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Cross-modal feedback of tactile and auditory stimuli for cyclists in noisy environments

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ABSTRACT

In recent years, with the increasing use of bicycles for environmental and health benefits, the importance of the feedback for cyclists is increasing. Moreover, as bicycles account for 23 % of all traffic accidents in 2022, improving bicycle safety is a crucial challenge. This study aimed to explore methods for enhancing safety and improving feedback to cyclists through auditory and tactile signals. Experiments were conducted using a cycling simulator and cross-modal reaction tests of tactile and auditory signals to simulate bicycle riding under actual external noise environments. The accuracy of the recognition and reaction times for both tactile and auditory signals were evaluated in situations with simulated road traffic sounds. Subsequently, the effectiveness of cross-modal feedback was assessed, optimal signal conditions were examined, and the relationship between variations in environmental noise and optimal auditory signals for cyclists was discussed. The results showed that cross-modal feedback led to faster reaction times, while the recognition accuracy of auditory signals varied depending on environmental noise levels. The present findings suggest the potential of cross-modal feedback to enhance cyclist safety, particularly when optimized for environmental conditions and individual perception.

1. Introduction

In recent years, driven by growing awareness of environmental benefits and health promotion, there has been a significant increase in the number of cyclists [1]. While there has been a downward trend in bicycle accidents, they still constitute a substantial proportion of traffic incidents, accounting for 23.3 % of total traffic accidents in Japan in 2022 [2]. This statistic underscores the critical importance of enhancing cyclist safety through improved feedback systems.

Recent advancements in sensor technology have significantly expanded the capabilities of real-time monitoring and environmental sensing. Optical fiber sensors, known for their high sensitivity and immunity to electromagnetic interference, are widely used to detect physical and chemical parameters such as refractive index and pH levels, with applications ranging from biomedical diagnostics to industrial monitoring [3]. Additionally, the use of advanced materials like laser-induced graphene (LIG) and localized surface plasmon resonance (LSPR) sensors has further enhanced sensitivity and specificity. LIG-based sensors offer improved electrochemical responses, while LSPR sensors excel in detecting nanoscale environmental changes [4,5]. These innovations enable multiparameter monitoring, paving the way for more sophisticated sensing systems.

Extensive research has been conducted on feedback systems for automobile drivers, including tactile signals from waist-worn belts [6], visual feedback from heads-up displays [7], and collision warning sounds [8]. However, while the use of feedback systems is on the rise, there is still not enough research into feedback systems designed specifically for cyclists.

Traditional navigation systems for cyclists primarily rely on auditory instructions or visual information displayed on maps. However, these methods have notable limitations. Turn-by-turn audio instructions can be overly lengthy, potentially causing distractions and requiring increased concentration to comprehend [9]. Moreover, the need for unobstructed auditory instructions and the necessity to shift attention from visual information such as maps to current traffic conditions can increase the risk of accidents [10].

Despite these challenges, researchers have explored various approaches to enhance cyclist safety and navigation. Recent studies have investigated different methods of providing feedback to cyclists, including vibrating devices worn on the waist [11] or attached to the handlebars [12], as well as displays projected onto the road surface [13]. Among these approaches, helmet-based feedback systems have gained

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particular attention because of the widespread use and legal requirement of helmets for cyclists in many countries, including Japan.

Helmet-based feedback systems have been developed for various purposes. Some incorporate warning systems with bone-conduction speakers [14], while others feature haptic feedback via helmet-mounted vibration devices and [15] turn indicators to alert riders behind [16]. Researchers have also explored navigation methods using the movement of helmet-mounted lights [17]. These studies demonstrate the potential of helmets as a versatile platform for delivering feedback to cyclists.

While these individual approaches show promise, there is a notable gap in research integrating multiple sensory modalities into helmet-based feedback systems. Cross-modal feedback, which combines different sensory inputs, has shown significant benefits in other contexts. For instance, in automotive applications, cross-modal feedback has led to increased driver awareness [18], improved navigation [19], and enhanced warning signals [20]. Studies have also demonstrated increased accuracy and reaction times among child cyclists using multi-sensory feedback [21].

Furthermore, research has shown that cross-modal feedback utilizing multiple senses can result in faster reaction times [20] and improved accuracy [22]. In the context of automobile drivers, combining vibration and sound in warnings has been found to shorten reaction times and improve accuracy [23]. However, this approach has not yet been extensively applied to cyclists.

The success of cross-modal feedback in related fields and the potential of helmet-based systems indicate there is a clear opportunity to explore the integration of tactile and auditory stimuli in cyclist helmets. This approach could potentially improve recognition accuracy and reaction speeds for cyclists, thereby enhancing overall safety.

Given this background, the present study aimed to investigate appropriate presentation signals for cross-modal feedback that can improve the recognition accuracy and reaction speed of cyclists. We propose a novel device integrated into bicycle helmets that provides tactile vibration and auditory stimuli during cycling. The primary goal of this study was to enhance safety for cyclists through the implementation of this innovative cross-modal feedback system.

The ultimate goal of this research is to clarify how a system combining tactile and auditory feedback influences cyclists' reaction speed and recognition accuracy, and to propose a new approach to enhancing safety based on these findings. by addressing the gap in current research and leveraging the potential of multi-sensory feedback, this study seeks to contribute to the development of more effective safety measures for cyclists. The integration of tactile and auditory stimuli in a helmet-based system offers a promising avenue for improving cyclist awareness, navigation, and overall safety in increasingly complex urban environments.

2. Methods

2.1. Experimental setup

The actual experiment is shown in Fig. 1(a), and a schematic of the location of each experimental setup is shown in Fig. 1(b). A city bicycle (A6SC11; Bridgestone, Tokyo, Japan) was used. To replicate a virtual cycling environment in the laboratory, the Blync (Kinbona Limited, Kitchener, Canada) system was used. Blync consists of a path sensor and a speed sensor attached to the wheels. Additionally, to replicate road traffic sound, speakers (HS8; Yamaha, Shizuoka, Japan) were placed beside the bicycle. The participants conducted the experiment in the simulated auditory environment. The details of the environmental noise emitted by these speakers are described in the next section. The path sensor, installed under the front wheel, measures the direction of the bicycle's rotation, while the speed sensor, attached to the hub of the rear wheel, measures the rotation speed, which is reflected in the virtual space, as shown in Fig. 1(c). To simulate actual riding conditions, a

