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Shoe-Based Interface Promoting Instinctive Avoidance Behavior in Poor Visibility Conditions Utilizing Averse Behavior

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ABSTRACT

In dangerous situations, such as water accidents, many people still refuse to evacuate despite being issued warnings or tend to be careless or negligent of the possible dangers because of optimistic bias. Additionally, poor visibility can likely cause serious injuries and accidents, such as falls and tumbles. Therefore, we propose a shoe-based interface that uses vibrotactile sensations to promote instinctive danger avoidance and evacuation behaviors during dangerous situations and poor visibility conditions. By leveraging the averse behavior of living organisms, the proposed interface promotes instinctive danger avoidance through unpleasant vibrations. We conducted a comparison experiment with existing sound warnings to verify the effectiveness of the shoe-based interface and evaluated the avoidance success and emotional responses of the selected participants using questionnaires and biological data. The results showed that the danger avoidance success rate was slightly lower than that of the sound warning; however, the reduction in the percentage of unpleasant and negative emotions elicited from without prior explanation to with prior explanation was lower than with existing sound warnings. Hence, our proposed shoe-based interface demonstrates a heightened ability to sustain discomfort and provoke negative emotional responses, indicating its effectiveness in mitigating the tendency to ignore warnings. In a post-experiment question, more than 90% of the participants expressed not wanting to proceed with either warning. Therefore, this interface is expected to have the same functionality as existing sound warnings and promote instinctive danger avoidance behavior under poor visibility conditions.

Keywords: Poor visibility, Warning, Evacuation behavior, Avoidance behavior, Vibrotactile

INTRODUCTION

In Japan, the number of water accidents has remained almost unchanged over the past 15 years from 2006 to 2022 (National Police Agency, 2022). These accidents mostly occur during fishing, particularly due to inattention to weather and sea conditions caused by poor visibility and carelessness and negligence toward danger, such as during nighttime (Japan Coast Guard, 2017). Moreover, a previous study stated that people tend to underestimate and have an optimistic bias toward disasters (Solberg et al., 2010). In addition, emotional factors are more important than judgments based on scientific information in promoting evacuation behavior during a disaster. Communication that promotes an intuitive sense of crisis is also necessary to facilitate evacuation behavior (Ohtomo et al., 2020). However, people are not always present during dangerous situations. Therefore, it is important to feel a sense of crisis, even in situations where no one is present. Thus, to promote evacuation and avoidance behaviors, it is necessary to prevent optimism and disregard for danger, which requires a sense of crisis.

In addition to the dark nighttime conditions mentioned earlier, there are other poor visibility conditions, such as dense fog and snowstorms. Studies evaluating the visibility of warning signs under foggy conditions have reported that the visibility decreases as the visibility conditions change from clear to foggy (Munehiro et al., 2006). Thus, there is a risk of serious injury or accident under poor visibility conditions owing to its low visibility. Vibrotactile warnings are effective under poor visibility conditions, as they do not interfere with the audiovisual senses. Research on this subject includes a warning system for back pain during work using vibrotactile feedback (Kawano et al., 2013) and a basic study on a vibrotactile warning system for automobiles (Murata, 2011). Although these systems are effective in providing danger warnings, their effectiveness in preventing optimistic biases toward danger and creating emotional factors that promote avoidance behavior is unclear.

In this study, we developed a shoe-based interface using vibrotactile sensation that promotes avoidance behaviors by instinctively inducing a sense of danger in people. This warning system is expected to provide a sense of danger and promote instinctive avoidance behavior even when there are no other people present.

SHOE-BASED INTERFACE PROMOTING INSTINCTIVE DANGER AVOIDANCE

Instinctive Danger Avoidance

In this study, we used the aversive behavior of creatures as a method to promote instinctive danger avoidance. This is an instinct of organisms that increases their probability of survival and refers to escape or avoidance behavior in response to what are called unpleasant emotions. Unpleasant emotions include tension, sadness, anxiety, aversion, and fear. In this study, we used vibrotactile stimuli to induce unpleasant emotions and aversive behavior and promote instinctive danger avoidance.

Using Foot

The foot is indispensable to bipedal humans, and shoes are objects many people wear for their feet. Because the foot is in contact with the ground, walking motion is based on tactile information from the ground. In the absence of visual acuity, tactile and sensory information from the foot is particularly important and necessary for understanding the ground situation. Thus, the tactile and sensory perception of the foot is the most directly involved part of gait, which is influenced by the transmission of information to the foot.

