Exploring the Effects of Regenerative Braking and the Auditory Cues for Alleviating Motion Sickness in Electric Vehicles

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ABSTRACT

Electric vehicles (EVs) are becoming increasingly popular in recent years. However, the popularization of EVs raises concerns about motion sickness (MS) among passengers. Despite this, few studies have explored the causes of and solutions to MS in EVs. The regenerative braking (RB), as a unique function in EVs, is believed to cause MS but has not been validated. In this study, we aim to investigate the effect of RB on MS development and explore the potential of providing auditory motion cues to mitigate MS among passengers, especially when RB is used. To achieve this, an on-road study with 16 participants who are susceptible to MS was conducted, with the level of regenerative braking (low-level versus high-level) and auditory motion cues (presence versus absence) as the within-subject factor. Our results confirmed that higher levels of regenerative braking led to the highest percentage of passengers experiencing MS. Simultaneously, providing auditory motion cues can mitigate MS when high-level RB was used, but the auditory motion cues had negligible effects or may even exacerbate MS under low-level RB. The findings of this study highlight the importance of providing motion cues to drivers in EVs and provide insights into the design of RB systems and corresponding human-machine interaction strategies.

Keywords: motion sickness; regenerative braking; on-road study; auditory cue; electric vehicle

1. Introduction

Electric vehicles (EVs), powered by electricity and driven by electric motors, have gained popularity and acceptance among consumers in recent years. The global market share of EVs reached nearly 14 million units by 2023, representing a substantial growth in market penetration from around 4% in 2020 to nearly 18% in 2023 IEA50 (2024). Projections indicate that by 2024, the market share of EVs could rise to 20% (IEA50, 2024). Unlike traditional gasoline-powered vehicles, EVs produce zero tailpipe emissions, effectively reducing air pollution and greenhouse gas emissions contributing to climate change (IEA50, 2024). Further, from the users' standpoint, EVs offer lower operating costs and superior handling performance when compared to gasoline vehicles (Constellation, 2024). However, despite the advantages of EVs, there are still challenges to the widespread adoption of EVs, and the increased incidence of motion sickness (MS) is one of them (Xie, Huang, et al., 2023).

Manifested as malaise, nausea, and, in severe cases, emesis (Smyth et al., 2021), MS is a common phenomenon in transportation, including aviation (Turner et al., 2000), maritime (Lawther & Griffin, 1986), rail (Suzuki et al., 2005), and on-road transportation (Xie, He, et al., 2023). A survey conducted in China revealed that over 80% of respondents experienced varying degrees of MS (So et al., 1999) in different modes of transportation. In particular, EVs have been found to cause more severe MS symptoms compared to traditional fuel vehicles (Xie, Huang, et al., 2023).

The heightened MS with EVs may be explained by several assumptions. Firstly, the dynamic response of the electrified drive system in EVs is quicker than that of combustion engines, which can increase the Motion Sickness Dose Value (MSDV), a metric quantifying motion-related MS induction (ISO2631-1, 1997). Additionally, the auditory cues from internal combustion engines are absent in EVs, which makes passengers unable to anticipate the vehicle motions. Finally, EVs are typically equipped with regenerative braking (RB) systems, leading to stronger yet more unpredictable vehicle deceleration. Numerous online complaints have highlighted that the RB system in EVs exacerbates MS (Korn, 2024). However, despite the continuous research in academia on the causes and alleviation of MS (Korn, 2024), academic attention to MS in EVs is relatively limited and the validity of the above-mentioned assumptions is not verified in empirical studies. Among these three assumptions, the MSDV because of the quick dynamic response of the electrified drive system is objective and can be calculated directly, and it is practically infeasible to inform the future motion of the vehicle in manual driving. Hence, only the effect of RB deserves further exploration in empirical study.

Despite the widespread belief that the RB system is a leading cause of increased MS in EVs, this phenomenon has not yet been validated. Hence, in this study, we aim to investigate the role of RB for MS induction in EVs and we have our first research question (RQ1): Does a higher intensity of the RB lead to more severe MS in EVs compared to a lower intensity of RB? At the same time, given the role of RB in

extending the range of EVs, it is necessary to explore ways to alleviate MS when RB is deployed. While previous research has largely focused on mitigating MS through visual motion cues, such cues occupy passengers' visual channels and rely on additional hardware in cabins (e.g., ambient lights, Bohrmann et al. (2022)). Thus, it may not be appropriate for all in-vehicle scenarios. In contrast, auditory motion cues might be more viable if proven effective, given that almost all vehicles are equipped with sound systems and hence this cue can be deployed through over-the-air updates (OTA). This leads to our second research question (RQ2): whether auditory motion cues informing the vehicle motion could alleviate MS, especially when the RB is deployed. To address these research questions, an on-road experiment was conducted, with drivers' MS levels and acceptability of the auditory cues collected.

2. Literature Review

2.1. Theories of MS

According to the sensory conflict theory (Reason, 1978), MS can be due to the conflicts among visual cues perceived by the eyes, acceleration sensed by the vestibular organs, and somatosensory signals obtained by self-body movement. For example, when a passenger watches a video in a moving car, the static environment perceived by eyes and the acceleration perceived by vestibular organs can lead to MS. In addition to sensory conflict theory, the accumulation of motion over time can also cause MS (Donohew & Griffin, 2004). Hence, the MSDV, which quantifies the accumulation of acceleration over time, has been widely adopted as an objective

measure of MS induced by vehicle dynamics (ISO2631-1, 1997). For example, vehicle acceleration at low frequencies and increased amplitude of acceleration can lead to more severe MS symptoms (Irmak et al., 2022). The RB can both increase the MSDV of the vehicle and impede the perception of the motion of the vehicle. Hence, the role of RB in MS induction in EVs deserves further exploration.

2.2 Solutions to MS in Vehicles

With the prevalence of smart cabins, mitigation of MS in vehicles has attracted much attention in recent years. Two categories of solutions have been explored, i.e., the vehicle-dynamics-related solutions and the interaction-based solutions.

The vehicle-dynamics-related solutions aim to regulate vehicle motions to reduce MS among passengers. For example, Jurisch et al. (2020) tried to reduce vertical oscillations by using specified vehicle suspension systems. Jain et al. (2023) and Htike et al. (2021) incorporated the MSDV as an objective in the motion planning algorithm of autonomous vehicles to generate more comfortable vehicle motion. Similarly, Siddiqi et al. (2022) proposed a path planning algorithm for MS mitigation in lang-changing and turning maneuvers with the MSDV as one of the objective functions. In addition to the MSDV, the acceleration at certain thresholds was also used to evaluate the planned paths. For example, Siddiqi et al. (2021) compared transition curves of autonomous vehicles in terms of MS induction based on the amplitude of acceleration within certain frequency ranges.

In contrast, the interaction-based solutions aim to enhance passengers' ability to predict future vehicle movements or perceive current vehicle motion through Human-Machine Interfaces (HMIs). For example, previous research found that MS can be alleviated by providing upcoming vehicle motion information through an array of vibrators in the passenger seat (Li & Chen, 2022), auditory displays (Maculewicz et al., 2021), and LED stripes (Karjanto et al., 2018). However, these solutions require upcoming motion information of the vehicle and are only applicable in the context of autonomous driving. The solutions to alleviate MS in manual driving primarily focused on the visual representation of current vehicle motion. For example, Li et al. (2024) effectively decreased passengers' MS levels by providing a visual cue informing current vehicle motion in the background of a mobile phone. Similarly, Miksch et al. (2016) found that using the live video of the road ahead as the background of texts can alleviate MS when passengers are reading. However, whether the auditory cues can help alleviate MS in EVs is not yet explored, despite its potential to be widely deployed in almost all current EVs.

