1.46	1.33

The meaning of all UEQ scales is positive (more than 0.8), indicating that user experience is generally favorable. The most rated dimension was the Efficiency (Mean = 1.79), then Attractiveness (Mean = 1.44), and lastly Perspicuity (Mean = 1.38). The mean ratings of 1.25 for stimulation and 1.21 for dependability were lower but still fell within the above-average to good range. Novelty (Mean = 1.33). The mean score of the Novelty scale was 1.33, indicating that the system was perceived as innovative and creative by the participants.

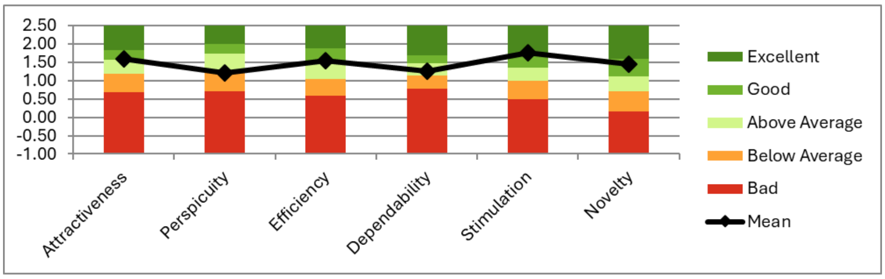

Figure 5 Benchmark Haptic

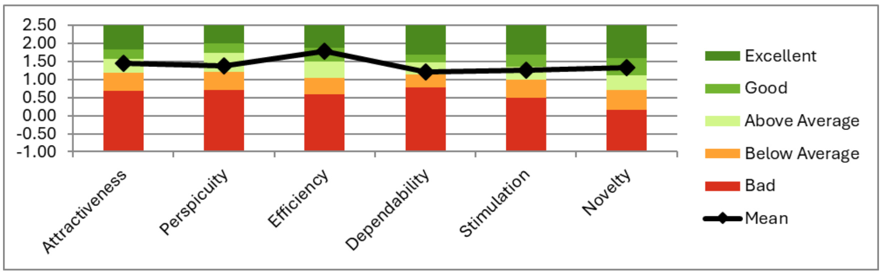

Figure 6 Benchmark Baseline

According to the comparison of the UEQ benchmark, the Haptic condition always scored higher on all six dimensions of UEQ than the Baseline condition, as shown in Figure 5. Stimulation and Attractiveness in the Haptic condition were in the range of Good to excellent, indicating that the hedonic quality was high and user involvement was also high. Efficiency and Dependability were also within the good range, indicating that the system was working reliably without interfering with the main activity. On the contrary, the Baseline condition exhibited an expected smaller benchmark positioning level as illustrated in Figure 6. The rest of the pragmatic dimensions (such as Perspicuity and Dependability) fell into the Above Average to Good category, whereas Stimulation and Novelty were significantly lower. This meant that the conventional task of reading on a tablet was not as engaging or experiential as the haptic condition. Comprehensively, the benchmark findings supported the benefit of the wrist-based haptic system in enhancing hedonic user experience without affecting pragmatic usability. The increase in the Haptic profile compared to the Baseline has proven that vibrotactile feedback contributes to greater enjoyment, motivation, and perceived value of the system, which is why it can be used in future autonomous vehicle passenger modes.

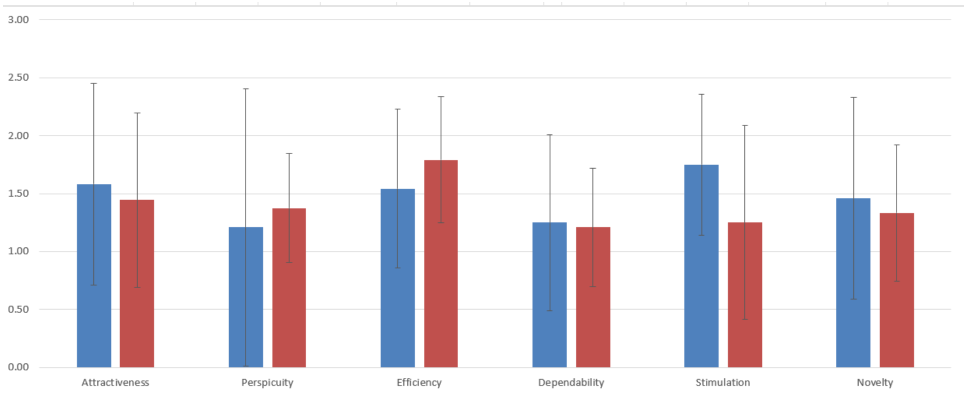

Figure 7 UEQ Scale Means and 95% Confidence Intervals for Haptic and Baseline Conditions

