Vibrotactile warnings design for improving risks awareness in construction environment

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Construction workers have difficulty identifying potential risks in harsh environments because traditional visual and acoustical alerts are inefficient. This study investigated a new communication method with a wearable tactile-based system to improve worker's hazard perception. Three experiments are reported in relation to this system. The first experiment exploited VR as an experimental tool to compare auditory and vibrotactile warning signals as well as their combination in a simulated construction working environment. Findings demonstrated that the vibrotactile cues induced faster response times and higher affective ratings than auditory alarms, and their combination provided the shortest reaction time. The second experiment compared 7 different vibrotactile patterns varying in intensity, duration, and interval, to identify configurations that led to a higher degree of awareness. The third experiment validated the effectiveness of three selected tactons for delivering information on 3 hazard levels, finding that subjects could identify three-parameter signals with relatively low error. Our findings provide guidelines for designing tactile warning signals, which could help improve hazard recognition and risk perception, especially in construction sites.

Keywords: vibrotactile warnings; wearable system; virtual Reality; response time; affective ratings; vibrotactile Patterns

1. Introduction

The construction industry is a high-risk industry around the world. Most construction accidents result from hazards associated with construction activities and complex environments which lead to high injury and fatality rates. The construction industry has been identified as the highest-risk sector with the highest number of work-related deaths (Enya, Dempsey, & Pillay, 2019). According to the Ministry of Emergency Management of China, there were 1303 deaths in the construction industry in the first half of 2022 (China Central Television, 2022). In the US, the construction and extraction occupations contributed to nearly 20% of fatalities in all occupations, representing 976 workplace deaths (U.S. Occupational Safety and Health Administration, 2020).

Construction accidents occur when employees work within unsafe conditions and are exposed to hazardous injury sources with potential risks of falling from height, object strikes, or mechanical injury (Chi & Han S, 2013; Alsharef et al., 2023). Accordingly, the distance between workers and construction equipment is identified as a measure to determine whether the workers are safe (Shen et al., 2016; Son et al., 2019). Zhao, Xu, and Zhou (2018) proposed a method to specify hazard zones around construction equipment based on the ALARP (As Low As Reasonably Practicable) principle, which differentiated the hazardous area into the core hazard zone, alert zone, and warning zone to indicate three different levels of risk.

Therefore, it is important that any potentially risky proximity between workers and equipment can be detected as early as possible so that construction accidents can be minimized. For this purpose, the application of information technologies and sensing devices on construction sites can help detect the proximity of workers to hazards, including technologies such as Radio-frequency

Identification (RFID), global positioning system (GPS), ultra-wideband (UWB), Bluetooth low energy (BLE) and Computer Vision (CV) (Soltanmohammadlou, et al., 2019). Furthermore, these real-time location systems (RTLS) can be integrated with Building Information Modelling (BIM) tools, allowing dynamic definition of hazardous areas within the model and using a real-time worker's location to alert them when they approach predefined risks (Park, Kim, & Cho et al., 2017). For example, Redpoint Positioning Corporation proposed a wearable system for real-time tracking and communication, which combined RTLS tags and the BIM platform to send warning signals via indicators on the safety vest (Kanan, Elhassan, & Bensalem, 2018).

However, whilst recognition of potential hazards and providing clues about risky proximity to unsafe locations is the first step, workers' promptly perceiving the detected information and taking the correct measures is the second step in accident prevention. Traditional forms of alerts on construction sites are visual and acoustical warnings, such as placing warning signs in hazardous areas using flashing lights or beeping sounds. However, these approaches were often found inefficient in harsh construction environments (Sakhakarmi, Park, & Singh, 2021), because most construction tasks involve a relatively high visual workload, and workers may not be aware of task-unrelated visual or auditory stimuli when they are focused on their work. This phenomenon is called "inattentional blindness" or "inattentional deafness" based on Multiple Resource Theory (MRT) (Basil, 1994), which proposes that high perceptual load in a task can reduce detection sensitivity in vision and hearing, as perceptual resources are limited. In many cases, sound alerts may be masked by ambient background noise generated from construction vehicles and activities. Thus, construction environments overload or mask workers' auditory and visual channels, which presents challenges for them to receive alarm signals and take action promptly.