The foot and gait are closely related, and several studies have been conducted on this topic. Examples include research on floor-type gait guidance system without audiovisual attention (Okazaki et al., 2022) and the effect of sole stimulation on the center-of-gravity sway during walking (Ishiyama et al., 2016). In addition, a study reported that vibration stimulation of the legs is more effective as an alarm than stimulation of the back or abdomen in the elderly whose sensory functions are deteriorating (Murata et al., 2011).

In this research, we developed a method to avoid danger and provide warnings under poor visibility conditions. To this end, we created a shoe-based interface that directly affects walking behavior by stimulating the foot, as in the above research. However, the center-of-gravity shift during walking is dangerous under poor visibility conditions because it may lead to falling (Ishiyama et al., 2016); therefore, the sole was not stimulated in this research for safety reasons.

EXPERIMENT FOR DETERMINING THE POSITION OF VIBRATION MOTORS ON THE FOOT

This particular experiment aims to determine the appropriate location of the vibration motor on the foot to fabricate a shoe-based interface. The foot has various parts, such as the toes and instep, that feel vibrations differently; therefore, it is necessary to determine the appropriate position of the foot as a stimulus that provides a warning. In additions, to convey danger as a warning, it is essential for the vibration to be effectively transmitted as a precondition. Therefore, the position where the vibration was most strongly felt on the foot was determined to be the appropriate location for the vibration motors in this experiment.

Method

The participants were seven healthy male university students in their 20s, all of whom were right-handed and right-footed. To simulate poor visibility, the participants were fitted with eye masks. Subsequently, they were asked to step on the spot, and vibration stimuli were applied to the toe, both sides, instep, and heel of their foot. Two vibration motors with a frequency of approximately 216 Hz were used for the vibration. After applying the vibration to each site, the participants were asked to answer a questionnaire using the 5-step SD method (semantic differential scale method) to evaluate how they felt about the vibration intensity. Additionally, only the foot opposite to the dominant foot was subjected to vibration stimulation for safety reasons.

Result

Based on the results of the questionnaire responses, the Friedman test was conducted with a significance level of 5%. We found a significant difference in the perception of vibration intensity in each part of the foot ($p = 0.0285 < 0.05$). The toe is the site where the vibration is felt most strongly among the four parts of the foot: toe, both sides, instep, and heel. This may be attributed to the fact that the toes are technically similar to fingers, which have a long, thin structure that amplifies the vibration of the vibration motor, thereby causing a stronger sensation. In this study, the toe was used as installation positions for the vibration motors.

EXPERIMENT FOR INVESTIGATING VIBRATION PATTERNS FOR UNPLEASANT AND NEGATIVE EMOTIONS

This particular experiment aims to investigate the vibration patterns that cause people to feel unpleasant and negative emotions to induce averse behavior.

In this study, we measured the peripheral skin temperature and electrodermal activity (EDA) using an E4 wristband (Empatica). These data were used to measure unpleasant emotions. Peripheral body temperature decreases when people are nervous or feel unpleasant emotions, such as disgust or fear (Shimada, 2004 and Ono, 2012). By contrast, EDA is used to assess emotions, arousal, stress, and tension. EDA is reported to increase during negative high arousal sessions or in states of stress or tension and remains almost unchanged at high values in states of negative low arousal (Dingding, 2018 and Mitsugi, 2021). In this study, we assumed that the participants felt unpleasant and negative emotions when their body temperature decreased and EDA increased.

Table 1. Five vibration patterns.

Vibration Patterns
1. Constant vibration time and stop time
2. Constant vibration time and decreasing stop time
3. Constant vibration time and increasing stop time
4. Constant stop time and decreasing vibration time
5. Constant stop time and increasing vibration time

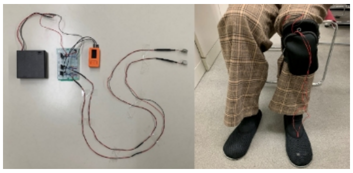

Figure 1: Developed device (left) and its appearance when worn (right).

Table 2. Percentage of participants who felt unpleasant and negative emotions.

	Constant Vibration	Periodic	Constant Vibration Time		Constant Stop Time	
			DS	IS	DV	IV
Percentage	57.1%		66.7%	57.1%	57.1%	57.1%

DS: Decreasing Stop Time. IS: Increasing Stop Time. DV: Decreasing Vibration Time. IV: Increasing Vibration Time.