2. Methodology

2.1 Participants

In total, 16 participants recruited from online forums and posters within the campus participated in our study (male = 8, female = 8), with a mean age of 20.3 years (min: 18, max: 24, standard deviation [SD]: 2.0). We intentionally selected participants who are more susceptible to MS, given they may benefit most from the

countermeasures to alleviate MS. Hence, all participants were required to be over 50th percentile (i.e., a minimum of 11.3 out of 54 scores) in the self-reported scores on the Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-short, Golding (2006); Li et al. (2023)). The average MSSQ score among participants was 21.3 (min: 11.3, max: 38.3; SD: 8.5). It should be noted that, given that the study was carried out in mainland China, a Chinese version of the MSSQ-short was used (Lin & Guo, 2022). All participants are self-reported to have good health and normal vestibular function.

2.2 Equipment

As illustrated in Figure 1, a hatchback EV with five seats (i.e., Yiwei 3 from JAC Motors) was utilized for this experiment. The vehicle has a length of 4025 mm, a width of 1770 mm, a height of 1560 mm, a wheelbase of 2620 mm, and a track width of approximately 1520 mm. It is powered by a front-mounted single electric motor, boasting a maximum horsepower of 100 kW, and a maximum torque of 175 N.m. In terms of RB efficiency, the JAC Yiwei 3 features three levels of RB modes - low, medium, and high. For this experiment, we focused only on the low and high levels of RB, which generate maximum acceleration values of 0.5/m^2 (low) and 1.5/m^2 (high) when releasing the accelerator pedal.

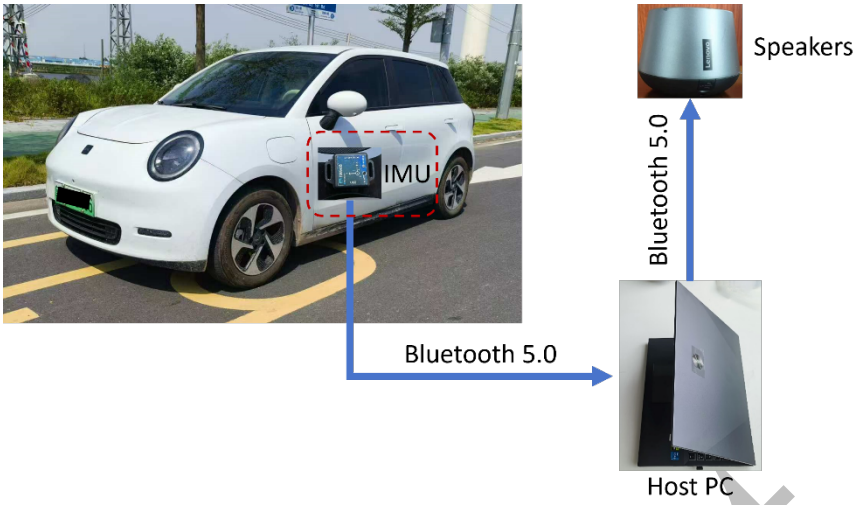


Figure 1. Equipment used for on-road data collection.

An IM948 Inertial Measurement Unit (IMU) was mounted on the horizontal surface of the glove compartment in the middle of the first row (see Fig. 1), which can gather linear acceleration data at a rate of 30Hz, with an accuracy of 0.01G. Following the right-hand coordinate system in ISO 8855:2011, the z-axis, x-axis, and y-axis point upwards (vertical), front (longitudinal), and right (lateral) of the vehicle, respectively.

A 9.7-inch iPad as an in-vehicle display (see Fig.2) was securely mounted at the back of the front passenger seat to replicate the commonly observed backrest display position in commercial vehicles. This was achieved using a specific holder, ensuring consistent location and orientation for the display across all trials. Additionally, two speakers were positioned at the front and rear of the passenger's seat to generate auditory motion cues in the experiment (see Fig. 2).

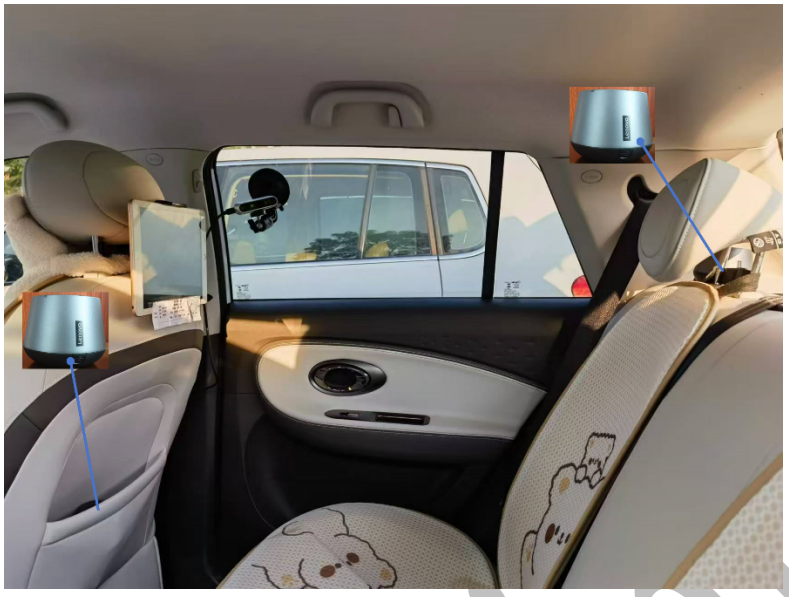


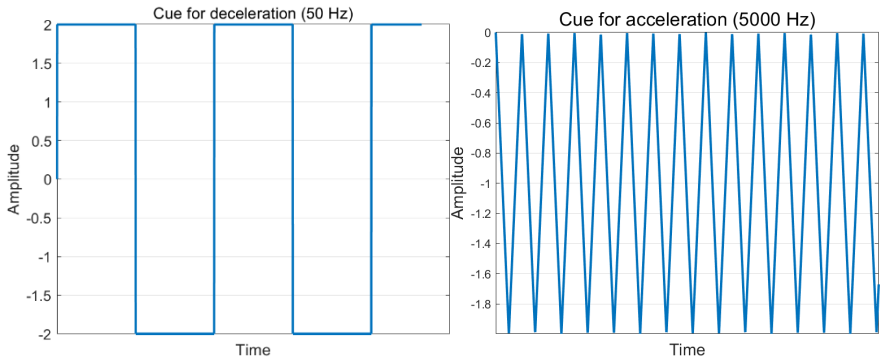
Figure 2. Position of in-vehicle display and speakers to generate auditory cues.

2.3 Auditory motion cues

A software program on the instrumented laptop utilized the x-axis acceleration data from the IMU to generate auditory cues (see Fig. 1). For acceleration, the front speaker generated a crisp sound (at a frequency of 5000 Hz, consisting of a triangular waveform, see Fig.3); for deceleration, the rear speaker generated a deep sound (at a frequency of 50 Hz, consisting of a rectangular waveform, see Fig.3). The amplitude of the wave was proportional to the magnitude of acceleration or deceleration, as described in Equation (1).

$$A = |a_x| / 0.5ms^{-2} \quad (1)$$

Where A stands for the amplitude of the wave and a_x stands for the longitudinal acceleration. For example, with an acceleration of 1.5 m/s^2, the volume generated by the speakers was around 90 dB.