Therefore, it is imperative to provide workers with additional senses that can offer reliable and intuitive information in harsh environments. MRT recommends that when the primary channels are overtaxed or unavailable, possible alternate sensory channels can be used to convey information (Wickens, 2008). Unlike vision and hearing which transmit cues through the air, the sense of touch can directly contact with skin and provide feedback more conspicuously (Kacznaarek & Bach-Y-Rita, 1995). Previous investigations with tactile displays have demonstrated its potential to improve situational awareness when vision or hearing may be restricted or overloaded, and it may be particularly useful for danger warning and navigation (Van Veen & Van Erp, 2003; Cassinelli, Reynolds, & Ishikawa 2006). For example, research in safe driving has reported that vibration signals can elicit faster responses by drivers in collision avoidance tasks than traditional visual and auditory warnings (Haas & Van Erp, 2014). Another critical question is the optimal means of presenting tactile signals, and researchers have attempted to identify combinations of tactile parameters for conveying information effectively (Jones, 2011).

Although the utilization of tactile displays as an information delivery mechanism supports a variety of applications in aerospace, military situations, and in-vehicle systems, few studies have compared the haptic modality with other channels in construction environments. Further, prior studies on tactile language do not address how to design effective tactile messages that comprise hazard information for construction safety.

In this study, we developed a head-mounted tactile device that can alert users to hazards on construction sites. Using this system, three experiments were conducted with the intent of determining whether tactile stimuli are effective in improving construction hazard recognition. The first experiment compared auditory and vibrotactile warning signals as well as their combination, which was tested in a virtual reality-based experiment environment. Participants were required to simultaneously carry out a simulated construction task (the main task) and a reaction time task (the secondary task). The reaction times and the subjective ratings of stimulation were measured. In the second experiment, 7 different vibrotactile patterns were created by manipulating parameters of vibration intensity, duration, and interval, with the aim of identifying combinations that boost a higher degree of awareness. Then, in the third experiment, three tactile signals were selected to further test the perception ability of users, in order to validate whether artificial tactile stimuli could be used effectively to deliver information on three hazard levels, response times, and error rates for distinguishing hazard rating were measured. In our first experiment, we conclude that (a) adding tactile cues to an existing auditory warning signal provided the shortest response time (1755.3ms on average) in the virtual construction workplace, and tactile alerts alone led to faster response than sound alerts (1900ms and 2626.3ms on average), and (b) vibrotactile signals alone or in combination with audio modality induced higher arousal and negative valence ratings. In our second experiment, we concluded that high-intensity vibrations were more noticeable than low-intensity ones, and signals with shorter duration and intervals were rated more alert and annoying. In the third experiment, we found that participants can identify 3-parameter signals with relatively low error, which means that tactile parameters can be used to map realistic hazard levels.

2. Related work

2.1. Comparing Tactile and Audio Modality

Several important perceptual properties of tactile modality bring its unique advantage in displaying information: it is a bi-directional, obligatory sense that can directly act on the skin and capture attention, its proximal nature also enables users to convey information in a private manner (Jones & Sarter, 2008). Moreover, the tactile signals can be detected in a “gaze-free” state regardless of users’ eye and head directions, so it was used to assist blind or visually impaired people to receive visual information at first (Dufresne, Martial, & Ramstein 1995). Palani et al. (2020) explored the feasibility of touchscreen-based haptic feedback for perceiving visual graphical elements. Further applications of tactile information presentation were mainly used for alertness, spatial orientation, and communication (Zhu et al., 2020; Lu et al., 2013).