METHOD

The participants were seven healthy male university students in their 20s, all of whom were right-handed and right-footed. The experiments were conducted under the same conditions as those described in the previous section. Vibration stimuli were applied to the toe in five vibration patterns (Table 1) while the participant was asked to step on the spot. After applying vibrations to each site, the participants were asked to answer a questionnaire using the 5-step SD method to evaluate how uncomfortable and tense they felt. In addition, this experiment was conducted using a wristwatch-type wearable device, the E4 wristband (Empatica), to obtain the skin temperature and EDA data, which were used to evaluate unpleasant emotions. The evaluation was performed by comparing the obtained skin temperature and EDA data from the participants with the baseline measurements (average) to determine whether there was an increase or decrease in values. In this experiment, "vibration time" and "stop time" were defined as the times when the vibration motor was vibrating and when the motor was stopped, respectively.

RESULT

Based on the questionnaire results, we conducted the Friedman test at a significance level of 5%. The results of the Friedman test showed no significant difference regarding feeling uncomfortable based on the vibration pattern ($p > 0.05$). For the tension items, we found a significant difference based on the vibration pattern ($p = 0.0032 < 0.05$). Therefore, the vibration pattern with a constant vibration time and decreasing stop time was found to be the vibration pattern with the most tension.

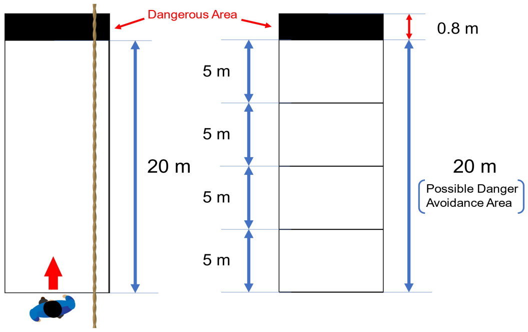

Figure 2: Model diagram of the experiment (left) and possible danger avoidance area (right).

Table 2 shows the percentage of participants who felt unpleasant emotions in each pattern using biological data. These results were based on data from six participants, excluding one participant whose data could not be measured owing to a measurement error during the experiment. The results showed that the vibration pattern with constant vibration time and decreasing stop time was considered appropriate for unpleasant and negative emotions.

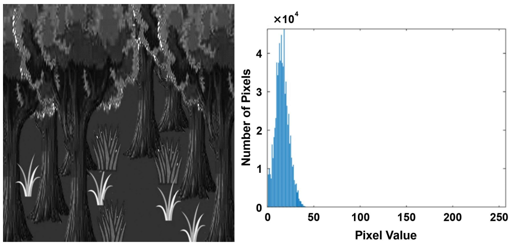

Figure 3: Illustration of poor visibility condition reproduced in VR (using Unity Asset: Fantasy Forest Environment) (left) and histogram of the actually presented footage (right).

OVERVIEW OF SHOE-BASED INTERFACE

Fig. 1 shows the developed shoe-based interface. The left side of the figure shows the control part for controlling the vibration motor and connecting the M5StickC, batteries, and vibration motor. The right side shows its appearance when installed. The vibration motor was controlled remotely via a Bluetooth connection to the M5StickC using a smartphone. The control unit was placed in a pouch, and the vibration motor was attached to the shoe. Based on the experimental results in the previous sections, we mounted the vibration motor in the toe and set the vibration pattern with constant vibration time and decreasing stop time.

EXPERIMENT FOR EVALUATING THE EFFICACY OF THE SHOE-BASED INTERFACE IN PROVIDING WARNINGS IN POOR VISIBILITY CONDITIONS

This particular experiment aims to verify whether the participant can avoid danger instinctively under poor visibility conditions by wearing the fabricated shoe-based interface device and verify its effectiveness in providing warnings under the said conditions. In this experiment, we compared the shoe-based interface with an existing sound warning. In addition, to prevent the participant from falling, only the leg opposite to the dominant leg was stimulated, and the participant was guided to walk straight along a string to ensure safety.

Relationship Between Danger Avoidance and Stopping Distance

In this experiment, we verified whether the participants were able to avoid danger after receiving a warning. Successful danger avoidance was defined in this experiment as the ability to respond to danger by avoiding it from a distance at which it was possible to avoid or stop. To determine the distance at which danger avoidance was not possible, we referred to a study that investigated the ability to suddenly stop when walking in terms of age and gender (Cheng et al., 1998). They reported that all ages, regardless of gender, must recognize the obstacle in front of them at approximately 0.77 m or more to achieve a 50% success rate in the task of stopping to avoid contact with an unexpected obstacle while walking at 1.3m/s.

Table 3. Vibration and sound patterns at different distances.