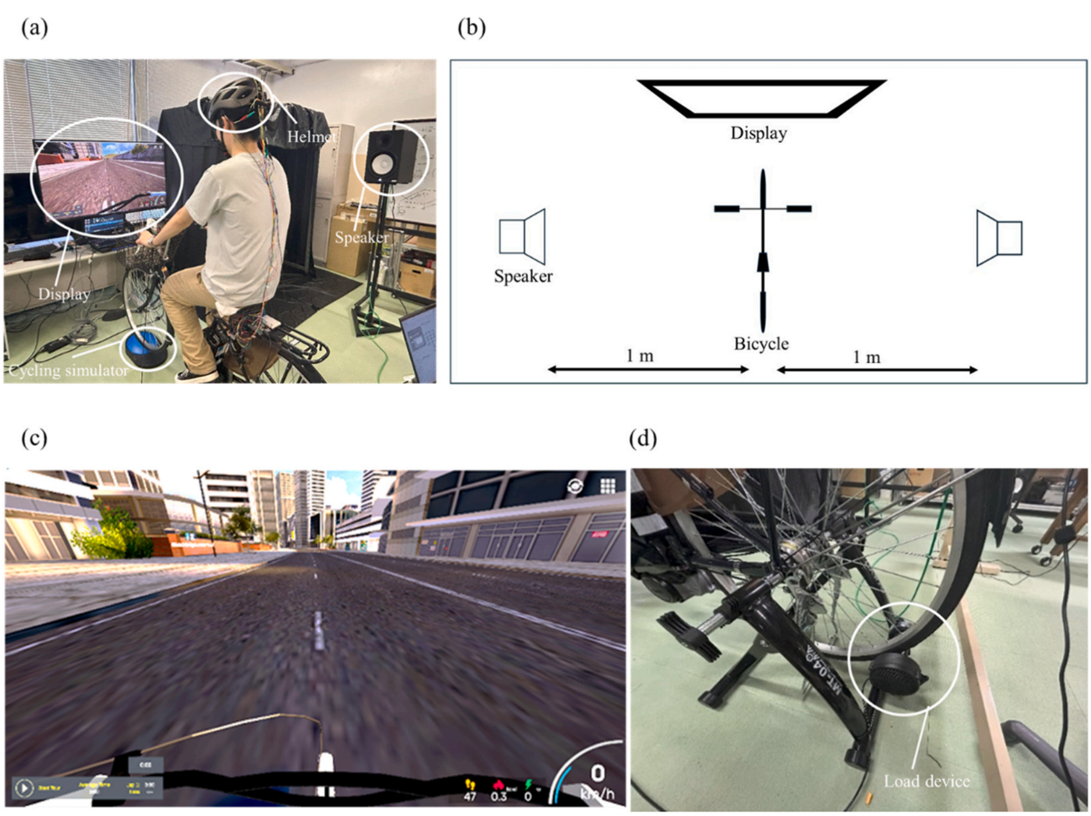

Fig. 1. Experimental situation and device. (a) Actual situation, (b) position of the bicycle and speakers, (c) cycling view in the cycling simulator, and (d) rear wheel load device.

stationary roller stand (B087B04LXK; CXWXC, Qiushi, China) was attached to the rear wheel, allowing for load application through friction, as shown in Fig. 1(d).

By using the abovementioned setup, the response speed of the participants to acoustic and vibrational alert stimuli given through vibrators and headphones while riding a bicycle was measured. To present tactile and auditory signals simultaneously and measure reaction times, LabVIEW (National Instruments, Austin, TX, USA) was used. LabVIEW is an integrated development environment for measurement, control, data acquisition, and analysis. It features a graphical programming environment that allows intuitive and visual representation of control algorithms and logic using block diagrams, thereby facilitating the construction of complex control systems. Next, a system was built to measure the reaction time from the presentation of the vibration and auditory alert signals to the pressing of a button using LabVIEW and a microcontroller board (Arduino Uno; Arduino, Turin, Italy), which controlled the vibration actuators, allowing for real-time adjustments to the vibration direction and signal duration through the program designed in LabVIEW. A button was installed on the handlebar, connected to the Arduino Uno, to measure the reaction time from signal presentation to button press (Fig. 2). Simultaneously, sound generation and output were managed through LabVIEW.

2.2. Simulated environmental noise

In this experiment, road traffic sound and white noise were presented from two speakers. Road traffic sounds were recorded as binaural audio data on sidewalks adjacent to two roads. The binaural audio data were recorded using an earphone-type binaural microphone, and equivalent A-weighted sound pressure level (L_{Aeq}) was measured using a standard sound level meter.

One recording was made on National Route 1, which has heavy traffic with cars continuously passing by. The L_{Aeq} was 76.5 dB, so for this experiment, it was calibrated to 75 dB for presentation. The other recording was made on a road with less traffic, where the L_{Aeq} was 58.3 dB, so it was calibrated to 60 dB for presentation. The L_{Aeq} in the laboratory was measured and set using a standard sound level meter at the head position of a person riding a bicycle.

In Experiment I, road traffic sound at an L_{Aeq} of 75 dB was presented. In Experiment II, to examine the influence of environmental sound pressure levels and types of environmental noise, white noise was added and sound pressure was varied at two levels. Road traffic sound at an L_{Aeq} of 60 dB, white noise at an L_{Aeq} of 60 dB, and white noise at an L_{Aeq} of 75 dB were presented.

2.3. Alert signal with vibration and sound

2.3.1. Tactile signal

The vibrators used in this study were linear resonance actuators (LRAs) (VLV152564W; Vybronics, Brooklyn, New York, USA). These LRAs have a resonant frequency of 80 Hz, and previous research [24] has indicated that vibrations above 150 Hz are perceived as unpleasant. Therefore, the tactile stimuli in this experiment were presented at a resonant frequency of 80 Hz. Vibration actuators were attached to the helmet, forehead, temples on both sides, and the back of the head, as shown in Fig. 3.

Fig. 2. Button on the handlebar to measure time.

2.3.2. Auditory signal

Auditory signals were delivered using open-ear earphone-type speakers (MWE001; NTT Sonority, Tokyo, Japan). Using in-ear earphones or headphones that block out environmental noise can increase danger by preventing cyclists from hearing surrounding traffic sounds. Therefore, in this experiment, open-ear earphone-type speakers were used. The auditory signals were pure tones at frequencies of 500, 1000, and 2000 Hz, with a signal-to-noise ratio (SNR) of –10 dB relative to the road traffic sound.

Therefore, as shown in Table 1, when the environmental noise in Experiment I was road traffic sounds with an L_{Aeq} of 75 dB, the sound pressure level of the auditory signal was 65 dB; when the environmental noise was road traffic sounds with an L_{Aeq} of 60 dB, as in Experiment II, the auditory signal was 50 dB; with white noise with an L_{Aeq} of 75 dB, the auditory signal was 65 dB; and with white noise with an L_{Aeq} of 60 dB, the auditory signal was 50 dB. Here, to clarify the sound pressure level, the auditory signal was measured using a dummy head.