Previous studies that compared the effectiveness of tactile modality and the audio modality usually focused on three metrics: reaction time, task accuracy, and psychological load. The relative benefits of unimodal tactile displays may depend on the type of information. Several studies have revealed that tactile modality may be appropriate for presenting warning information (Chai et al., 2022). For example, in driving simulation experiments, drivers responded to the vibrotactile warning with a directional cue faster than the auditory warning signal (Murata, Tanaka, & Moriwaka, 2011; Chang, Hwang, & Ji, 2011), indicating that the utilization of tactile stimuli can promote driver alertness better. Murata and Kuroda (2015) found that the response time of the auditory cue increased with the increase of noise level, while the tactile signal was not affected by the surrounding noisy conditions. Similar results were found when participants performed the auditory numerical serial search task (ACT); tactile cues had advantages in terms of search time and accuracy (Hopkins et al., 2017). Moreover, in a simulated flight scenario study, Lutnyk et al. (2023) found that the use of a tactile belt significantly improved the identification of external waypoints and reduced the cognitive workload of pilots. However, some studies found that there was no significant difference between auditory and vibrotactile warning devices (Calhoun et al., 2003), and in situations wherein complex information being transferred, auditory warnings promoted faster reaction to the hazard (Freeman E et al., 2017). In certain situations that require transferring complex information, participants were unable to associate tactile stimuli with warning signals because their capacity is more limited than visual and auditory capacities (Jones & Safter, 2008).

In addition, multimodal warning signals can be constructed by combining vision, hearing, and touch. However, research that compared the effectiveness of multimodal and unimodal warning displays has demonstrated inconsistent results. According to a meta-analysis, adding redundant tactile displays on the basis of visual or auditory displays could improve performance when presenting alert and spatial information (Chai et al., 2022). Several car-driving-related studies have demonstrated that multimodal displays (a combination of visual, acoustic, and vibrotactile) led to faster reaction times and lower psychological load than single mode (Ho, Reed, & Spence, 2007). An investigation conducted by Lee et al. (2006) has yielded inconsistent results, which compared a visual icon, an auditory warning tone, two different tactile signals, and a trimodal combination of them; no significant differences in response times between the multimodal and unimodal signals were found.

Most of the previous works that compared different sensory modalities were conducted in the lab, and only a few tests were carried out in the field environment. Although a lab-based test is useful in minimizing risks for hazardous tasks, it cannot fully replicate truly environmental conditions, and the perceptual load is relatively low in the lab without exerted workload or physical danger (Lavie, 2005). Besides, unlike a structured lab environment, there are a number of variables in a real environment; any ambient vibration and users' body movement might interfere with the ability to perceive and process tactile cues. Accordingly, tactile warning signals should be tested under ecological conditions of high perceptual load Meng and Spence (2015). It should be noted tests in real construction sites might cause challenges in building a controlled experimental setup, including uncertainties and risks that endanger the safety of participants. Therefore, Jelonek and Herrmann (2019) suggested that virtual reality (VR) can be used to provide experimental environments for risky behavior tests, in which realistic hazard scenarios and dynamic threats can be simulated with no exposure to any actual risks. VR has emerged as a safety training tool by emulating construction work tasks, and it supports maintaining the attention of participants (Fiala, Jelonek, & Herrmann, 2020). Moreover, the VR model enables researchers to detect and record users' threat avoidance behavior, which may generate data for further analysis (Kim & Ahn, 2020). Based on these findings, in order to examine the effectiveness of three different warnings in helping avoid danger, the first experiment of this paper evaluated participants' physical responses to hazards in virtual reality environments, in which a construction phase and hazardous situations were re-enacted based on a construction site model.

2.2. Tactile design

The perception of vibrotactile stimulation depends on frequency, amplitude, temporal pattern, and spatial pattern (Kerdegari, 2017), which can be manipulated to encode information. The parameters of vibrotactile frequency and amplitude will affect perceived intensity. Temporal attributes of vibration, including duration, the inter-stimulus interval (ISI), the repetition period, and the number of pulses, are other variables that can be grouped to create rhythm. Other attributes that have been used to represent spatial cues include tactor location, inter-tactor spacing, stimulus area (size), the number of tactors, and their spatial arrangement.