		0≦x < 5 (Area 1)	5≦x < 10 (Area 2)	10≦x < 15 (Area 3)	15≦x < 20 (Area 4)
Vibration Patterns	V Time	1000 [ms]	1000 [ms]	1000 [ms]	1000 [ms]
	S Time	800 [ms]	500 [ms]	300 [ms]	100 [ms]
Sound Patterns	On Time	1000 [ms]	500 [ms]	100 [ms]	100 [ms]
	Off Time	1000 [ms]	200 [ms]	100 [ms]	50 [ms]

V Time: Vibration Time. S Time: Stop Time. On Time: Time that the sound continuously plays. Off Time: Time when no sound is heard.

Using this study as a reference, we set the distance at which danger avoidance is impossible to 0.8 m, and successful danger avoidance was defined as stopping at a distance greater than 0.8 m from the danger. Accordingly, the experimental conditions were set, as shown in Fig. 2. The total length was 20.8 m. As shown on the right diagram, the distance between 0 and 20 m from the starting point was defined as the possible danger avoidance area. If the participant stopped at the possible danger avoidance area, the participant was considered to have successfully avoided the danger. If the participant advanced more than 20 m to the danger area, the participant was considered to have failed in avoiding the danger. The possible danger avoidance area was divided into four, which were 5 m apart from each other.

METHOD

The participants were 16 healthy male university students in their 20s, all of whom were right-handed and right-footed. This experiment was designed as a comparative experiment conducted under identical conditions. It aimed to assess the effectiveness of the shoe-based interface, proposed in this study and utilizing tactile stimulation for the feet, in comparison to a sound warning system based on the sound standards specified for household electrical appliances by AEHA (Association for Electric Home Appliances, 2018). To make the visibility as realistic as possible, we asked the participants to wear an HMD (Meta Quest 2) and reproduced the poor visibility conditions in VR. In addition, the VR view was set to move according to the gait of the participant. The participants were asked to walk straight through the area shown in Fig. 2 while viewing images with poor visibility reproduced by VR. Fig.3 shows illustration of poor visibility condition reproduced in VR and histogram of the actually presented footage. We compared the shoe-based interface with an existing warning system by measuring whether the subjects stopped after receiving the warning (success or failure of danger avoidance), the stopping distance, questionnaire responses, and biometric data using the E4 wristband. The participants listened to the warning sounds via wireless earphones (SONY WF-1000XM4). Table 3 shows the vibration pattern of the warning system and that of the warning sound of home appliances. Vibration and sound patterns were set for each distance of the possible danger avoidance area so that the closer the participant approaches the danger area, the greater the urgency of the alarm. The vibration and sound patterns were remotely controlled using a smartphone application.

Table 4. Danger avoidance success rate and average stopping distances.

	Warning	Number of participants who succeeded (%)	Average stopping distances	
			all	Participants who stopped
Without prior explanation	Vibration	9 (56.3%)	14.0 [m]	10.4 [m]
	Sound	10 (62.5%)	11.7 [m]	6.6 [m]
With prior explanation	Vibration	12 (75.0%)	11.0 [m]	8.9 [m]
	Sound	13 (81.25%)	8.5 [m]	6.9 [m]

Table 5. Percentage of participants who felt unpleasant and negative emotions during the experiment (verification of effectiveness in danger avoidance).

	Without prior explanation		With prior explanation	
	Vibration	Sound	Vibration	Sound
Percentage	83.3%	85.7%	66.7%	57.1%

The experiment was conducted under four conditions: two vibration and sound warnings without prior explanation and two vibration and sound warnings with prior explanation. The details of each warning are presented in Table 3. The participants were initially warned without prior explanation of an incoming warning, and subsequently warned with prior explanation. To counterbalance the warning, the 16 participants were divided into two groups; one group was given the vibration warning first, whereas the other was given the sound warning first. After being warned, we asked the participants to answer a questionnaire using the 5-step SD method to evaluate their feelings of discomfort, tension, and sense of crisis. They were then asked to answer a questionnaire with the question "Do you still want to move forward despite receiving a warning (vibration or sound)?"

RESULTS

Based on the questionnaire responses, a Wilcoxon signed-rank sum test was conducted with a significance level of 5%. The results of the Wilcoxon signed-rank sum test showed no significant differences on items pertaining to feeling uncomfortable, tension, and a sense of crisis ($p > 0.05$) for both the shoe-based interface and the sound warning.