The confidence intervals indicate a high degree of overlap between the two conditions across the six UEQ scales. This overlap implies that the differences in the mean scores are not significant. A comparison of the means of the UEQ scales, with 95% confidence intervals, under both conditions is represented in Figure 7. Using the Welch t-test, a comparative analysis was conducted between the Haptic and Baseline conditions. The findings indicated that there were no statistically significant differences between all the UEQ scales ($p > 0.05$). Descriptive trends were observed, although the results were not statistically significant. The haptic condition scored higher in hedonic dimensions, particularly in stimulation, attractiveness, and Novelty, indicating higher involvement and emotional attraction. Baseline condition, in its turn, was slightly higher in Efficiency ($M = 1.79$) and Perspicuity ($M = 1.38$). This disparity likely resulted from the participants being accustomed to the standard tablet-reading activity with no additional interventions. These results suggest that, although the haptic system did not impair task performance or usability, it increased the system's perceived quality.

3.5 Usability and System Practicability.

The User Experience Questionnaire (UEQ) was used to gain insight into the haptic and pragmatic factors of the haptic intervention. Generally, respondents scored the system highly, especially in the hedonic levels that included Stimulation, Attractiveness, and Novelty, which indicated that the technology was interesting and popular. Pragmatic qualities, such as Efficiency and Perspicuity, were maintained at acceptable levels, indicating that usability and clarity were not compromised. There were no statistically significant differences in the Haptic and Baseline conditions on any of the scales of UEQ. Notably, the use of wrist-based vibrotactile feedback had no adverse effect on comfort, usability, or perceived system quality. Benchmark analysis also demonstrated that the Haptic condition scored as Good to Excellent in attributes related to stimulation, which was a positive response from the participants with the system.

3.6 Discussion

The outcome of the MSAQ results revealed no significant decrease in the subjective motion sickness symptoms with wrist-based vibrotactile haptic feedback compared to the baseline. This finding indicates that the intervention, as designed and implemented, was not effective in providing sufficient sensory data to have a significant impact on the perception of motion sickness in the participants when they were not driving [21]. Yet this does not mean that haptic feedback is ineffective; on the contrary, it highlights the intricacy of sensory integration in motion sickness mechanisms [22].

The causes of motion sickness are the discrepancies between the visual, vestibular, and somatosensory signals. It is not sufficient to add a haptic cue without it having a significant effect on the error of sensory prediction, which triggers discomfort. Purely anticipatory vibrotactile cues have been previously studied, yielding the same results: vibrotactile cues alone are insufficient to reduce motion sickness, despite participants reporting that the cues were effective or informative [23]. The usefulness of anticipatory vibrotactile signals is inconclusive. Studies indicate that in cases where motion cannot be predicted, or the cues lack contextual significance, symptom reduction is minimal. These findings suggest that although haptic feedback can be used to provide anticipatory information and facilitate sensory anticipation, it may not always prevent motion sickness in everyone [24]. Thus, haptic cues at the wrist can be used as a more effective perceptual support system, but not as an intervention to suppress symptoms [25].

The objective MSDV analysis established that the two experimental conditions subjected the participants to large amounts of motion, especially those that occur along the lateral axis, which is a well-known strong source of motion sickness in turn dynamics [26]. The fact that consistent acceleration dose curves are produced on both axes demonstrates that the driving profile successfully replicates real-world autonomous vehicle motion exposure commonly found in the passenger environment. Moreover, a more homogeneous accumulation of MSDV with the haptic condition would imply that the availability of vibrotactile feedback affects the way participants perceive the movement, even though the actual movement itself remains unaffected [15]. The fact that exposure to physical motion (MSDV) does not correlate with subjective symptoms supports the fact that predictability and anticipatory sensory information are crucial in motion sickness.