2.4. Experimental design

In Experiment I, the participants performed the experiment under road traffic sound conditions with an L_{Aeq} of 75 dB. The experiment varied the frequency component of the signal, vibration direction, and signal duration of the auditory signals, as shown in Table 2. Each participant was presented with 32 patterns, comprising two signal durations (0.5 s, 1.0 s), four vibration directions (front, back, left, right), and four auditory signal conditions (500 Hz, 1000 Hz, 2000 Hz, and none), repeated three times, resulting in a total of 96 presentations. Vibration direction accuracy, reaction time, and sound accuracy were measured for each condition.

Regarding the vibration direction accuracy, the participants were asked to indicate which of the four directions they vibrated in when the signal was presented. Reaction time was measured from the time the signal was presented to the time the participants pressed the button on the handlebar. For the sound response rate, participants were asked to choose between hearing and not hearing the auditory signal when it was presented. The participants were instructed to ride in the leftmost of the four available lanes on the simulator to adhere to actual traffic regulations (Fig. 4), with a cycling speed of 14–16 km/h. As shown in Fig. 5(a), the duration of the experiment was three sets of 30 min each, with a 5-minute break between each set.

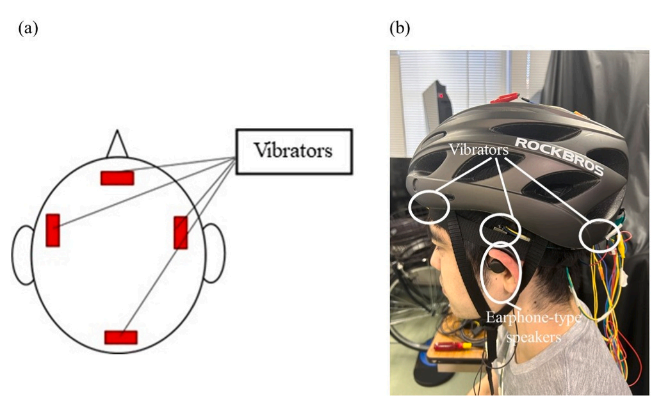

Fig. 3. Position of the vibrators. (a) Schematic view from above and (b) actual situation.

Table 1
Experimental conditions of the sound pressure level for each of the auditory alert signals.

Experiment	Environmental noise	Auditory signal
I	Road traffic sounds (75 dB)	65 dB
II	Road traffic sounds (60 dB)	50 dB
	White noise (75 dB)	65 dB
	White noise (60 dB)	50 dB

Table 2
Relationship among the frequency components, direction, and duration of the alert signals in each of the experiments.

Experiment	I	II
Environmental noise	Road traffic sounds (75 dB)	Road traffic sounds (60 dB), White noise (75 dB), White noise (60 dB)
Frequencies of auditory signal (Hz)	N/A, 500, 1000, 2000	N/A, 500, 1000, 2000
Direction of tactile signal	Front, right, left, back	Front, right, left, back
Signal duration (s)	0.5, 1.0	1.0

Fig. 4. Leftmost lane in the cycling view.

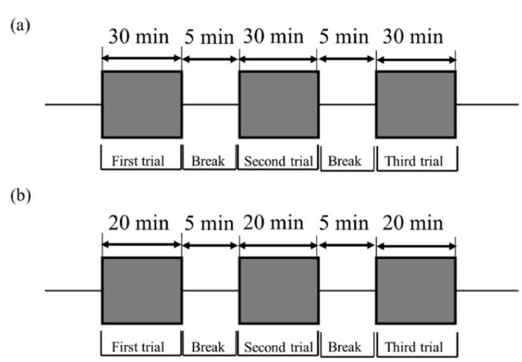

Fig. 5. Flowchart of (a) Experiment I and (b) Experiment II.

Experiment II investigated the perception of this signal under different noise conditions (road traffic sounds at an L_{Aeq} of 60 dB, white noise at an L_{Aeq} of 60 dB, and white noise at an L_{Aeq} of 75 dB). As a shown in Table 2, the signal duration was 1.0 s. Each participant was presented with 48 patterns, combining the three types of noise, four vibration directions, and four auditory signal conditions (500 Hz, 1000 Hz, 2000 Hz, and none), repeated three times, resulting in a total of 96 presentations.

Reaction time and sound accuracy were measured. As shown in Fig. 5 (b), the duration of the experiment was three sets of 20 min each, with a 5-minute break between each set.

2.5. Participants

In total, 14 participants (14 males, mean age ± standard deviation [SD]: 23.4 ± 1.0 years) participated in Experiment I, and 10 participants (10 males, mean age ± SD: 23.4 ± 0.6 years) participated in Experiment II. Because fatigue has been shown to slow reaction time [25] and males have been found less likely to experience fatigue than females, [26] to minimize the effects of fatigue, all participants in these experiments were male. The number of participants was determined with reference to a previous experiment [27] in which an equivalent number of participants was used to examine the relationship between subjective impressions of sound and their effects on neurologic behavior. All participants were recruited by an e-mail sent to students at the author's institution. In accordance with EN 50332–1 and −2 proposed by the European Committee for Electrotechnical Standardization [28,29] as sound pressure regulations for portable audio players and the ethical guidelines of the Tokyo University of Science, this experimental study was designed to be noninvasive. Informed consent for the experiment was obtained from all participants after being briefed on the purpose of the study and experimental methods, as well as on the anonymization and use of data. Prior to the study, all participants were asked about their hearing ability, which was tested using the hearWHO hearing test app [30], and assured that all of their ears were normal (all participants had a score > 75, indicating good hearing).

2.6. Statistical analysis

A multi-way analysis of variance (ANOVA) was conducted to examine the main and interaction effects of each factor on the participants' responses. Specifically, acoustic factors included auditory signal frequency (500 Hz, 1000 Hz, 2000 Hz), vibration direction (front, rear, left, right), road traffic sound condition (road traffic sounds at 60 dB, white noise at 60 dB, white noise at 75 dB) and signal duration (0.5 s, 1.0 s).

In Experiment I, the presence or absence of auditory signals was used as a factor in Student's *t*-test, and a three-way ANOVA was performed on the factors of auditory signal frequency, vibration direction, and signal duration of the auditory signal. In Experiment II, a two-way ANOVA was conducted with the frequency of the auditory signal and the direction of vibration as factors for each noise condition. In addition, the presence or absence of auditory signals was used as a factor in Student's *t*-test for each noise condition.

The ANOVA was performed using JMP (SAS Institute Inc., Cary, NC, USA). Following the ANOVA, to investigate pairwise differences between different levels of each acoustic factor, multiple comparisons were carried out using Tukey's method and Student's *t*-test. This approach helps identify specific conditions that significantly differ from each other in terms of reaction times and accuracy in perceiving auditory and tactile signals. For all statistical tests, a significance level of $p < 0.05$ was adopted.

The parameters of Cohen's d were calculated to estimate effective sizes [31], where the threshold of the extent of effectiveness was defined as follows: $0.2 < d < 0.5$: small, $0.5 < d < 0.8$: medium, and $0.8 < d < 1.0$: large.