Through manipulating one or more of these dimensions, tactile icons (tactons), which are structured abstract tactile "messages", have been designed to convey complex information (Brewster & Brown, 2004). Pasquero (2006) proposed that effective tactile icons must be universal, intuitive, and easy to learn and memorize with meaningful content. To facilitate the creation of tactons, a variety of authoring tools and platforms have been developed for editing and testing tactile patterns. For instance, Enriquez and MacLean (2003) developed a software tool that enables users to create new tactons either by recording direct motion or concatenating predefined waveforms varying in amplitudes, frequencies and durations. Swindells et al. (2006) indicated that complete haptic icons require considerations of haptic types, interactions, biological properties and meaning, and their haptic icon prototyping tools introduced the 'haptic tiles' concept to organize haptic icon primitives for rapid iteration. The authoring tool developed by Ryu and Choi (2008) included several novel interaction features such as a multi-channel timeline interface, which enables designers to design tactile patterns for multiple vibration motors. Additionally, several vibration editors have been implemented using web tools that provided multiple types of example access for users to learn vibrotactile design conventions (Schneider &

MacLean, 2016), and some of these tools were specially developed to support the design of vibrotactile patterns for mobile and wearable applications (Terenti & Vatavu, 2023).

However, transmitting information via tactons is much more difficult than using visual icons or auditory icons because our capacity for processing tactile information across the skin is limited. For example, Brown and Kaaresoja (2006) developed seven tactons that could be used to convey three different types of alerts and the priority of each alert, and participants could recognize 75% of these tactile alerts. Another study evaluated tactons presented at the forearm and index finger (Azadi & Jones, 2013), but their participants' identification rate was low (57%). Cho and Park (2018) generated tactons varying in intensity, duration, and interval within a certain range and found that three distinguishable signals were clearly identified for the signal intensity and duration. However, for the intervals between signals, participants were only able to distinguish two separate categories. Thus, given the narrow bandwidth of the tactile channel and limited perceptual resolution, it is suggested that tactile signals should be simple, distinguishable, and interpretable so that users can recognize and understand them immediately (Baldwin et al., 2012).

Therefore, an important issue that should be considered is the optimal means of presenting tactile warning signals for conveying urgent information. Among different dimensions of vibration, temporal variation and body locus hold the most promise for encoding tactile information efficiently (Wenzel & Godfroy-Cooper, 2021). Wolf and Kuber (2018) investigated the effects of the tactile parameters (amplitude, interval, and waveform) on participants' situational awareness, and the findings revealed that the changes in the interval were rated more useful and noticeable. Seifi and Maclean (2013) identified that vibrotactile rhythm patterns (duration of vibrations, intervals, and the number of pauses) would affect subjective ratings (calm/alarming, unpleasant/pleasant). They found that longer vibrations with fewer pauses were rated as stronger, smoother, and pleasant, while the patterns with short vibrations were perceived more alarming and unpleasant. Lins et al. (2018) recommended pulse with lengths of 150ms and 2 or 3 repetitions for maximum attention. Previous studies have shown that tactile warnings with a higher vibrotactile intensity would also increase the level of perceived urgency (White, 2011), which results in faster response times and more accurate responses (Lee & Spence, 2008).

However, in the context of tactons design for hazardous construction scenarios, existing research that directly investigated the relationship between the parameters of vibration and the perception of alert is limited. In order to further examine the effects of stimulus intensity and temporal attributes on the affective ratings and response times, seven representative patterns were employed in the second experiment of this paper. Three patterns were chosen and mapped to hazard levels (low, medium, and high) to examine the detection and identification performance of tactile patterns in participants.

2.3. Application of tactile technology in industry

Tactile cues can be delivered through cutaneous devices and provide noticeable tactile signals but are not aversive. Particularly for the AEC (Architecture, Engineering & Construction) industry applications (Nnaji C & Awolusi, 2021), it may be desirable to integrate tactors with garments or protective gears that are wearable and attached to the user's body. The main types of haptic devices are haptic vests, jackets and belts, and haptic devices that can be mounted on the head, wrist, fingers, legs, and feet. Vibrotactile tactors are commonly used to create continuous tactile stimulation on the skin due to their low cost, smaller size, and relatively good control qualities (Adilkhanov, Rubagotti, & Kappassov, 2022). The implementation of wearable sensing devices offers positive prospects for safety and health monitoring within the AEC industry, as workers do not need to carry additional devices or rely on solely on innate sensing (hearing and vision).