Table 4 shows the success rate of danger avoidance for each warning with and without prior explanation. The success rate of danger avoidance was higher with the sound warning, although the difference was only by one person in the cases with and without prior explanation. In addition, Table 4 shows the stopping distances for each warning with and without prior explanation. A corresponding t-test was conducted with a significance level of 5% for the stopping distance for each vibration and sound warning. The t-test results showed $p = 0.0496$ (< 0.05) and $p = 0.0331$ (< 0.05) for the case without and with prior explanation, respectively. Therefore, we found a significant difference in the stopping distance for both vibration and sound warnings with and without prior explanation. In both cases, the stopping distance was shorter with the sound warning.

Table 5 shows the percentage of participants who felt unpleasant and negative emotions as determined using their body temperature and EDA. Two participants failed to have their biological data measured, and several participants were unable to measure their EDA in each experimental condition. Therefore, we only presented the data of those who were able to measure both their temperature and EDA. The percentage of participants who felt unpleasant and negative emotions was 83.3% for the case of vibration warning without prior explanation and 85.7% for that of sound warning without prior explanation, with the latter having a higher percentage. In the case of warnings with prior explanation, 66.7% of the participants felt unpleasant and negative emotions for the vibration warning and 57.1% for the sound warning, with the former having a higher percentage.

In addition, based on the results of the interview with the participants after the experiment, more than 90% of them did not want to move forward with receiving both warnings.

DISCUSSIONS

The results in Table 4 indicate that the existing sound warning was more effective in preventing people from walking than the vibration-based, shoe-based interface. However, because the difference was only observed in one person, it was not considered a large difference.

Regarding unpleasant and negative emotions, we did not find a significant difference between the sound warning and the shoe-based interface using vibration in terms of discomfort, tension, and sense of crisis from the results of the questionnaire. However, the measured biological data showed that the percentage of unpleasant and negative emotions without prior explanation was more than 80% for both warnings (Table 5). Therefore, although both systems cause unpleasant and negative emotions, there are individual differences in the degree of unpleasantness.

Regarding the difference in the percentages between the cases with and without prior explanation, the percentages of feeling unpleasant and negative emotions decreased by 16.6 and 28.6 points for the vibration and sound warnings, respectively. This implies that it is easier to become accustomed to sound as a stimulus compared to vibration. Additionally, habituation to warnings is thought to cause disregard or carelessness of warnings. Therefore, it is an important warning element that the user does not easily become accustomed to the stimulus and continues to feel unpleasant emotions. Therefore, the proposed system is superior in this respect.

The reason for the lower danger avoidance rate in this system may be due to the difference in the rates of sensory information perception and experience. The percentage of information perceived by the five senses is 11.0% and 1.5% for hearing and touch, respectively (Editorial Committee on Educational Equipment, 1972), suggesting that there is a difference in the amount of information received by sensing the stimuli, and that sound may have been more important. The amount of information received by sensing the stimuli may have been greater for sounds. In this study, the installation position and vibration pattern were identified; however, the vibration intensity was not considered. The difference in perception should have been considered by increasing the vibration intensity. Another reason for the difference in experience is that most of the warnings in our surroundings are visual and auditory, and those used in this experiment are also used in home appliances; therefore, the sound can be easily understood as a warning. In the post-experiment interviews, several participants responded in this manner. This implies that the success rate of sound warnings is high because they are familiar to the participants through experience. Alternatively, about the vibration, more than half of the participants stopped walking after sensing something, despite their unfamiliarity with it as a warning. This can be interpreted as an instinctive avoidance of danger. In the interview conducted after the experiment, approximately 94% of the participants opt not to continue walking after receiving our warning, which is also the case with the sound warning. Therefore, we assume that the proposed interface may serve as a warning that calls for instinct.

CONCLUSION

In this study, we developed a shoe-based interface using vibrotactile sensation that does not interfere with audiovisual perception under poor visibility conditions and instinctively promotes danger avoidance. Subsequently, we conducted a comparative experiment to validate the effectiveness of our proposed shoe-based interface, which relies on tactile foot stimulation. We compared its performance with that of a sound warning system adhering to the sound standards established for household electrical appliances by AEHA (AEHA, 2018). The results showed that the interface was slightly inferior to the existing sound warning in terms of the ability to stop a participant from walking; however, this was only observed in one of the participants. The interface exhibited similar and even better performance in terms of generating unpleasant and negative emotions, and reminding people not to keep walking. Moreover, about the vibration, more than half of the participants stopped walking, as they sensed something despite their unfamiliarity with vibration as a warning. Therefore, the interface is considered to be effective in promoting instinctive danger avoidance. Future work will include increasing the intensity of vibration and the number of vibration motors to improve performance. This research is expected to provide a basis for to how to promote more effective avoidance behaviors.

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