3. Results

3.1. Experiment I

The results of the vibration direction accuracy are shown in Fig. 6. The figure demonstrates a 100 % accuracy rate in determining vibration direction for all four directions, indicating that tactile signals for cyclists under road traffic sound conditions did not significantly impact tactile perception and could be adequately recognized. Moreover, the direction of vibration was distinguishable without difficulty. However, because the experiment was conducted in an ideal laboratory environment,

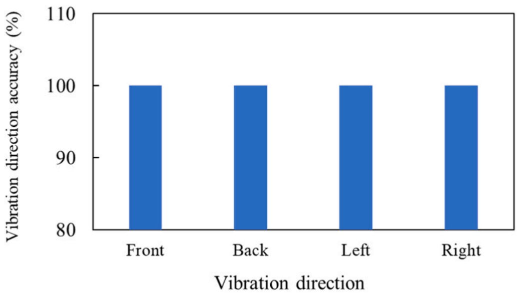

Fig. 6. Results regarding the vibration direction accuracy.

consideration should be given to the potential effects of road surface conditions and weather on tactile signals.

Next, a three-way ANOVA was conducted on the reaction time results, considering the factors of auditory signal frequency, vibration direction, and signal duration. Additionally, Student's *t*-test was performed with the presence or absence of auditory signals as a factor. For the presence or absence of auditory signals, we considered only whether there was sound, regardless of the type of frequency. The ANOVA table is shown in Table 3. Regarding reaction time, significant differences were found for the vibration direction factor ($p < 0.01$) and the auditory signal frequency factor ($p < 0.01$). The results of subsequent Tukey's multiple comparison tests at the 5 % significance level for the vibration direction are shown in Table 4 and Fig. 7. Significant differences were found between the rear and left ($p < 0.01$) as well as the rear and right ($p < 0.01$) vibration directions.

Table 5 and Fig. 8 show the results of Student's *t*-test for the presence or absence of auditory signals. From Table 5 and Fig. 8, it is evident that the simultaneous presentation of tactile and auditory signals resulted in faster reaction times compared with tactile signals alone. This suggests that the back of the head is suitable for transmitting tactile signals, and that cross-modal feedback combining tactile and auditory signals can improve reaction times.

Similarly, a three-way ANOVA was conducted on the sound accuracy results, with the ANOVA table shown in Table 6. Table 6 reveals a significant effect for the auditory signal frequency factor ($p < 0.01$). However, no significant differences were observed for the vibration direction factor ($p = 0.45$) or the signal duration factor ($p = 0.13$). The results of Tukey's multiple comparison tests for auditory signal frequency are shown in Table 7 and Fig. 9. Table 7 and Fig. 9 show significant differences between the frequencies of 500 Hz and 1000 Hz ($p < 0.01$) as well as between 1000 Hz and 2000 Hz ($p < 0.01$). These findings indicate that the accuracy of 1000 Hz signals may decrease under road traffic noise conditions.

Table 3
Analysis of variance table of the reaction times in Experiment I.

Factor	Sum of squares	df	Mean square	F-value	P-value	Significance[a]
Frequency	338,507	3	112,836	5.2	<0.01	**
Vibration direction	438,481	3	146,160	6.7	<0.01	**
Signal duration	14,752	1	14,752	0.7	0.41	NS
Frequency - Vibration direction	27,740	9	3082	0.1	0.99	NS
Frequency - Signal duration	77,329	3	25,776	1.2	0.31	NS
Vibration direction - Signal duration	14,538	3	4846	0.2	0.88	NS
Frequency - Vibration direction - Signal duration	133,466	9	14,830	0.7	0.68	NS

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

3.2. Experiment II

Based on the results of reaction time and sound accuracy obtained from the experiment, a two-way ANOVA was conducted with the frequency of the auditory signal and the direction of vibration as factors for each noise condition. The results are shown in Table 8. For reaction time, no significant interactions or main effects of the frequency of the auditory signal or the direction of vibration were found under any of the noise conditions. Additionally, a *t*-test was conducted to examine the effect of the presence or absence of the auditory signal on reaction time, with the results shown in Table 9 and Fig. 10. As seen in Table 9 and Fig. 10, no significant differences were found for under 60 dB road traffic sounds ($p = 0.91$) and 60 dB white noise ($p = 0.33$). However, a significant difference was found ($p < 0.05$) under 75 dB white noise, with reaction times significantly shorter.

Next, a two-way ANOVA on sound accuracy was performed for each noise condition, with the results shown in Table 10. As seen in Table 10, significant differences were found for the frequency factor of the auditory signal under all noise conditions: 60 dB road traffic sound ($p < 0.01$), 75 dB white noise ($p < 0.01$), and 60 dB white noise ($p < 0.05$). However, no significant differences were found for the interaction effect or vibration direction factor under any conditions. This indicates that the frequency has a significant effect under all noise conditions, and that the vibration direction does not depend on the sound accuracy.

Subsequently, Tukey's multiple comparison test was conducted for each frequency condition of the auditory signal under each noise condition, with the results shown in Table 11 and Fig. 11. From Table 11 and Fig. 11, under 60 dB road traffic sound, significant differences were found between the auditory signal frequencies of 500 Hz and 1000 Hz ($p < 0.05$) and 1000 Hz and 2000 Hz ($p < 0.01$), indicating that the accuracy rate for 1000 Hz was significantly lower. Under 60 dB white noise, significant differences were found between the auditory signal frequencies of 500 Hz and 2000 Hz and 1000 Hz and 2000 Hz ($p < 0.05$), indicating that the accuracy rate for 2000 Hz was significantly lower. Finally, under 75 dB white noise, significant differences were found between the auditory signal frequencies of 500 Hz and 2000 Hz and 1000 Hz and 2000 Hz ($p < 0.01$), indicating that the accuracy rate for 2000 Hz was significantly lower.

4. Discussion

As shown in Fig. 7 of Experiment I, the difference in reaction speed due to vibration direction is consistent with previous research [32], which demonstrated faster reaction times and higher recognition accuracy at the occiput in a stationary state. This suggests that responses to stimuli at the occiput remain swift, even during cycling. Therefore, stimulating the occiput may be the most effective approach when sending warning signals.

Next, the results from Fig. 8 in Experiment I show that using auditory in conjunction with tactile signals significantly reduces reaction times compared with tactile signals alone, demonstrating the effectiveness of cross-modal feedback for cyclists. Additionally, no significant differences in reaction time due to signal duration were observed, indicating that the signal presentation time does not influence cross-modal feedback. Comparing these results with Fig. 10 in Experiment II, similar to the results in Experiment I, reaction times were significantly faster when combining tactile and auditory signals at an environmental noise level of 75 dB compared with tactile signals alone. However, regardless of the type of environmental noise, no significant difference was found at the 60 dB noise level. This suggests that the sound pressure level of the auditory signal influenced the results. When environmental noise is set at 75 dB, the auditory signal presented at an SNR of –10 dB is 65 dB, while at 60 dB environmental noise, it is 50 dB. According to previous research [33], stronger stimulus intensity results in shorter reaction

Table 4
Results of Tukey's multiple comparison tests for the vibration direction.