(a) (b)

Figure 3. Waveform of deceleration and acceleration cues

2.4 Motion Stimuli and Driving Tasks

In the experiment, participants experienced rides in the instrumented vehicle, which navigated through a predetermined trajectory on a closed road located in Guangzhou, China (see Fig.4). The route contains a straight, six-lane, two-way road, where the vehicle's acceleration varied. We consider the distance from the start to the end in one direction of the road as a single road section unit, with each unit measuring approximately 1.45 kilometers. Each trial lasted for 20 minutes, covering approximately 8.2 to 8.4 road section units (see Fig.4). Additionally, as the stop-and-go driving scenarios exacerbate MS (Ramaioli et al., 2023), we designed a vehicle motion profile that mimicked the dynamics of stop-and-go driving in congested urban traffic (Amap, 2021; Suh & Yeo, 2016) with cyclic acceleration and deceleration and an average speed of approximately 35 to 36 km/h.

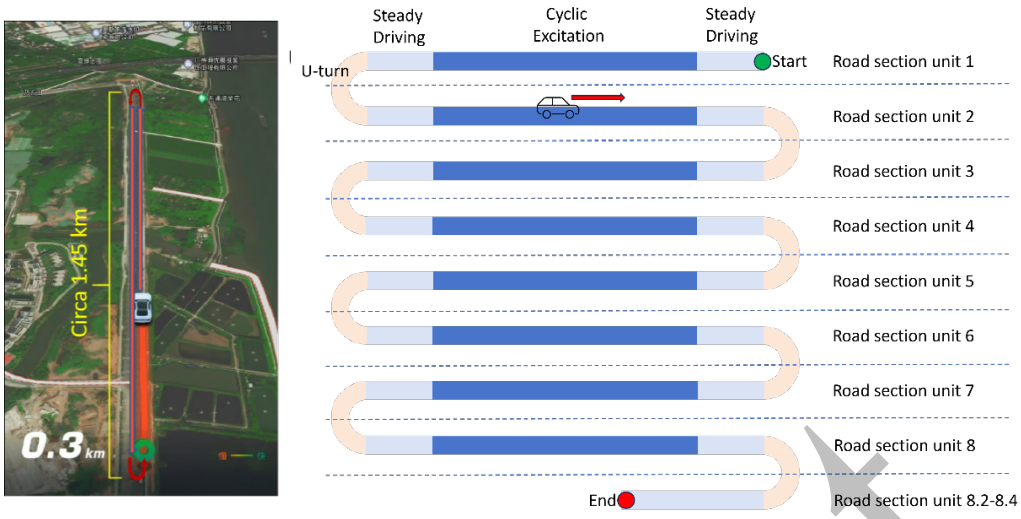


Figure 4. Predefined route, trajectory, and vehicle dynamic behavior for motion stimuli control.

To ensure consistency in the dynamic behavior of the vehicle and to minimize the influence of the driver's behavior on the results, the speed of the vehicle was controlled, utilizing the cruise control (CC) feature to accelerate and different intensities (i.e., low and high level) of RB to decelerate. A road section unit involved four phases of driving: steady driving, cyclic excitations, another period of steady driving, and U-turns.

- **First steady driving phase**: Upon entering the straight road section, CC was activated, and the RB system was manually adjusted to the designated target level (low or high, as per the experimental condition), maintaining a steady speed of 30km/h for around 5 seconds.
- **Cyclic excitations phase**: In this phase, the passengers experienced 6 excitation cycles. As shown in Figure 5, in each cycle, the experimenter changed the CC

speed to 40km/h via steering wheel buttons, allowing the vehicle to automatically accelerate from 30km/h to 40km/h. Upon reaching 40km/h, the CC was briefly deactivated, and the vehicle decelerated to 30km/h under RB. Then, the next cycle started by re-activating the CC after 1 to 5 seconds of cruising at 30 km/h. Note the gaps between the cycles varied, as the traveled distance depended on the intensity level of RB. Thus, we varied the gaps between the cycles to ensure each cyclic excitation phase included the same number of cycles.

- **Second steady driving phase**: Upon completing the excitation cycles, the vehicle would resume steady driving, maintaining a consistent speed of 30 km/h by using CC.
- **U-turns phase**: When the vehicle approached the U-turn slot, the RB system was manually adjusted to the low level and the experimenter slowed the vehicle to 12-20 km/h, manually executing a U-turn to enter the opposite lane to start another road section unit.

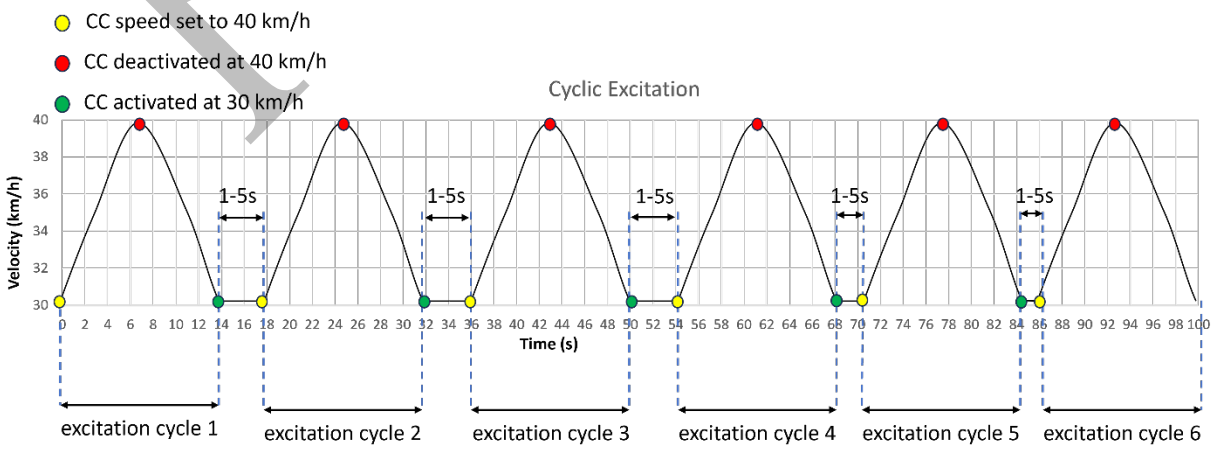


Figure 5. Cyclic excitation in a road section unit consisting of 6 excitation cycles.

It is important to mention that as we tried to ensure that participants received the same duration of stimuli (i.e., 20 minutes), the total distance in a trial can vary slightly depending on the intensity of the RB. In the concluding 0.2-0.4 road section units of each trial, the vehicle consistently maintained a speed of 30 km/h, utilizing CC mode for steady driving.

2.5 Video-Watching Task

As visual activity may influence MS development (Butler & Griffin, 2009), we introduced a standardized visual task to control passengers' visual activities during rides. Specifically, throughout each ride, participants were shown documentary video clips on an in-vehicle display, with topics on history, culture, or the military. These clips were all in Chinese, the participants' native language, to avoid any comprehension difficulties. To encourage participants to engage in the video-watching task, they were informed that their bonus would depend on their answers to the video-related questions after the rides. To ensure sustained attention across all rides, as shown in Figure 6, the video clips varied across rides, yet the order of videos was the same for all participants. The consistent order of videos, combined with a Latin square experiment design of the experimental conditions, can eliminate the potential influence of video content on MS development.

2.5 Experiment Design

The experiment utilized a within-subject design, incorporating two variables: RB (low versus high levels) and the auditory cue (presence versus absence). This setup

resulted in four distinct experimental conditions, requiring each participant to undergo four separate rides. To ensure participants had enough time to recover from any MS experienced during a ride, a minimum interval of three days was ensured between rides for the same participant.

To control order effects, which could influence the results, the sequence of experimental conditions was counterbalanced using a Latin square design (see Fig. 6), creating four unique sequences. Each experimental condition was experienced by four participants (2 males and 2 females), leading to a total of 64 rides for the study (4 rides/participant × 4 sequences × 4 participants/sequence).

