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QUANTIFYING AND MITIGATING MOTION SICKNESS IN AUTONOMOUS VEHICLES THROUGH PSYCHOACOUSTIC MODELING AND NEUROPHYSIOLOGICAL INSIGHTS

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ABSTRACT

Motion sickness (MS) remains a critical challenge for autonomous vehicles as they evolve into multifunctional spaces for productivity and entertainment. This study explores the relationship between MS and neurophysiological responses, focusing on electroencephalogram (EEG) and heart rate variability (HRV) indicators to quantify the degree of MS. Using advanced psychoacoustic modeling, we also developed and tested a feed-forward audio-visual notification system designed to reduce MS symptoms by enhancing situational awareness. Results from real-world driving and simulated conditions reveal significant correlations between EEG delta and alpha power changes and MS severity. Moreover, the integration of preemptive sensory cues demonstrated a substantial reduction in MS symptoms. These findings contribute to developing effective mitigation strategies for improving passenger comfort in autonomous vehicles and provide a foundation for future psychoacoustic applications in motion perception.

Keywords: *motion sickness (MS), autonomous vehicle (AV), audio-visual stimulation, psychophysiological, situation awareness (SA)*

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1. INTRODUCTION

Autonomous vehicles are evolving beyond transportation means into multifunctional spaces for activities such as work and leisure [1]. However, as passengers' active involvement in vehicle control decreases, motion sickness (MS) has emerged as a significant concern [2]. Visual-vestibular conflict, unpredictability of vehicle motion, and psychological tension have been identified as primary factors exacerbating MS in autonomous driving environments [3].

Previous studies have utilized neurophysiological indicators such as electroencephalogram (EEG) and heart rate variability (HRV) to quantify motion sickness symptoms. EEG analyses have shown changes in delta, theta, and alpha activity within sensory integration and attention-related brain regions, including the central, parietal, and occipital areas, under MS conditions [4-5]. HRV analyses also indicate stress responses during MS conditions, characterized by increased LF and LF/HF ratio, along with decreased HF [6].

Recent studies have proposed strategies using sensory stimuli such as visual, auditory, and vibrotactile cues to mitigate MS. Predictable visual information, advance information about acceleration, and ambient light cues have demonstrated effectiveness in enhancing situation awareness (SA) and reducing MS symptoms [7]. However, these findings rely primarily on subjective assessments such as MISC, lacking objective physiological validation.

Thus, this study aims to quantitatively assess MS induced by driving environments using EEG and HRV measurements and to verify the effectiveness of an audio-visual sensory cue system. Ultimately, this research intends to contribute to improved physiological comfort and enhanced passenger experiences in future mobility environments.

2. METHOD

To investigate the physiological mechanisms that induce and mitigate MS in vehicular environments, this study conducted three distinct experiments.

2.1 Track driving

The first experiment was conducted on a closed-track circuit with six adult participants. Driving sessions were performed on straight, figure-eight, and zigzag road segments. During the sessions, participants' psychophysiological responses to MS were collected using EEG, HRV, and Misery Scale (MISC).

2.2 Real-world driving

The second experiment involved real-road driving conditions, during which EEG, HRV, and MISC data were collected to observe physiological responses under naturalistic conditions. This experiment followed a pre-driving rest – driving – post-driving rest sequence, with a driving duration of approximately 30 minutes.

2.3 MS mitigation test

The third experiment evaluated the effect of light and sound cues in mitigating MS, as illustrated in Figure 1. This feed-forward sensory cue system was designed to enhance SA and reduce MS. Six participants completed two experimental conditions: a cue-present (Cue O) and a control (Cue X) condition. Data collected included subjective questionnaires (MSSQ, MISC, SART, UX) and physiological signals (EEG, HRV).

The experimental procedure consisted of a 3-minute pre-questionnaire and resting-state physiological measurement, followed by a 20–30 minute driving session, and a 5-minute post-driving questionnaire. Each condition was conducted on a separate day across two consecutive days. The audio-visual cues were automatically triggered according to specific driving events including left turns, right turns, acceleration, and deceleration.

The driving route followed a loop-type course lasting approximately 25–30 minutes. Each loop included 17 U-turns, 9 left turns, 26 acceleration events, and 26 deceleration events. Immediate visual and auditory cues were provided in response to each event. The mitigation effect was analyzed based on biometric responses and MISC scores.

This multi-phase experimental design enables comprehensive comparison of MS induction and mitigation under various driving conditions and provides a quantitative basis for evaluating EEG and HRV indicators.