Direction (i)	Direction (j)	Mean difference (i – j)	SE	*T*	P-value	Cohen's *d*	Significance[a]
Front	Back	15.26	11.47	1.33	0.54		NS
	Left	−28.24	11.45	−2.46	0.07		NS
	Right	−25.84	11.47	−2.25	0.11		NS
Back	Left	−43.50	11.44	−3.80	<0.01	0.23	**
	Right	−41.10	11.45	−3.59	<0.01	0.22	**
Left	Right	2.40	11.44	0.21	1.00		NS

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

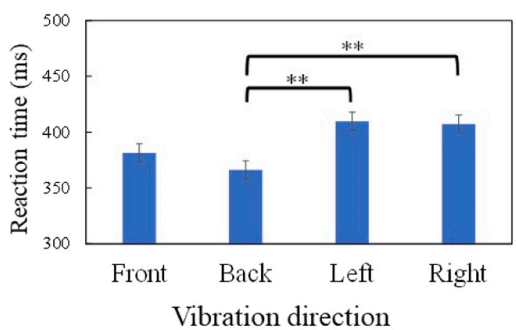

Fig. 7. Results for the reaction time by vibration direction (*$p < 0.05$, **$p < 0.01$).

times, which explains why no improvement in reaction speed was observed when combining auditory signals at environmental noise of 60 dB, as the 50 dB auditory signal was weak. Furthermore, the equivalent noise level of the chain and pedal sounds when pedaling a bicycle in a quiet environment was 51.5 dB, which might have made the 50 dB auditory signal difficult to hear. This suggests that the effectiveness of cross-modal feedback depends on the sound pressure level of the auditory signal.

Moreover, the results from Figs. 9 and 11 in Experiment I indicate that auditory signal recognition is highly dependent on frequency, regardless of the environmental noise level. Under road traffic sound conditions, at both 60 dB and 75 dB noise levels, the accuracy for 1000 Hz signals significantly decreased compared with 500 Hz and 2000 Hz. Under white noise conditions, at both 60 dB and 75 dB, the accuracy for 2000 Hz signals decreased compared with 500 Hz and 1000 Hz. Fig. 12 shows an A-weighted frequency characteristics analysis of the four types of noise used in this experiment.

From Fig. 12, comparing road traffic sounds and white noise at the same noise levels (75 dB and 60 dB), the sound pressure level of road traffic sound peaks at 1000 Hz, likely masking the 1000 Hz auditory signal. For white noise, the sound pressure level increases with higher frequencies, potentially masking the 2000 Hz auditory signal. Notably, at 500 Hz, the sound pressure level is lower than the peak for both road traffic sounds and white noise, suggesting that it was not masked.

5. Limitations

The present study has some limitations. First, this study analyzed 14 and 10 participants in Experiments I and II, respectively, by referring to and increasing the number of participants found to be useful in previous studies [34] without using the results of a prior power analysis. Thus, the findings of this study need to be verified in an extended experiment with a larger sample size, which could be determined based on the means and SDs obtained in this study.

Second, this study has several limitations that need to be considered. Firstly, the experiments were conducted in a controlled laboratory environment using simulated road traffic and white noise. While sound pressure levels and the arrangement of sound sources were carefully adjusted based on pre-measured data from real roads to mimic realistic traffic situations, the laboratory setting cannot fully replicate the complex factors of real-world cycling environments. These include weather conditions, road surfaces, and the presence of other traffic participants, which may influence the effectiveness of the feedback system. Additionally, factors such as different wind speeds and humidity, which

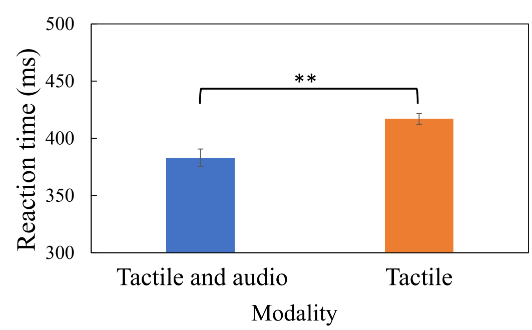

Fig. 8. Results for the reaction time by modality (*$p < 0.05$, **$p < 0.01$).

Table 6
Analysis of variance table of the sound accuracy in Experiment I.

Factor	Sum of squares	df	Mean square	F-value	P-value	Significance[a]
Frequency	7110	2	3555	21.4	<0.01	**
Vibration direction	119	3	40	0.2	0.87	NS
Signal duration	331	1	331	2.0	0.16	NS
Frequency - Vibration direction	1012	6	169	1.0	0.42	NS
Frequency - Signal duration	165	2	83	0.5	0.61	NS
Vibration direction - Signal duration	119	3	40	0.2	0.87	NS
Frequency - Vibration direction - Signal duration	1131	6	189	1.1	0.34	NS

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

Table 5
Results of Student's *t*-tests for the presence or absence of auditory signals in Experiment I.

Modality (i)	Modality (j)	Mean difference (i – j)	SE	*t*	P-value	Cohen's *d*	Significance[a]
Tactile and audio	Tactile	−30.75	9.27	3.32	<0.01	0.18	**

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

Table 7
Results of Tukey's multiple comparison tests for the auditory signal frequency in Experiment II.

Frequency (i)	Frequency (j)	Mean difference (i – j)	SE	t	P-value	Cohen's d	Significance[a]
500 Hz	1000 Hz	10.42	1.72	6.04	<0.01	0.31	**
	2000 Hz	1.49	1.72	0.86	0.66		NS
1000 Hz	2000 Hz	−8.93	1.72	−5.18	<0.01	0.33	**

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

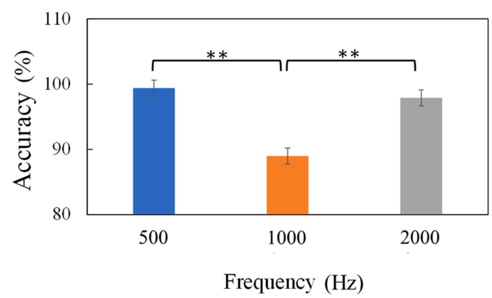

Fig. 9. Results for the sound accuracy by auditory frequency (*$p < 0.05$, **$p < 0.01$).

affect sound propagation, were not taken into account. To address these limitations, future studies will involve field tests under various cycling conditions, including urban areas with heavy traffic and quiet residential neighborhoods. This approach aims to assess the system's performance and limitations in real-world settings.