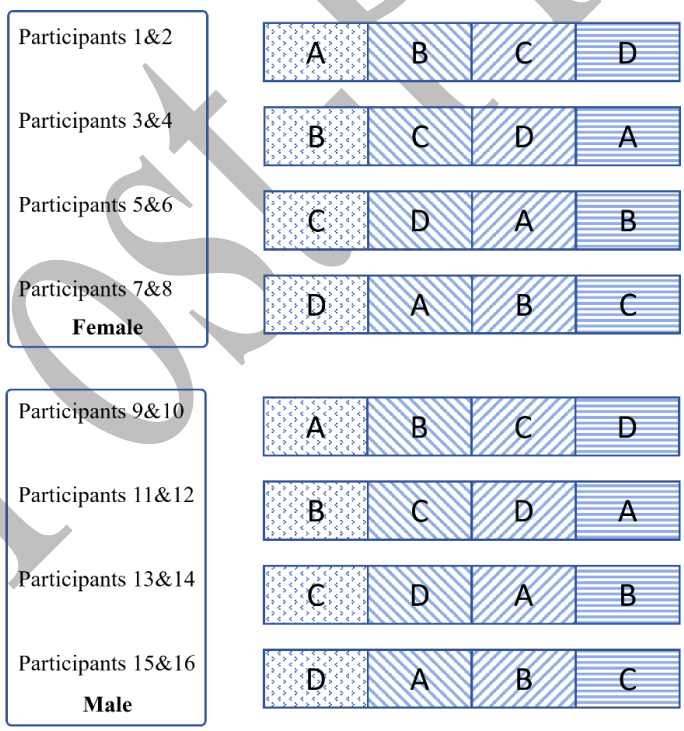


Figure 6. Latin square design of the experiment. Alphabets A to D represent different experimental conditions (A: low RB × cue absence; B: high RB × cue absence; C: low RB × cue presence; D: high RB × cue presence). The order of video clips played was

consistent across all participants, with blocks of the same background pattern indicating the same video clip.

2.6 Experiment Procedures

Following the guidelines by Suwa et al. (2022), one day before the experiment, participants were advised to prioritize self-care for maintaining good health, ensure sufficient sleep the night before, and avoid alcohol intake. On the day of the experiment, they were required to finish meals at least one hour before the experiment. Upon arrival, each participant signed a consent form detailing the objectives, procedures, associated risks, and potential benefits of the experiment. They were explicitly informed of their right to withdraw from the experiment at any point, particularly if they were unable to tolerate MS-induced nausea. If this happened, the experiment would be halted at the nearest safe location, allowing the participant to exit the vehicle.

Before the experimental ride commenced, participants were introduced to a Chinese version of the MIsery SCale (MISC) (Lin & Guo, 2022) that measures MS levels (Bos et al. (2005), see Table 1). During the ride, participants watched video clips on an in-vehicle display while periodically reporting their MS levels orally using MISC. An auditory alert (with a loudness of 90 dB, frequency of 1000 Hz, and duration of 1 second), emitted at minute intervals, prompted participants to provide their responses. To aid participants in understanding the scale, the MISC was printed and displayed on the screen frame (see Fig.2). The cabin environment was

standardized with controlled wind speed, temperature, chair positioning, inclination, and audio narration levels across all trials.

The experiment concluded upon reaching the time limit (20 minutes), upon participant request, or if MISC scores exceeded 7 ("Rather Nausea"), a common stopping threshold in previous MS-related studies. Following each ride, participants answered questions regarding the content of the video. In addition, for the experimental conditions where an auditory cue was provided, participants also filled out a questionnaire adopted from Li et al. (2024) to evaluate the auditory cue design (see Table 2). Participants received monetary compensation at a rate of 60 Yuan per hour, with full compensation granted upon completion of all four rides. The experimental protocol was approved by the Human and Artefacts Research Ethics Committee of the Hong Kong University of Science and Technology (HREP-2023-0193).

Table 1. MISC for MS evaluation during the rides

Symptoms		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness, sweating, blurred vision, yawning, burping, tiredness, salivation, . . . but no nausea	Vague	2
	Little	3
	Rather	4
	Severe	5
Nausea	Little	6
	Rather	7
	Severe	8
	Retching	9
Vomiting		10

Table 2. Subjective evaluation of the cue design

Questions	Low-level RB	High-level RB	Overall
Q1: Are the cues easy to notice? Not easy (1) — easy (5)	Mean: 3.75 SD: 1.18	Mean: 3.8 SD: 1.32	Mean: 3.77 SD: 1.23
Q2: Can the cues remind you of accurate motion stimuli? Inaccurate (1) — accurate (5)	Mean: 3.63 SD: 0.89	Mean: 3.73 SD: 1.10	Mean: 3.68 SD: 0.98
Q3: Is the cognitive cost of the cues high? High (1) — low (5)	Mean: 2.63 SD: 1.02	Mean: 2.8 SD: 1.08	Mean: 2.71 SD: 1.04
Q4: Do the cues negatively affect your experience of watching the video? Very much (1) — not at all (5)	Mean: 2.5 SD: 0.82	Mean: 2.13 SD: 0.92	Mean: 2.32 SD: 0.87

2.7 Statistical Analysis

In this study, we used *R* 4.4.1 for a three-step analysis:

Step 1: Since engagement in video-watching tasks can aggravate MS (Kato & Kitazaki, 2006), we first evaluated the association between the two experimental factors and video-watching performance, quantified as the correctness of responses to the video-related questions after the ride, using a two-way repeated measures ANOVA test:

$$\text{lmer}(\text{correctness} \sim \text{cue} + \text{RB} + \text{cue:RB} + 1|\text{participant})$$

Step 2: We then investigated how cue presence and RB levels influenced the development of MS. Given that we cannot estimate participants' MISC scores if they discontinued the rides early, we padded the MISC values for the rest of the rides using their final reported value. This is based on the assumption that once participants reach a MISC score of 7 or higher, their score will not decrease under ongoing motion stimuli, which is a common practice in MS-related research (Irmak et al., 2021; Kuiper et al., 2018; Kuiper et al., 2020).

Due to this padding method, it is unfair to directly compare the MISC scores of participants who stopped early with those who completed the rides. Consequently, following previous research (Kuiper et al., 2018) that adopted a similar early discontinuation strategy, and given our specific interest in factors leading to MS above a threshold, we built three linear mixed-effects models. These models investigated the percentage of participants reporting an MISC score of 2 or higher, 4 or higher, and 6 or higher during a ride. The independent variables in all three models included cue, RB condition, time in a ride, and their two-way interaction:

$$lm(percentage \sim cue + RB + time + cue{:}RB + time{:}cue + time{:}RB)$$

In these models, and all subsequent analyses, the time in a ride was treated as a continuous variable, ranging from 1 minute to 20 minutes with a step of 1 minute. The cue (i.e., cue absence versus cue presence) and RB levels (i.e., low-level versus high-level) were treated as categorical variables.

Step 3: Finally, given that the auditory cue is in addition to video playing, we evaluated participants' subjective evaluations of the auditory cue design in different RB conditions, using a Wilcoxon rank sum test (WRST), given that the data did not match the normality distribution assumption of paired t-test.

In the first step of our analysis, we conducted a repeated measures ANOVA (Childs et al., 2021), using the "lmerTest" package in R (Kuznetsova et al., 2020). For the linear regression models in step 2, we utilized the "lm" package (Marc, 2015). The "emmeans" package in *R* was used for post hoc pairwise comparisons (Lenth et al.,

2024) of significant ($p < .05$) main or interaction effects, with the "Tukey" method used for p-value correction.