Yadav (2017) tested four haptic devices to identify the optimal location for the wearable haptic device, including a wristband, neckband, safety vest, and hard hat. According to the phenomenological interview, participants showed their preference for haptic hardhat, which they deemed more weatherproof, traceable, and acceptable. Li et al (2014) proposed an intelligent helmet to detect workers' abnormal and unsafe behaviours. Vibration motors were integrated into the helmet to alert the operator, and the risk of an accident was calculated by combining head gesture recognition with the EEG data. Kerdegari, Kim, and Prescott (2016) developed a tactile display that can be fit inside the helmets for guiding users in low-visibility environments. Results showed that continuous tactile commands presented by the head-mounted device can facilitate rapid reactions to obstacles. Data from the Likert scale also proved that the tactile helmet was acceptable to wearers, as they considered it to be comfortable and easy to use, and the vibrotactile tactors were not irritating.

The above studies indicate the potential for using head-mounted tactile displays. However, compared to a hand-mounted or waist-mounted haptic device, there is still a general paucity of studies exploring the design space for interacting with vibratory motors placed on the head. Research suggests that the tactile discrimination and sensitivity of the skin vary across different body parts (Dim & Ren, 2017). Gilliland and Schlegel (1994) reported that 100% of tactile stimuli presented on the scalp could be detected by all participants. Moreover, participants' responses to identifying the signal location would be slower with the increase in the number of different stimulus sites. Myles and Kalb (2010) performed a series of studies according to the international 10-20 system for electrode placement, which identified that the forehead, temple, and occipital regions of the head were more sensitive to vibration than other regions of the head. Their further research confirmed that glabrous skin was more sensitive than hairy skin. Oliveira et al (2016) also assessed the perception of four regions around the head (frontal, temporal, occipital, and frontotemporal positions), the glabrous skin of the forehead was found to be the most sensitive position with high tactile spatial acuity. Research undertaken by Diener et al. (2017) has shown inconsistent results regarding perceptual thresholds for head regions. In their study, compared to the occipital and temple regions, the frontal regions of the head were less sensitive, with a relatively low accuracy at localizing stimulation.

Based on these studies, there is a need to investigate the effects of head-mounted tactile displays on improving risk awareness. Therefore, we developed a vibrotactile head-mounted prototype described in section to alert users approaching predefined hazardous areas in virtual construction, providing an example of using VR as an experimental tool to investigate users' behavior. The ultimate goal of this work is to provide guidelines for designing wearable tactile displays for the construction industry.

3. Research Methodology

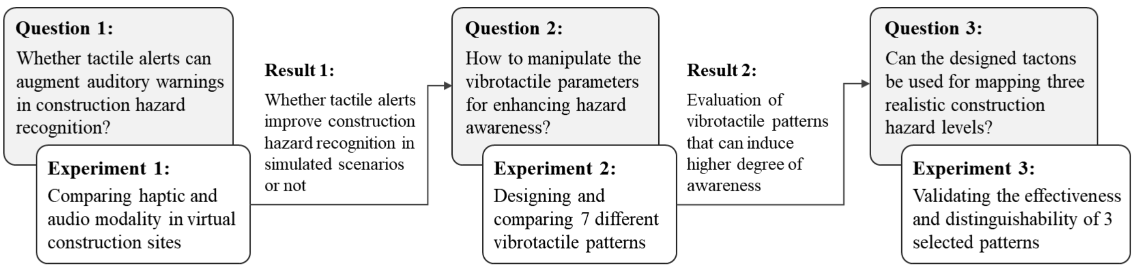


Figure 1. The research framework of our study

The aim of our research is to develop a warning method of the tactile-based warning system that can improve the hazard perception of workers, and to explore the design space for presenting tactile commands in construction environments. The research unfolds across three interconnected experiments, each designed to address a specific research question (see Figure 1).

The research question 1 is whether tactile alerts can augment auditory warnings in construction hazard recognition, in order to confirm that the addition of tactile warnings can boost hazard awareness compared to existing acoustic warnings. Thus, in our first study, we test and compare the effectiveness of tactile modality, auditory modality and their combination. To minimize the gap between the lab setting and the actual construction sites, and to ensure a completely safe test setting, our first experiment is conducted in the VR-based environment. This environment enables us to simulate the on-the-job construction tasks and observe participants' responses to repeated hazardous situations. The reaction times and the subjective ratings of stimulation are measured to identify whether tactile alerts can improve hazard recognition in simulated construction scenarios.