Third, the participants of this study were relatively young males, with a mean age of 23.4 years, limiting the generalizability of the results. Previous research has shown that age and gender can affect cognitive responses [35], suggesting the need for experiments with a more diverse range of participants. Future studies will include individuals of different ages, genders, and cycling experiences to better generalize the findings to a broader population. Additionally, long-distance cycling was not fully explored, as the experiments consisted of three 30-minute sessions. The impact of sustained use on comfort and usability should be further investigated by conducting longer-duration tests to evaluate the effects of fatigue, stress, and discomfort.

Moreover, the feedback intensity and frequency may need to be adjusted based on individual users' preferences and sensory characteristics. Personal differences in auditory abilities and tactile sensitivity suggest that a personalized feedback system could improve the effectiveness of cross-modal stimuli. Future research will explore the development of algorithms for personalization and user-specific settings.

Lastly, while this study focused on two types of environmental noise, future work should investigate a wider variety of noise conditions. Real-world cycling environments feature diverse sounds, such as wind, human voices, and different vehicle noises. To optimize the feedback system for various scenarios, future experiments will consider additional noise types and sound pressure levels, which may reveal the effects of different noise characteristics on the recognition and response to cross-modal feedback.

6. Conclusion

In this study, with the aim of enhancing cyclist safety, we investigated appropriate presentation signals for cross-modal feedback that

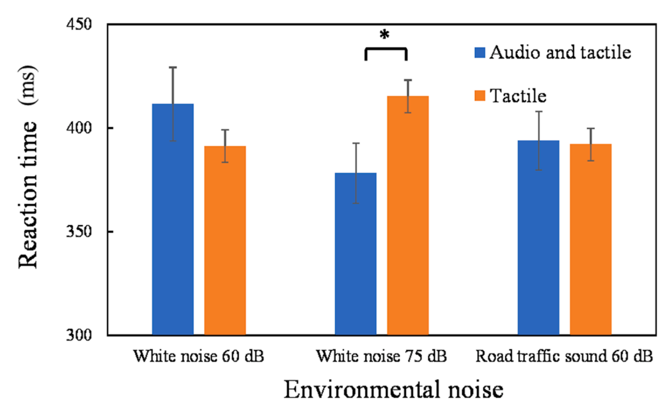

Fig. 10. Results of the reaction time under each environmental noise condition (*$p < 0.05$, **$p < 0.01$).

Table 8
Analysis of variance table of the reaction time in Experiment II.

Environmental noise	Factor	Sum of squares	df	Mean square	F-value	P-value	Significance[a]
White noise 60 dB	Frequency	17,207	3	5,736	0.14	0.93	NS
	Vibration direction	203,917	3	67,972	1.71	0.16	NS
	Frequency - Vibration direction	175,178	9	19,464	0.49	0.88	NS
White noise 75 dB	Frequency	164,451	3	54,817	1.92	0.13	NS
	Vibration direction	63,144	3	21,048	0.74	0.53	NS
	Frequency - Vibration direction	137,116	9	15,235	0.53	0.85	NS
Road traffic sounds 60 dB	Frequency	18,384	3	6,128	0.20	0.89	NS
	Vibration direction	221,862	3	73,954	2.44	0.06	NS
	Frequency - Vibration direction	142,572	9	15,841	0.52	0.86	NS

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

Table 9
Results of Student's t-tests for the presence or absence of auditory signals in Experiment II.

Environmental noise	Frequency (i)	Frequency (j)	Mean difference (i – j)	SE	t	P-value	Cohen's d	Significance[a]
White noise 60 dB	Tactile and audio	Tactile	19.61	20.64	0.95	0.34		NS
White noise 75 dB	Tactile and audio	Tactile	−37.84	17.12	−2.21	<0.05	0.24	*
Road traffic sounds 60 dB	Tactile and audio	Tactile	0.69	17.11	0.04	0.97		NS

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

Table 10
Analysis of variance table of the sound accuracy in Experiment II.

Environmental noise	Factor	Sum of squares	df	Mean square	F-value	P-value	Significance[a]
White noise 60 dB	Frequency	1,500	2	750	3.8	<0.05	*
	Vibration direction	28	3	9	0.0	0.99	NS
	Frequency - Vibration direction	500	6	83	0.4	0.86	NS
White noise 75 dB	Frequency	4,463	2	2,232	8.9	<0.01	**
	Vibration direction	176	3	59	0.2	0.87	NS
	Frequency - Vibration direction	130	6	22	0.1	1.00	NS
Road traffic sounds 60 dB	Frequency	5,389	2	2,695	6.0	<0.01	**
	Vibration direction	1,926	3	642	1.4	0.24	NS
	Frequency - Vibration direction	3,574	6	596	1.3	0.25	NS

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

Table 11
Results of Tukey's multiple comparison tests for the auditory signal frequency in Experiment II.

Environmental noise	Frequency (i)	Frequency (j)	Mean difference (i – j)	SE	*T*	P-value	Cohen's *d*	Significance[a]
White noise 60 dB	500 Hz	1000 Hz	0.00	3.15	0.00	1.00		NS
		2000 Hz	−7.50	3.15	2.38	<0.05	0.35	*
	1000 Hz	2000 Hz	−7.50	3.25	2.38	<0.05	0.35	*
White noise 75 dB	500 Hz	1000 Hz	0.83	3.53	0.24	0.97		NS
		2000 Hz	13.33	3.53	3.77	<0.01	0.59	**
	1000 Hz	2000 Hz	12.50	3.53	3.54	<0.01	0.54	**
Road traffic sounds 60 dB	500 Hz	1000 Hz	11.67	4.72	2.47	<0.05	0.42	*
		2000 Hz	−4.17	4.72	−0.88	0.65		NS
	1000 Hz	2000 Hz	−15.83	4.72	−3.35	<0.01	0.61	**

[a] Significance level (*$p < 0.05$, **$p < 0.01$).

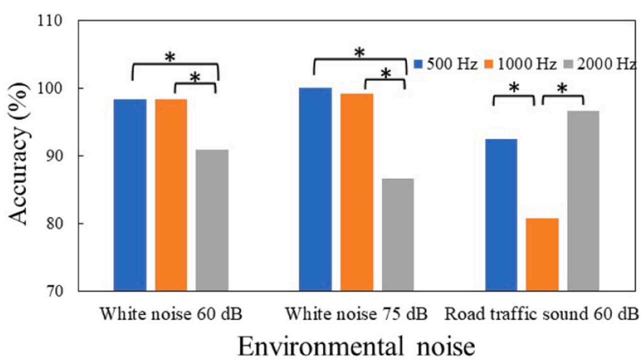

Fig. 11. Results of the sound accuracy under each environmental noise condition (*$p < 0.05$, **$p < 0.01$).