3. Results

3.1 Performance on Video-Watching Tasks

As shown in Table 3, the two-way ANOVA results showed no significant differences across experimental conditions ($p > .05$), suggesting that no bias was introduced by the variations in task engagement.

Table 3. Accuracy of participants' responses to video-related questionnaires

		RB Level	
		Low	High
Availability of cue	Presence	Correctness: 84.4% SD: 20.2%	Correctness: 83.7% SD: 18.8%
	Absence	Correctness: 74.5% SD: 30.6%	Correctness: 71.9% SD: 28.6%

3.2 Early Discontinuation of Rides

In total, 5 out of 16 participants discontinued at least one ride, and 8 out of 64 rides were discontinued, either by participants or by the experimenter due to high MISC scores (i.e., >7). Specifically, one participant stopped the ride under the cue absence condition with high RB at the 11th minute (MISC of 8) and with low RB at the 16th minute (MISC of 8). This participant also discontinued when RB was high and cues were present, at the 14th minute (MISC of 9). Another participant stopped rides with high RB both with cue presence (at the 16th minute, MISC of 8) and cue absence (at the 15th minute, MISC of 8). Additionally, two participants discontinued rides when RB was high and cues were absent, at the 18th and 13th minutes, both

with an MISC of 8. Lastly, one participant stopped at the 19th minute when RB was high and cues were present, with a MISC of 7. Figure 7 provides a visual representation of early discontinuation rates across different experimental conditions.

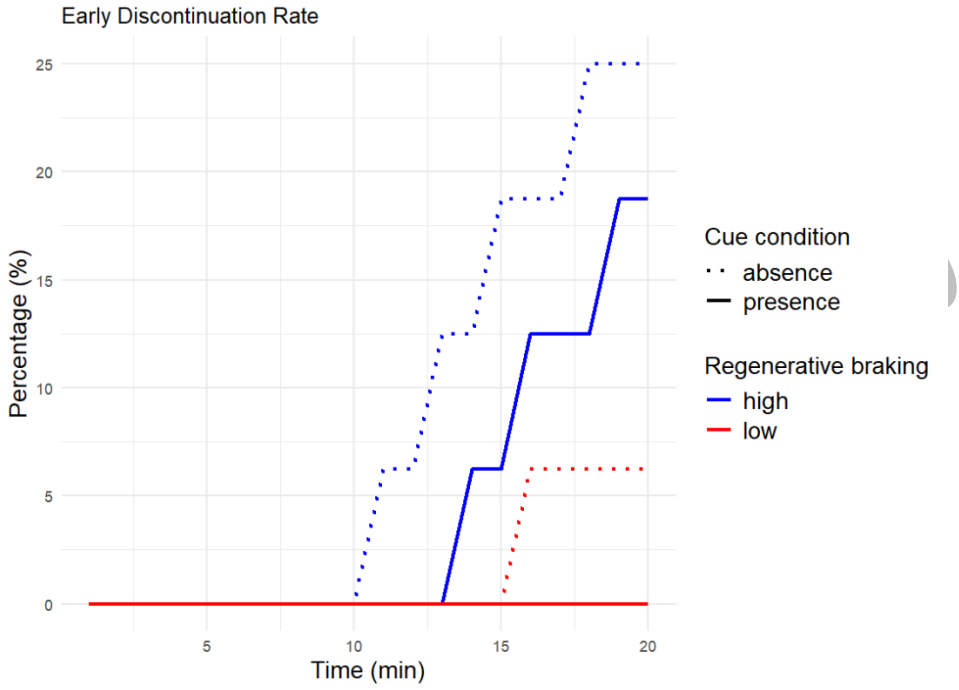
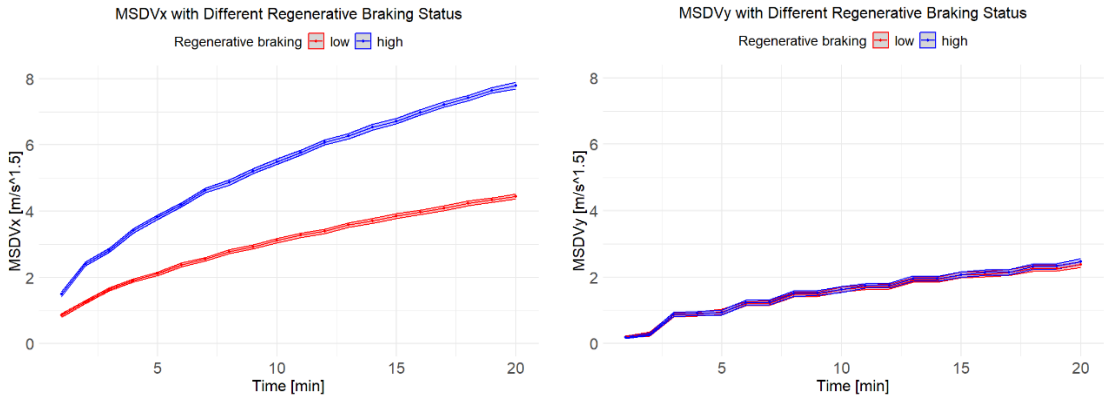


Figure 7. Early discontinuation rate (out of 16 participants) over time across experimental conditions.

3.3 Motion Profiles

The MSDVs for the horizontal (Yunus et al., 2021) and vertical (ISO2631-1, 1997) axes were calculated and are displayed in Fig.8. It can be observed that the MSDVx (longitudinal) during high-level RB was higher than that during low-level RB, while the MSDVz (vertical) and MSDVy (lateral) were similar across RB levels. This result aligns with our expectations, as the level of RB primarily impacts the acceleration in the longitudinal direction.



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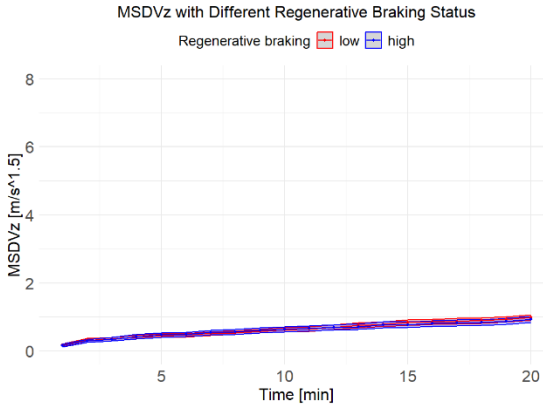


(c)

Figure 8. The MSDVs in longitudinal (a), lateral (b), and vertical (c) axes.

3.4 Subjective Motion Sickness

Figure 9 shows the average MISC of all trials across experimental conditions. Additionally, Figure 10 shows the proportion of participants who reached a certain threshold of MISC at the time of measurement.