Once the capability of tactile alerts for enhancing hazard perception has been demonstrated, further study is needed to identify the effective vibration signal profiles for the warning purpose. Therefore, the research question 2 is how to manipulate the vibrotactile parameters for enhancing hazard awareness. In our second study, we manipulate three parameters of vibration to create a set of tactons, which include intensity, signal length, and intervals between consecutive pulses. The resulting vibratory patterns are evaluated in the controlled lab setting for comparison of reaction times under both sedentary and exercise conditions, to avoid distractors and extraneous variables. The results of Experiment 2 provide insights on which vibration parameters are perceived more noticeable and rated as more alert and annoying.

The research question 3 is whether the designed tactons can be used for mapping three realistic construction hazard levels. And in the third experiment, three vibrotactile profiles and their characteristics that induce high levels of alertness (implied faster reaction times and higher arousal ratings) are selected to map actual construction hazard levels (low, medium, and high). And we compare perception accuracy, perceived urgency, learnability and memorability of these vibration patterns to validate the effectiveness of tactile signals as an information delivery mechanism.

4. Experiment 1：Comparing Haptic and Audio Modality in Virtual Construction Sites

4.1. Objectives

This research was undertaken to determine whether vibrotactile signals are effective in improving hazard recognition on a construction job site. Different modalities of alarm presentation (auditory, vibrotactile, and combinations of acoustic and vibrotactile) were tested and compared, and reaction time and individuals' affective ratings of stimulus (arousal and valence) were measured.

4.2. Virtual Environment (VE) and Technical Setup

An immersive virtual experimental environment was developed in three phases. Firstly, a deep foundation pit project was selected for the VE development scenario, within which life-threatening hazards in construction sites were simulated. Interactive components and scripts associated with construction tasks were also developed in the VE. Instructions were delivered via the headphones equipped with the HMD, and an ambient construction site recording was looped through wireless speakers.

A pilot experiment was then conducted with eight volunteers to evaluate the presence and credibility of virtual scenarios using the 7-point scale. All participants had prior work experience on construction sites. The average presence and credibility scores are 5.4 and 5.1, respectively, suggesting that the realistic experience was well replicated. Several participants put forward some recommendations, such as adding virtual workers in the VE, to make the presence of the content more convincing. The audio and vibration warning signals were created to represent the hazards in virtual scenarios. To send this information, the Unity 3D engine was used to simulate dangerous situations, and the data from the simulation could be communicated wirelessly to an ESP32 development board driving the buzzer and vibration motor (located at the centre of the head).

As illustrated in Figure 2, the developed hazard communication system consists of the VE software platform, immersive VR displays, and a head-mounted prototype for alarms. This platform can receive data from the hazard proximity detection module in the VE and transmit warning information to participants through sound or vibration. Participants were asked to react to risks when they perceived the transmitted signals. The vibrotactile tactor and buzzer were encased within a custom headband to minimize participants' response times to warning cues, which was adjustable and could be fastened tightly around the head. The response button was also secured with a band and velcro tapes, which could be wrapped around the upper arm and be pressed by participants. The Unity platform and Arduino were connected via Bluetooth communication for this experiment, and the resulting latency of the system is low (with the longest trigger-to-feedback interval recorded under 200 ms).