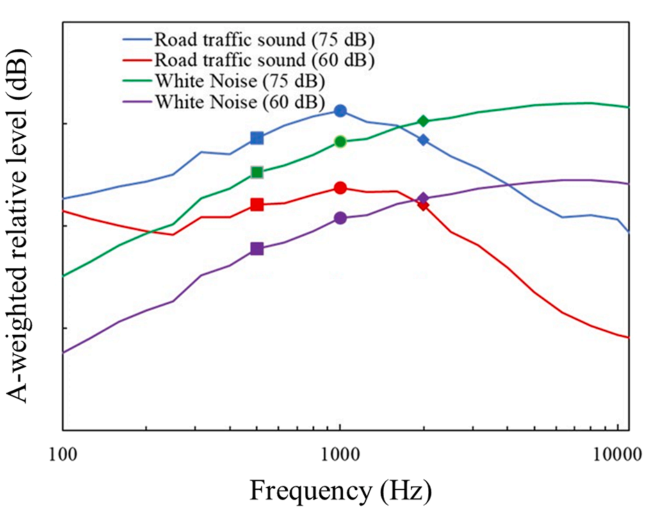

Fig. 12. A-weighted frequency characteristics of noise. Squares are at 500 Hz, circles at 1000 Hz, and diamonds at 2000 Hz, respectively.

could improve the recognition accuracy and reaction speed of cyclists using a new device integrated into bicycle helmets that provides tactile vibration and auditory stimuli during cycling.

First, the results of our study demonstrate the effectiveness of cross-modal feedback in significantly reducing reaction times compared with tactile signals alone. Herein, the back of the head is the most effective location for delivering warning signals. Even during cycling, stimulation of the occiput consistently showed faster reaction times and higher recognition accuracy.

Second, the recognition of auditory signals was found to be highly frequency-dependent, with optimal frequencies varying according to noise conditions. Under the road traffic sound condition, 1000 Hz signals showed lower recognition accuracy compared with 500 Hz and 2000 Hz signals, while under white noise conditions, 2000 Hz signals had lower recognition accuracy than did 500 Hz and 1000 Hz signals. These findings revealed the potential for masking effects due to the frequency characteristics of environmental noise. Road traffic sounds, which peak around 1000 Hz, tend to mask signals at this frequency, while white noise, with its increasing sound pressure level at higher frequencies, is more likely to mask high-frequency signals around 2000 Hz.

Third, it is important to note that the effectiveness of cross-modal feedback appears to be dependent on the sound pressure level of the auditory signal.

These findings provide valuable insights for the design of safety systems for cyclists and suggest that cross-modal feedback systems should consider both the frequency and intensity of auditory signals in relation to environmental noise conditions. In conclusion, the present findings suggest the potential of cross-modal feedback to enhance cyclist safety, particularly when optimized for environmental conditions and individual perception.

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Authors' contributions

Conceptualization: TA; Methodology: RU; Software: RU; Validation: TA, RU; Formal analysis: RU; Investigation: TA, RU; Resources: RU; Data curation: RU; Writing - Original draft: RU; Writing - Review & editing: TA; Visualization: RU; Supervision: TA; Project administration: TA; Funding acquisition: TA.

Author statement

Conceptualization: RU, TA, Methodology: RU, Software: RU, Validation: TA, RU, Formal analysis: RU, Investigation: TA, RU, Resources: RU, Data Curation: RU, Writing - Original Draft: RU, Writing - Review & Editing: TA, Visualization: RU, Supervision: TA, Project administration: TA, Funding acquisition: TA

Declarations

None

CRediT authorship contribution statement

Takumi Asakura: Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ryosuke Uemura:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