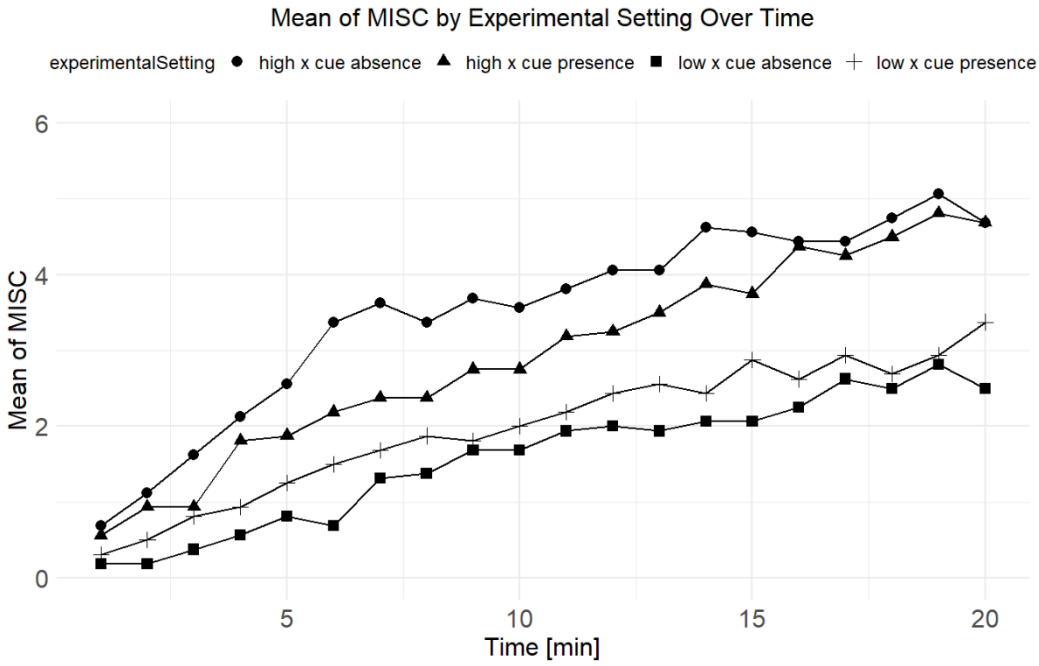
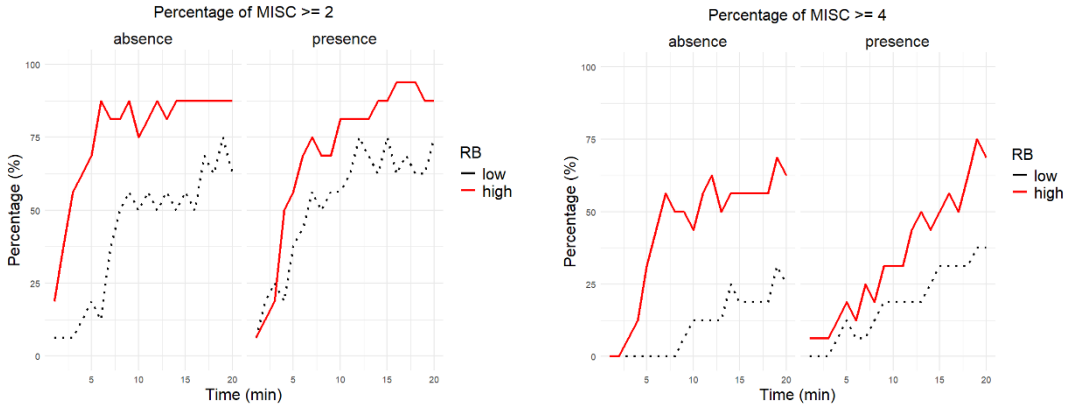
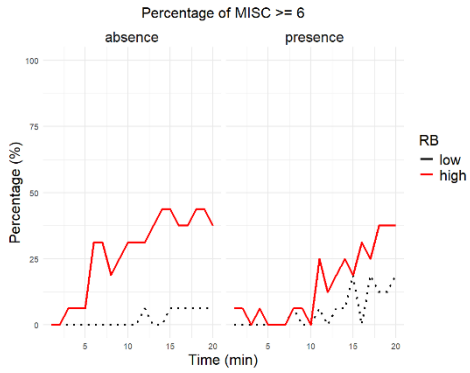


Figure 9. Mean MISC scores across different experimental conditions for all trials. For trials that were discontinued early, the last MISC score was carried forward to the end of the trial, based on the assumption that the MISC score would not decrease if the trial had continued.



(a) (b)



(c)

Figure 10. Percentage of participants reaching specific MISC thresholds as rides progressed.

Table 4 summarizes the findings from three linear mixed models with MISC thresholds of 2 (Model 1), 4 (Model 2), and 6 (Model 3). These models explored the impact of the auditory cue, RB level, time, and their interactions on the proportion of participants reporting MISC scores at or above certain thresholds. Post-hoc analyses were performed on significant independent variables identified in the models.

Table 4. Model results of M1, M2, and M3 models

Variables	M1: Percentage (MISC ⩾ 2)		M2: Percentage (MISC ⩾ 4)		M3: Percentage (MISC ⩾ 6)	
	F-value	*P*	F-value	*p*	F-value	*p*
Cue	F(1,73) = 0.47	.5	F(1,73) = 0.58	.5	F(1,73) = 0.42	.5
RB	F(1,73) = 29.87	**<.0001***	F(1,73) = 24.67	**<.0001***	F(1,73) = 9.73	**.003***
Time	F(1,73) = 52.94	**<.0001***	F(1,73) = 49.69	**<.0001***	F(1,73) = 10.20	**.002***
RB *Cue	F(1,73) = 9.50	**.003***	F(1,73) = 28.48	**<.0001***	F(1,73) = 37.11	**<.0001***
RB *Time	F(1,73) = 0.02	.9	F(1,73) = 32.04	**<.0001***	F(1,73) = 48.65	**<.0001***
Cue *Time	F(1,73) = 1.30	.3	F(1,73) = 3.04	.09	F(1,73) = 0.30	.6

Note: in this table and the following tables, * marks significant ($p < .05$) results.

3.4.1 M1 Model with MISC Threshold of 2

For M1, two significant independent variables were identified: time and the interaction effect between RB and cue. Specifically, with each 1-minute increase, the percentage of passengers reaching the MISC of 2 increases by 3.0%, with a 95% confidence interval (95%CI) of [2.2%, 3.8%]. Regarding the interaction effect between cue and RB conditions (see Fig.11), it was observed that, compared to low-level RB, high-level RB resulted in a significantly higher percentage of passengers experiencing low-level MS or above (MISC ≥ 2), but to different extents when the auditory cue was present (difference (Δ) = 16.9%, 95%CI: [6.7%, 27.1%], t(73) = 4.36, p = .0002) or absent (Δ = 33.8%, 95%CI: [23.6%, 43.9%], t(73) = 8.72, p < .0001).

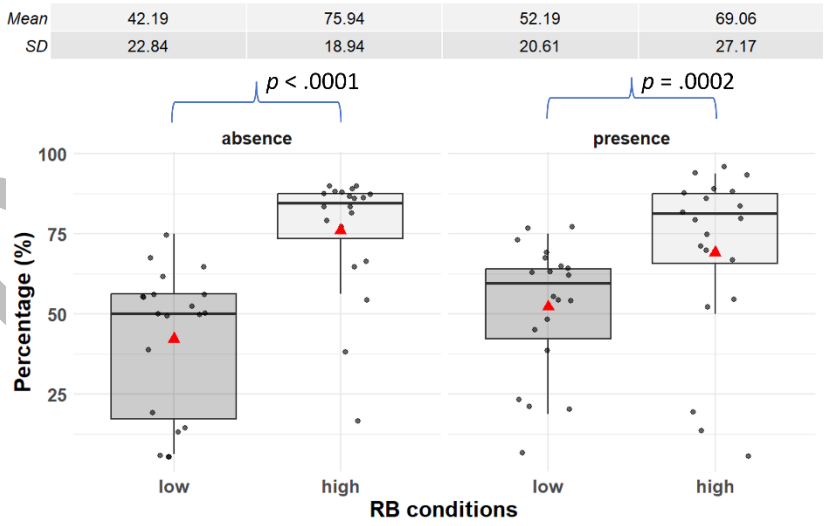
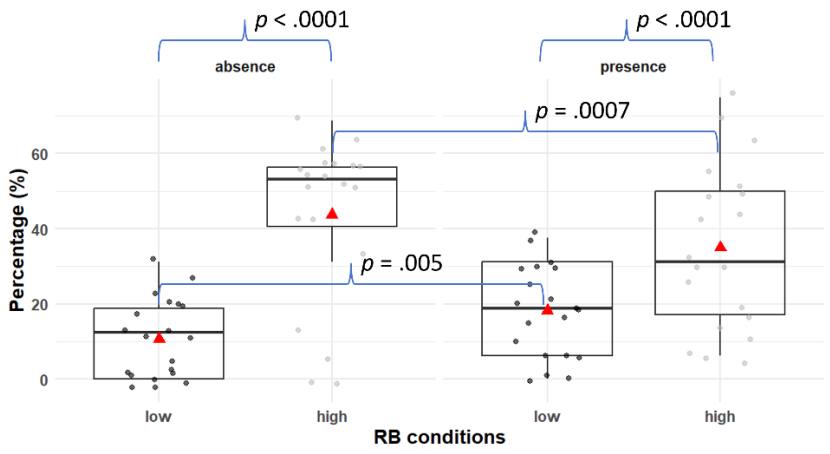