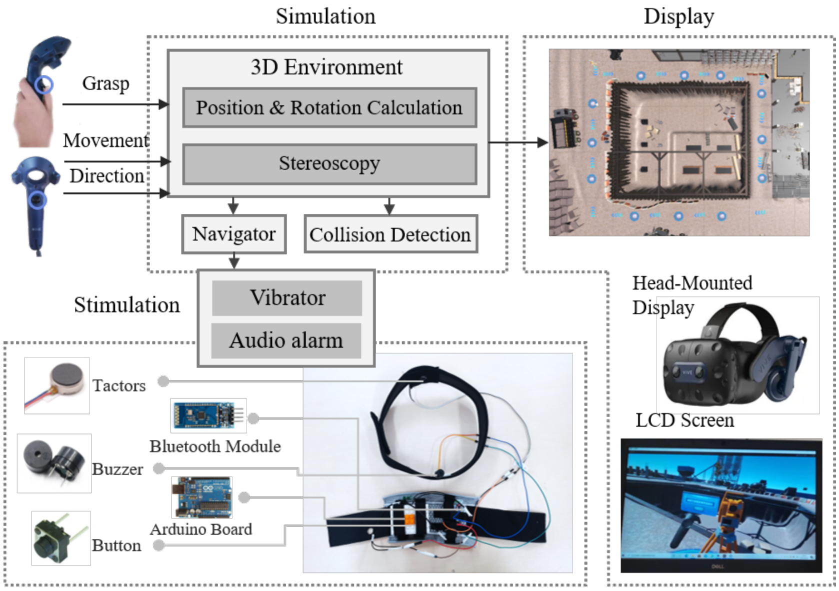


Figure 2. The hazard communication system

4.2.1 The Virtual Construction Environment Setup

The virtual construction environment was based on an already existing model provided by the Unity asset store, modifying the source files significantly to fit the purpose of this research. The measurement process of deep foundation pit was built and modeled, as such a scenario is generally complex and high-risk due to the congested work areas. Dynamic tasks and the surrounding infrastructure repeatedly expose workers to struck-by hazards and other kinds of fatal risks.

Potential hazard scenarios are simulated around the deep pit (see Figure 3), including the area of façade scaffolding, pit edges without safety fence, electrical equipment, moving excavators, the area underneath the tower crane hook, and moving dump trucks. In these dangerous zones, workers would be exposed to risks of being struck by objects, falling from height, contact with

Figure 3. Potential hazard scenarios signals

electricity, or being hit by moving vehicles. The hazardous zone could be defined as a circular region around the working equipment, as shown in Figure 3 (right). The boundary of the high-risk area is based on the size of the equipment and its working ranges. These zones are not visible to the participants, but when they enter the predefined zones, a warning signal will be given immediately to alarm them. The boundary range can be changed in Unity considering the type of equipment; for example, the radius of a circle with a dump truck as the centre was set to 2.5m.

Participants viewed and interfaced with the VE from a first-person view through an HTC Vive Pro headset and two hand controllers (teleporting). In the virtual environment, they were instructed to carry out tasks along the perimeter of the pit, where participants were allowed to move from one telepoint to another by the controller-emitted laser. Six different types of risk scenarios were arranged in a specific order around the designated route; each hazard type appeared three times. Participants would experience a total of 18 hazardous scenarios near the workplace (i.e., 18 alerts would be triggered for each subject). A soundscape of a construction site was looped and played through two loudspeakers in order to simulate a general situation for ambient noise.

4.2.2 VR-based Construction Tasks

To close the gap between the experimental environment and the realistic working conditions, virtual construction tasks were set up to simulate the highly attention-demanding situation and maintain the cognitive load on participants. Participants had to fulfill a measurement task using the virtual levelling instrument, as such tasks are common in monitoring foundation-pit projects. The levelling instrument is an essential tool for measuring height differences. However, replicating the survey operation may be difficult, because several complicated motions cannot be implemented with high accuracy, such as the rotation of the hand (adjusting the knob) or looking through the level's telescope. For ease of use, the process of using it was simplified in this study. All participants started from the same location in the VE, and then they were instructed to follow six steps to complete the task (see Figure 4):

(1) grab the tripod that was attached to the levelling instrument via the VR hand controllers and move them to different locations,
(2) follow directional arrows on the ground to find the benchmark location (255 light circles) near the deep pit, place the tripod in the middle of the circle,
(3) when the tripod was stable, the corresponding user interface would appear in the VE. The participants should level the device and adjust the telescope by clicking the 'Confirm' button of the interface; voice prompts would be given to help participants continue their tasks.
(4) lean towards the instrument, see the device's crosshairs, and focus on an object through the telescope. An interface that projects the same view from the virtual telescope would appear for they to observe,
(5) read the vertical levelling staff shown in the view, and confirm the height difference by interacting with the VR interfaces.
(6) after reading the number, find the next spot and repeat these operations. There were 12 benchmark locations deployed in the virtual site, and the participants had to follow them in sequence.