3. ANALYSIS AND RESULT

3.1 Physiological indicators related to MS

For EEG analysis, power spectral density (PSD) data collected from the first experiment were examined. Electrodes Fp1, F3, and C3, which reflected overall trends across all channels as shown in Figure 2, were selected as regions of interest (ROIs).

Based on these ROIs, delta and alpha power were analyzed for both the first (Track Driving) and second (Real-World Driving) experiments. In the Track Driving experiment, delta power generally increased during figure-eight and zigzag track conditions, which were identified as MS-inducing. In the Real-World Driving experiment, increases in delta power were observed after more than 15 minutes of driving. In contrast, alpha power showed a decreasing tendency at the same time points where delta power increased in both experiments. These findings suggest the potential for quantifying MS susceptibility and severity through delta and alpha power analysis within the selected ROIs.

Comparison of EEG indicators with MISC scores revealed that the highest MISC ratings occurred under conditions with the greatest increase in delta power and decrease in

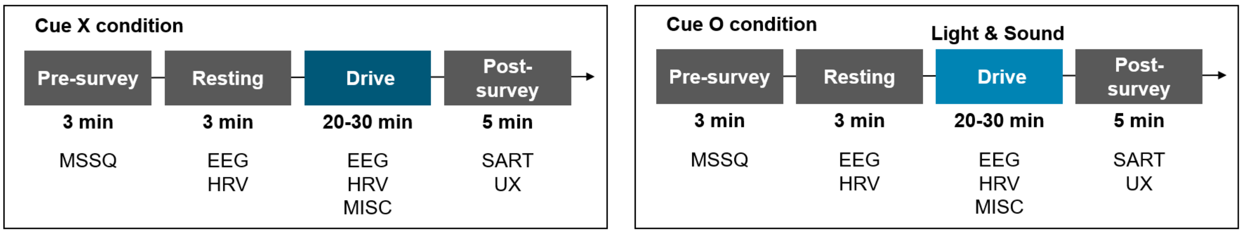

Figure 1. Experiment protocol for measuring MS mitigation (Experiment 3)

alpha power. Correlation analysis further showed that in the C3 region, delta power had a significant positive correlation with MISC scores ($r = .70$, $p < .01$), while alpha power had a significant negative correlation ($r = –.66$, $p < .01$). These results suggest that physiological responses are closely associated with subjectively experienced MS symptoms.
HRV analysis showed that parameters such as LF, SDNN, ln(TP), and pNN50 exhibited similar temporal patterns to changes in EEG delta power at the C3 region. Sympathetic nervous system activation and parasympathetic suppression were observed during MS-inducing segments. These findings support the potential of HRV as an autonomic nervous system marker for MS, in addition to EEG-based indicators.

3.2 Analysis of MS mitigation effects

In the analysis of MS mitigation effects depending on cue presence, it was found that the condition with cues (Cue O), in which Light & Sound cues were provided, resulted in a slower rate of MISC score increase compared to the condition without cues (Cue X), delaying the onset of MS by approximately 4 minutes and lowering the average score by about 0.9 points. Additionally, among the 28 MS symptom items, about a 52% reduction in symptoms was reported.
As shown in Figure 3, physiological signal analysis further revealed that, compared to Cue X, the Cue O condition exhibited smaller increases in EEG delta power and smaller decreases in alpha power. Similarly, HRV analysis showed that increases in LF and LF/HF were lower in the Cue O condition. These results suggest that the presentation of Light & Sound cues induces a physiologically stabilizing

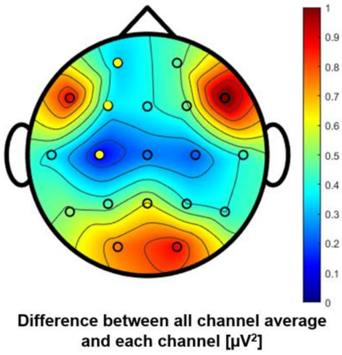

Figure 2. Difference between overall and individual channel frequency power. Yellow circles indicate selected ROIs.

effect associated with motion sickness alleviation.
These findings experimentally demonstrate that preemptive visual-auditory sensory cues can enhance SA and regulate neurophysiological responses, thereby contributing to the mitigation of MS in autonomous vehicle environments.