Studies of control methods, including adaptive lateral control methods that suppress the frequency content of motion sickness, have shown that objective motion profiles can be manipulated to reduce physiological discomfort [27]. Although our experiment did not directly control the movement of the vehicle, the correlation between the same level of MSDV and consistent symptom levels under haptic control is consistent with the view that the predictability of sensation, rather than the magnitude of motion, is predictive of subjective response to sickness. Thus, a future study combining anticipatory cues and motion-sensitive control methods may be an opportunity worth pursuing, given the recommendations of recent studies on mitigating motion sickness in autonomous vehicles [15].

The results of UEQ indicated that participants tended to feel positively about the wrist-based haptic feedback, both in pragmatic and hedonic aspects. The scores for Stimulations, Attractiveness, and Novelty were high, indicating that the system was interesting and enjoyable, even when undertaking challenging visual tasks. The differences between the Haptic and Baseline conditions were not significant; however, the descriptive tendencies of diverging towards the haptic condition in the hedonic characteristics indicate that the vibrotactile cues could improve emotional involvement and perceived connectedness to the vehicle motion [18]. The assessment of user experience with instruments such as the UEQ is typical of studies on interactive systems, as it encompasses both task-oriented usability and emotional experience, including enjoyment and stimulation. in addition to traditional measures of symptom severity. Earlier studies have strongly highlighted that interventions to prevent motion sickness must not only be physiologically effective but also consider the user experience, as the positive experience factor can enhance the overall system's feasibility and readiness for use in real-world environments [28].

The layout of the wrist-based vibrotactile haptic feedback was a limitation of this research, as the necessary sensory channels may not have been sufficiently utilized to eliminate motion sickness on a considerable scale. The non-driving visual tasks and short-duration exposure to motion were the focus of the experiment and may not reflect more long-term or interactive driving tasks. Moreover, only one modality was applied, and no additional visual or auditory information was presented, which may have possibly underestimated the effectiveness of a multimodal intervention [9,16]. For Future Studies, it is suggested that the next generation of haptic systems should investigate multimodal systems that incorporate haptic, visual, and auditory anticipatory feedback to enhance cross-sensory predictability and mitigate motion sickness. Research should also be conducted to test varying feedback intensities, timings, and locations, as well as to investigate the impact of different task types and extended exposure. The incorporation of haptic feedback into motion-conscious control systems, along with further evaluation of user experience metrics, will help sustain interventions that are physiologically active and well received by passengers.

4. Conclusion

In conclusion, the study's objectives were successfully achieved. The Wizard of Oz driving protocol consistently generated very similar vehicle dynamics across all test sessions. The subjects were exposed to similar longitudinal, lateral, and vertical accelerations, thereby creating a controlled, repeatable experimental environment. An analysis of objective motion exposure revealed that lateral motion was the leading cause of motion sickness, with MSDV values above 6 $ms^{-1.5}$ for all participants. This proved that the driving route provided an adequate motion stimulus to cause mild motion sickness. Nevertheless, the participants demonstrated an extremely high rate of acceptability for the defensive automated driving style, and they also stated that the experience felt comfortable, safe, and pleasant during the test rides. There were also subjective measurements, in which motion sickness symptoms were primarily elicited during non-driving-related activities, especially while reading. The level of motion sickness was low in passive driving but high in activity-demanding tasks. Nevertheless, the participants could attend all the experimental sessions even when they felt discomfort. The vibrotactile haptic feedback system, as a wrist-based system, did not produce a statistically significant difference in overall motion sickness severity. However, it helped stabilize participants' reactions and reduce symptom levels during non-driving-related activities. The evaluation of user experience also revealed that the haptic system was highly accepted, engaging, and perceived as useful. To conclude, this experiment has demonstrated that defensive automated driving behavior was tolerated by Malaysian passengers and that motion sickness was primarily determined by the involvement of visual tasks, rather than the driving style in isolation. Although the present wrist-based haptic feedback system was only partially physiologically mitigated, it was nevertheless viable and highly accepted, providing a solid basis for future refinement and optimization.

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