Figure 11. Interaction effects between cue and RB conditions in the M1 model

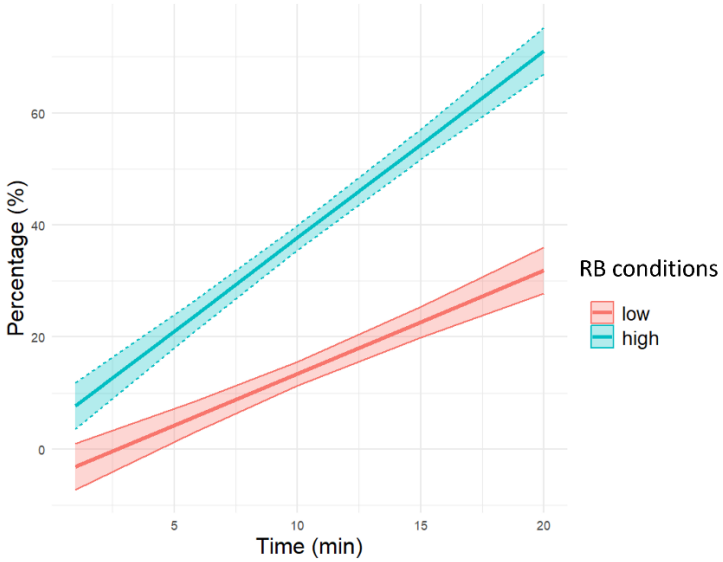
3.4.2 M2 Model with MISC Threshold of 4

For M2, two significant interaction effects were identified: the interaction between cue and RB conditions and the interaction between time and RB conditions. Specifically, as shown in Fig. 12a, for the interaction between cue and RB conditions, a significantly higher percentage of passengers experienced medium-level MS or above (MISC ≥ 4) in high-level RB conditions compared to low-level RB conditions, regardless of the presence (Δ = 16.9%, 95%CI: [11.2%, 22.5%], t(73) = 7.84, p < .0001) or absence (Δ = 33.1%, 95%CI: [27.5%, 38.8%], t(73) = 15.4, p < .0001) of the auditory cue. At the same time, in the high-level RB condition, providing auditory cues resulted in a lower percentage of passengers experiencing medium-level MS or above (Δ = -8.8%, 95%CI: [-14.4%, -3.1%], t(73) = -4.06, p = .0007). However, in the low-level RB condition, providing auditory cues increased the percentage of passengers experiencing medium-level MS or above (Δ = 7.5%, 95%CI: [1.8%, 13.2%], t(73) = 3.48, p = .005).

Mean	10.62	43.75	18.12	35
SD	10.36	21.65	12.48	21.69



(a)



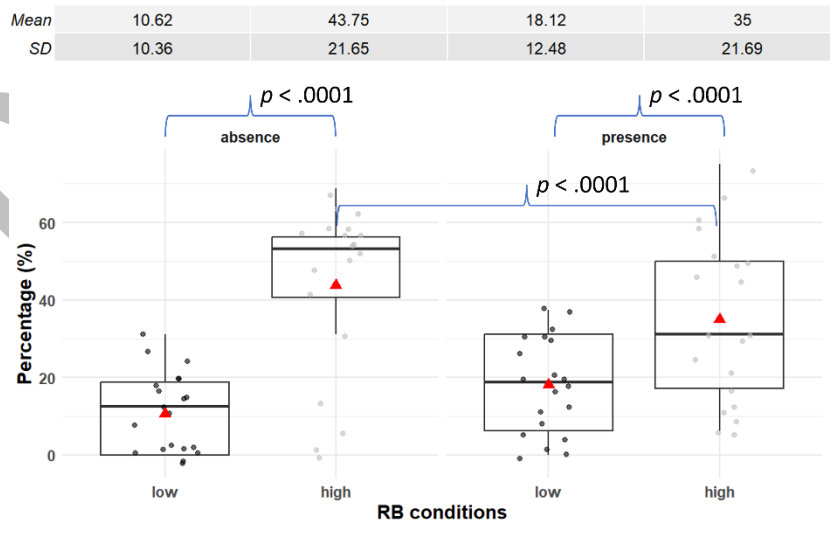
(b)

Figure 12. Interaction effects between cue and RB conditions (a), and between time and RB conditions (b) in the M2 model

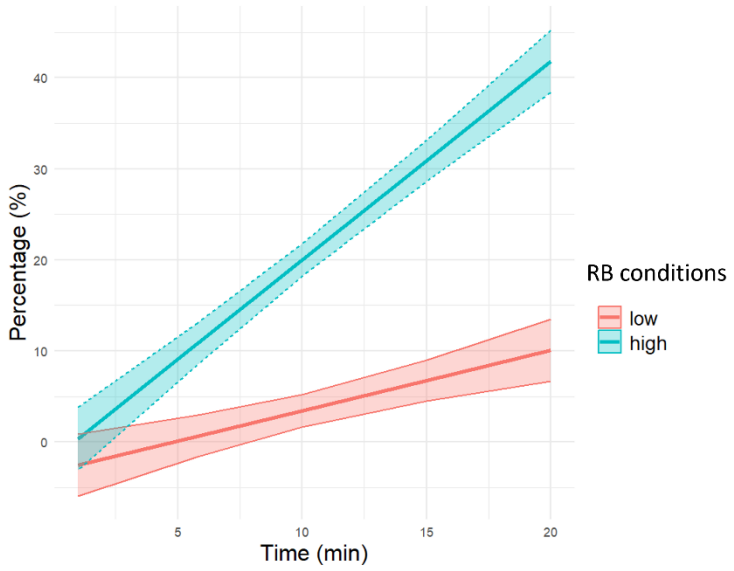
For the interactions between RB and time (see Fig.12b), we observed that with each minute increase in time, the low-level RB condition resulted in a 1.5% lower percentage of passengers experiencing medium-level MS or above compared to the high-level RB condition (95%CI: [-2.0%, -1.0%], t(73) = -5.66, p < .0001). Specifically, within the low-level RB scenario, for every minute added, there was a 1.8% increase in the proportion of passengers experiencing medium-level MS or higher, with a 95% CI of [1.5%, 2.2%]. In the high-level RB scenario, each additional minute led to a 3.3% rise in the percentage of passengers experiencing medium-level MS or above, with a 95% CI of [3.0%, 3.7%].