4. DISCUSSION

This study quantitatively analyzed MS responses in autonomous vehicle environments using EEG and HRV indicators and experimentally verified the effect of sensory-based predictive driving cues on MS mitigation. The main findings and implications are as follows.
First, EEG analysis revealed that in the ROIs centered on Fp1, F3, and C3, delta power consistently increased during MS-inducing segments, while alpha power decreased. This aligns with neurophysiological responses reported in

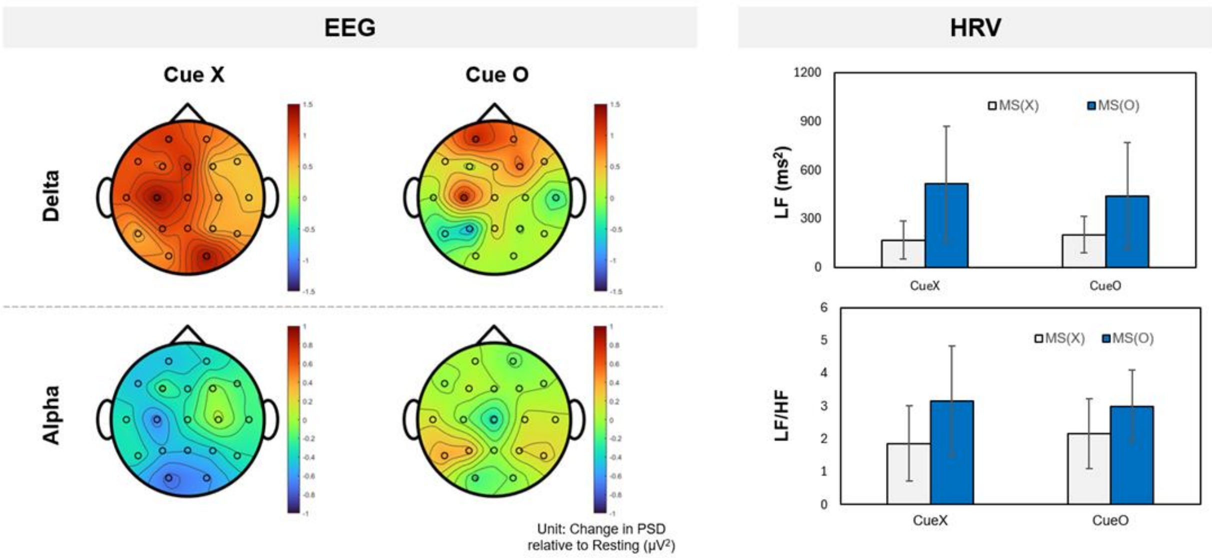

Figure 3. Comparison of physiological signals (EEG, HRV) between cue conditions.

previous studies on sensory conflicts and showed high correlations with subjective MS scores (MISC), thereby strengthening the validity of EEG as an objective MS marker.

Second, HRV analysis showed that indicators such as LF, SDNN, TP, and LF/HF exhibited similar patterns to EEG delta power changes, confirming sympathetic activation and parasympathetic suppression during MS episodes. This suggests that HRV, alongside EEG, can serve as a key biomarker for multidimensional understanding of the physiological mechanisms underlying MS.

Third, results from the MS mitigation experiment using Light & Sound cues demonstrated delayed MISC score increases and reduced MS symptoms in the Cue O condition. Corresponding EEG and HRV data also reflected enhanced physiological stability. These findings support the neurophysiological theory that sensory-based predictive cues reduce prediction errors in the brain and enhance SA, thereby effectively modulating MS responses in autonomous vehicles.

5. SUMMARY

This study quantitatively analyzed physiological responses associated with MS during vehicle driving using EEG and HRV and experimentally investigated the effect of sensory-based predictive driving cues on MS mitigation.

EEG analysis revealed that delta power increased and alpha power decreased significantly in the Fp1, F3, and C3 regions during MS-inducing conditions, with these changes being most prominent under conditions with the highest MISC scores (particularly in the C3). These findings suggest that EEG markers can effectively reflect individual MS sensitivity and sensory conflicts in specific situations.

The MS mitigation experiment using Light & Sound cues showed a significant alleviating effect under the Cue-present condition (Cue O). Specifically, MISC analysis indicated a delayed onset of MS and an average reduction of approximately 0.9 points in MISC scores. Furthermore, a symptom evaluation based on 28 items showed a symptom reduction of approximately 52%.

Physiological signal analysis showed that the Cue O condition exhibited attenuated increases in EEG delta power and less pronounced decreases in alpha power, suggesting neurophysiological stabilization associated with enhanced SA. In addition, HRV indices under the Cue condition showed relatively lower increases in sympathetic activation during MS episodes, along with reduced decreases in HF and smaller increases in the LF/HF ratio.

These results indicate that both EEG and HRV are reliable physiological indicators for assessing MS severity and mitigation effects.

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