References

[1] Japan Bicycle Promotion Institute, Report on Survey of Bicycles Ownership and Usage. ⟨https://jbpi.or.jp/wp-content/uploads/2022/12/own_report_2021.pdf⟩ (accessed 20 August 2024).
[2] Metropolitan Police Department, Impact of Bicycle-related Traffic Accidents. ⟨https://www.npa.go.jp/koutsuu/kikaku/bicycle/kentokai/01/siryou07.pdf⟩ (accessed 20 August 2024).
[3] G. Lopes, N. Cennamo, L. Zeni, R. Singh, S. Kumar, A.J. Fernandes, C. Marques, Innovative optical pH sensors for the aquaculture sector: comprehensive characterization of a cost-effective solution, Opt. Laser Technol. 171 (2024) 110355, https://doi.org/10.1016/j.optlastec.2023.110355.
[4] H.C. Gomes, X. Liu, A. Fernandes, C. Moreirinha, R. Singh, S. Kumar, C. Marques, Laser-induced graphene-based Fabry-Pérot cavity label-free immunosensors for the quantification of cortisol, Sens. Actuators Rep. 7 (2024) 100186, https://doi.org/10.1016/j.snr.2024.100186.
[5] R. Singh, W. Zhang, X. Liu, B. Zhang, S. Kumar, WaveFlex biosensor: MXene-Immobilized W-shaped fiber-based LSPR sensor for highly selective tyramine detection, Opt. Laser Technol. 171 (2024) 110357, https://doi.org/10.1016/j.optlastec.2023.110357.
[6] M. Krüger, T. Driessen, C.B. Wiebel-Herboth, J.C. de Winter, H. Wersing, Feeling uncertain—effects of a vibrotactile belt that communicates vehicle sensor uncertainty, Inf. 11 (7) (2020), https://doi.org/10.3390/info11070353.
[7] C. Dijksterhuis, A. Stuiver, B. Mulder, K.A. Brookhuis, D. de Waard, An adaptive driver support system: user experiences and driving performance in a simulator, Hum. Factors 54 (5) (2012) 772–785, https://doi.org/10.1177/0018720811430502.
[8] R. Gray, Looming auditory collision warnings for driving, Hum. Factors 53 (1) (2011) 63–74, https://doi.org/10.1177/0018720810397833.
[9] A. Bouwer, F. Nack, A.E. AliLost in Navigation: Evaluating a Mobile Map App for a Fair ACM Press in: Proc. of ICMI'122012, 222610.1145/2388676.2388712.
[10] A.I. Giesa, Navigating through Haptics and Sound: A Non-Visual Navigation System to Enhance Urban Bicycling, in: Design, User Experience, and Usability. Design for Contemporary Interactive Environments: 9th International Conference, DUXU 2020, Held as Part of the 22nd HCI International Conference, HCII 2020, Copenhagen, Denmark, July 19–24, 2020, Proceedings, Part II, vol. 22, Springer International Publishing, 2020, pp. 640-652. https://doi.org/10.1007/978-3-030-49760-6_45.
[11] S. Steltenpohl, A. BowerVibrobelt: tactile navigation support for cyclists : Proc. of the 2013 International Conference on Intelligent User Interfaces2013, : Proc. of the International Conference on Intelligent User Interfaces201341742610.1145/2449396.2449450.
[12] M. Pielot, B. Poppinga, W. Heuten, S. BollTacticycle: Supporting exploratory bicycle trips : Proc. of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services2012, 36937810.1145/2371574.2371631.
[13] A. Dancu, V. Vechev, A.A. Ünlüer, S. Nilson, O. Nygren, S. Eliasson, J.-E. Barjonet, J. Marshall, M. FjeldGesture bike: examining projection surfaces and turn signal systems for urban cycling ACM in: Proc. of the 2015 International Conference on Interactive Tabletops & Surfaces2015, in: Proceedings of the International Conference on Interactive Tabletops & Surfaces201515115910.1145/2817721.2817748.
[14] E. Schoop, J. Smith, B. HartmannHindSight: Enhancing spatial awareness by sonifying detected objects in real-time 360-degree video New York, NY, USA ACM in: Proc. of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)2018, in: Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '18)201810.1145/3173574.3173717.
[15] D. Vo, J. Saari, S. Brewster, TactiHelm: tactile feedback in a cycling helmet for collision avoidance, : CHI Conf. Hum. Factors Comput. Syst. (2021) 1–5, https://doi.org/10.1145/3411763.3451580.
[16] E.M. Jones, T. Selker, H. Chung, What You Said About Where You Shook Your Head: A Hands-Free Implementation of a Location-Based Notification System, in: CHI '07. Extended Abstracts on Human Factors in Computing Systems (CHI EA '07), ACM, New York, NY, USA, 2007, pp. 2477–2482, https://doi.org/10.1145/1240866.1241027.
[17] H.-Y. Tseng, R.-H. Liang, L. Chan, B.-Y. ChenLEaD: Utilizing light movement as peripheral visual guidance for scooter navigation ACM in: Proc. of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services2015, 32332610.1145/2785830.2785831.
[18] S. Petermeijer, P. Bazilinskyy, K. Bengler, J. de Winter, Take-over again: Investigating multimodal and directional TORs to get the driver back into the loop, Appl. Ergon. 62 (2017) 204–215, https://doi.org/10.1016/j.trf.2019.06.011.
[19] A. Matviienko, A. Löcken, A. El Ali, W. Heuten, S. BollNaviLight: Investigating ambient light displays for turn-by-turn navigation in Cars ACM in: Proc. of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services2016, 28329410.1145/2935334.2935359.
[20] I. Politis, S. Brewster, F. PollickEvaluating Multimodal Driver Displays of Varying Urgency ACM Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications2013, 929910.1145/2516540.2516543.
[21] A. Matviienko, S. Ananthanarayan, S.S. Borojeni, Y. Feld, W. Heuten, S. BollAugmenting bicycles and helmets with multimodal warnings for children, in: Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services2018, 11310.1145/3229434.3229479.
[22] G. Huang, B. PittsAge-related differences in takeover request modality preferences and attention allocation during semi-autonomous driving, in : Proceedings of the International Conference on Human-Computer Interaction2020, 13514610.1007/978-3-030-50252-2_11.
[23] C. Geitner, F. Biondi, L. Skrypchuk, P. Jennings, S. Birrell, The comparison of auditory, tactile, and multimodal warnings for the effective communication of unexpected events during an automated driving scenario, Transp. Res. Part F Traffic Psychol. Behav. 65 (2019) 23–33, https://doi.org/10.1016/j.trf.2019.06.011.
[24] K. Myles and J.T. Kalb, "Guidelines for Head Tactile Communication," DTIC Document, Tech. Rep., ARL-TR-5116, 2010.
[25] T.H. Milroy, Fatigue studied in reaction time experiments, Q. J. Exp. Physiol. Transl. Integr. 2 (3) (1909) 277–282, https://doi.org/10.1113/expphysiol.1909.sp000040.
[26] M. Mani, I. Ito, K. Kikuchi, Studies on the muscular endurance Report 3, Jpn. J. Phys. Fit. Sports Med. 15 (1) (1966) 27–30, https://doi.org/10.7600/jspfsm1949.15.27.
[27] A. Murata, T. Kuroda, W. Karwowski, Effects of auditory and tactile warning on response to visual hazards under a noisy environment, Appl. Ergon. 60 (2017) 58–67, https://doi.org/10.1016/j.apergo.2016.11.002.
[28] EN50332-1. (2013). EN 50332-1:2013. Sound System Equipment: Headphones and Earphones Associated with Personal Music Players—Maximum Sound Pressure Level Measurement Methodology, Part 1: General method for "one package equipment." Brussels, Belgium: CEN-CENELEC.
[29] EN50332-2. (2013). EN 50332-2:2013. Sound System Equipment: Headphones and Earphones Associated with Personal Music Players—maximum Sound Pressure Level Measurement Methodology. Part 2: Matching of Sets with Headphones If Either Or Both Are Offered Separately, Or Are Offered as One Package Equipment But with Standardised Connectors between the Two Allowing to Combine Components of Different Manufacturers Or Different Design. Brussels, Belgium: CEN-CENELEC.
[30] K.C. De Sousa, C. Smits, D.R. Moore, S. Chada, H. Myburgh, D. Swanepoel, Global Use and Outcomes of the hearWHO mHealth Hearing Test, Digit. Health 8 (2022) 20552076221113204, https://doi.org/10.1177/20552076221113204.
[31] Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum.

[32] V.A. de Jesus Oliveira, L. Nedel, A. Maciel, L. Brayda, Spatial Discrimination of vibrotactile stimuli around the head, 2016 IEEE HAPTICS Symp. (HAPTICS) (2016) 1–6, https://doi.org/10.1109/HAPTICS.2016.7463147.
[33] D.L. Kohfeld, J.L. Santee, N.D. Wallace, Loudness and Reaction Time: I, Percept. Psychophys. 29 (1981) 535–549, https://doi.org/10.3758/BF03207370.
[34] M. Karam, R. Wilde, P. Langdon, Somatosensory Interactions: Exploring Complex Tactile-Audio Messages for Drivers, in: Advances in Human Factors and System Interactions: Proceedings of the AHFE 2016 International Conference on Human Factors and System Interactions, July 27–31, 2016, Walt Disney World, FL, USA, Springer International Publishing, 2017, pp. 117-128. https://doi.org/10.1007/978-3-319-41956-5_12.
[35] J.L. Fozard, M. Vercruyssen, S.L. Reynolds, P.A. Hancock, R.E. Quilter, Age differences and changes in reaction time: the Baltimore Longitudinal Study of Aging, J. Gerontol. 49 (4) (1994) 179–189, https://doi.org/10.1093/geronj/49.4.P179.

Glossary

L_{Aeq}: A-weighted sound pressure level
LRAs: Linear resonance actuators
SNR: Signal-to-noise ratio
ANOVA: A multi-way analysis of variance

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