3.4.3 M3 Model with MISC Threshold of 6

Similar to M2, significant interactions between cue and RB conditions, and between RB conditions and time, were observed in M3. Specifically, high-level RB condition was associated with a higher percentage of passengers experiencing high-level MS or above (MISC $\geqslant$ 6) than low-level RB condition (see Fig.13a), but to different extents when the auditory cue was present (Δ = 9.7%, 95% CI: [5.0%, 14.4%], t(73) = 5.45, $p < .0001$) or absence (Δ = 25%, 95% CI: [20.3%, 29.7%], t(73) = 14.07, $p < .0001$). Furthermore, in high-level RB conditions, providing an auditory cue significantly decreased the percentage of passengers experiencing high-level MS or above compared to not providing the cue (Δ = -12.2%, 95% CI: [-16.9%, -7.5%], t(73) = -6.86, $p < .0001$).



(a)



(b)

Figure 13. Interaction effects between cue and RB conditions (a), and between time and RB conditions (b) in the M3 model

Similar to M2, for the interaction between RB and time (see Fig. 13b), we observed that with each 1-minute increase in time, the low-level RB condition resulted in a 1.5% lower percentage of passengers experiencing high-level MS or above compared to the high-level RB condition (95% CI: [-2.0%, -1.1%], t(73) = -6.98, $p < .0001$). Specifically, within the low-level RB scenario, for every minute added, there was a 0.6% increase in the proportion of passengers experiencing high-level MS or higher, with a 95% CI of [0.4%, 1.0%]. In the high-level RB scenario, each additional minute led to a 2.2% rise in the percentage of passengers experiencing high-level MS or above, with a 95% CI of [1.9%, 2.5%].

3.4.4 Subjective evaluation of cues design

As shown in Table 2, overall, the auditory cues provided satisfactory accuracy regarding the current motion information of the vehicle. However, we also recognized that our auditory cue negatively impacted participants' video-watching experience to some extent. Further, WRST results indicate that no significant differences in subjective evaluations were observed across two RB conditions ($p > .05$), suggesting that the participants' evaluation of the auditory cue was not influenced by RB levels.

4. Discussion

In this study, we conducted an on-road experiment to investigate the effect of the regenerative braking (RB) system of electric vehicles (EVs) on motion sickness (MS) (RQ1) and validate the effectiveness of MS mitigation through auditory motion cues (RQ2). Using a predefined route and motion stimuli (see Fig.4 and 5), we effectively controlled the motion stimuli in the vertical and lateral axes, with the longitudinal axis motion stimuli being moderated by RB levels (see Fig.8).

First, despite widespread online complaints about more severe MS caused by RB (Korn, 2024), our study confirmed the influence of RB in EVs. Specifically, statistical analysis showed that a high level of RB could result in a higher percentage of passengers experiencing all levels of MS (as quantified by MISC scores of 2, 4, and 6), both with and without auditory motion cues. The post hoc analysis of the significant interaction between time and RB further confirmed that high-level RB can result in more severe MS compared to low-level RB with the progress of time. The

higher MSDVx of high-level RB compared to low-level MSDVx may explain this result, given that previous research has found a larger MSDV (Turner & Griffin, 1999) and higher acceleration amplitude (Irmak et al., 2021) can result in severe MS.

The decreased predictability of the vehicle motion may also explain the relationship between RB and MS development. In our instrumented vehicle, the RB system activates as soon as the driver releases the accelerator pedal (Yiwei 3, JAC (2024); Aion Y, GAC (2024)), leading to unexpected vehicle deceleration. While passengers can predict the driver's intentional braking actions based on road conditions, they may hardly anticipate unexpected RB-generated decelerations. Previous research has suggested that drivers are less likely to experience MS compared to passengers (Rolnick & Lubow, 1991) potentially because they are less capable of anticipating vehicle motion. Therefore, the unexpected RB-generated deceleration may have exaggerated the MS. It would be advisable to make RB activation perceivable (e.g., only engage RB when drivers intentionally press the brake pedal).

Our results have supported the role of perceiving vehicle acceleration in alleviating RB-related MS. Specifically, in line with a few studies that have focused on providing visual motion cues representing the current state of the vehicle (Li et al., 2024; Meschtscherjakov et al., 2019), our auditory cues were effective in mitigating medium (MISC$\geqslant$4) to high (MISC$\geqslant$6) levels of MS, especially when the high level of RB was adopted. This effectiveness might be explained from two perspectives.

First, as there can be a temporal lag between the vehicle's motion dynamics and the passengers' actual body movement (Li et al., 2024), the designed real-time auditory cues can enhance passengers' awareness of upcoming motion stimuli, similar to the role of anticipatory motion cues provided in previous studies (Maculewicz et al., 2021; Reuten et al., 2023). Second, the auditory cues can enhance passengers' perception of the vehicle's motion sensed by the vestibular organs, allowing them to be mentally and physically better prepared for vehicle motions.

This enhanced perception of vehicle motion may explain the increased medium to high levels of MS when auditory cues were provided for low-level RB. Specifically, without the auditory motion cues, passengers might have been occupied by the video-watching task and may not notice the minor acceleration (Bos, 2015). In contrast, with the auditory motion cues, users might be more aware of the vehicle motion, which can exaggerate the visual-vestibular conflict and elevate MS. However, the alleviation effect of the motion cues may shadow the conflict caused by the cues with the high-level RB, given that even without cues, the drivers can still perceive the strong deceleration generated by the RB. Thus, adaptive motion cues may need to be provided, based on the vehicle setup and passengers' states.

5. Limitations

In this study, we primarily focused on individuals who are highly susceptible to MS (MSSQ score > 50th percentile), as they are more likely to experience MS and may benefit the most from MS mitigation strategies in vehicles. Future research

should consider a more diverse population to validate our findings. To better control the motion stimuli, we selected a closed road section, where acceleration and deceleration were strictly managed by the cruise control and regenerative functions. However, future studies could explore a broader range of motion profiles, including lane changing and thus lateral acceleration, and validate the results in naturalistic driving scenarios on open roads, with a larger sample size. Our auditory cues were designed to signal longitudinal deceleration caused by regenerative braking and longitudinal acceleration triggered by cruise control. Future work may expand the auditory cues to include different semantic information, covering a broader range of driving behaviors such as turning and lane changing. Next, due to equipment constraints, we were not able to fully deactivate the RB in the experiment and our results cannot compare the rides with and without RB. Although, to the best of our knowledge, the RBs in most EVs cannot be fully turned off, future research may still further reveal the role of RB in MS induction by fully deactivating the RB. Finally, our study focused solely on video-watching tasks. The effectiveness of auditory cues could be further validated with other types of in-vehicle tasks, such as reading and writing, or even when no tasks were provided.

6. Conclusion

In this study, we investigated the effect of RB in EVs on MS development and the effectiveness of mitigating MS through auditory motion cues. Our findings are as follows:

- High-level RB resulted in a higher percentage of passengers experiencing MS compared to low-level RB, suggesting that EVs can benefit from optimizing the RB system to alleviate passengers' MS.
- Auditory motion cues significantly mitigated MS only during dramatic deceleration/acceleration (i.e., high-level RB), but were less effective during smooth deceleration/acceleration (i.e., low-level RB), suggesting the need to design adaptive MS mitigation strategies.
- The auditory cue can be easily understood, with high acceptance, and requires no additional hardware in the cabin. However, the auditory cues can interfere with in-vehicle tasks (e.g., watching videos). Future research can further compare the effectiveness of auditory cues versus visual cues in mitigating MS in vehicles and optimize the auditory cues, for example, by integrating them with the audio channels in the video.

Declaration of Competing Interest

The authors acknowledge that they have no conflicts of interest in this work.

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