4.2.3 Signal transmission design

Auditory warning signals. The volume of the background sound used in this experiment was set to around 70 dB(A). This level was set as it was the permissible daytime average according to the Chinese emission standard of environmental noise for the boundary of construction sites (China's Ministry of Ecology and Environment, 2011). For an alarm, it needs to be 10-15dBs above the environmental noise levels (Suter, 2002). A buzzer (42mm×25mm, DC3-24V) was used to

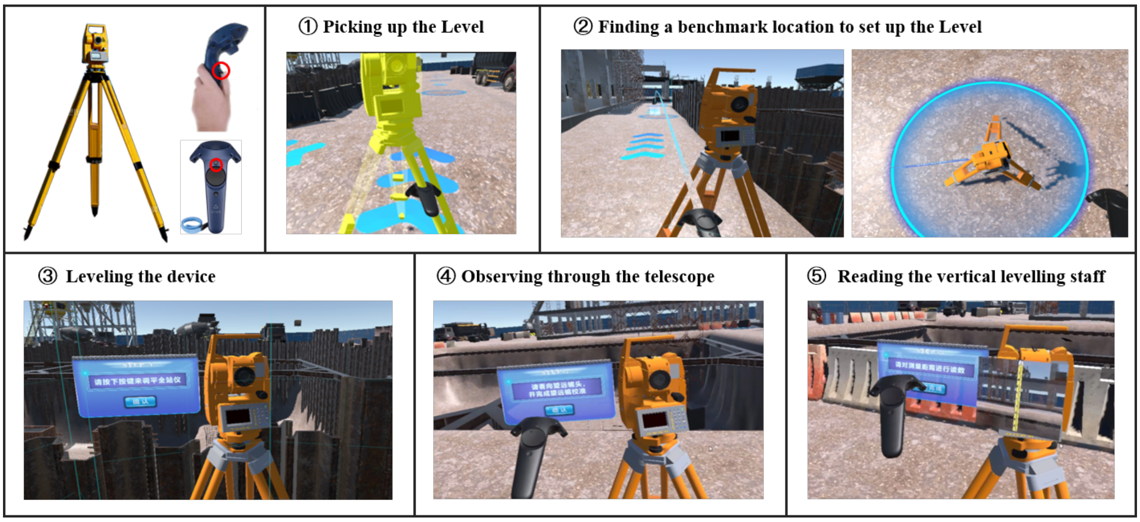


Figure 4. Steps of VR-based Construction Tasks

provide auditory warnings; it can produce a sound pressure level of 85 dB, which is below the threshold that would cause hearing loss (Tikka et al., 2017). Based upon previous studies that explored the optimum design of warning signals (Sanders & McCormick, 1992), signal duration should be more than 500 milliseconds. The duration of audio signals in this study was 600 ms, as recommended by Halabi et al. (2019). It was fastened at the head's occipital region with the headband (see Figure 2).

Tactile warning signals. For communication purposes, easily perceivable strength and temporal parameters were selected to create the vibration signals presented herein. According to tactile design guidelines proposed by Van Erp (2002), intervals between the pulses should be no less than 100 ms. Further, based on recent research using tactile warning signals (Qian, Kuber, & Sears, 2011; Halabi et al. 2019), a duration of 1000ms and an interval of 500 ms were used in this experiment for the signal profiles. The vibrotactile stimulus is provided by the shaftless coin vibration motor via the eccentric rotating mass (ERM) technology (Dobrzynski et al., 2012), which has a diameter of 10 mm and a height of 3.4 mm (Figure 2). The intensity of the motor can be easily perceived when applying 3.3 V power. The vibration motor is equipped with an eccentric rotor (also known as an unbalanced weight or vibration weight) that has a mass of 100 grams-force (gf). The motor operates with a rated current of 80 milliamps (mA) and achieves a rated speed of 12,000 revolutions per minute (rpm), with an allowable variance of plus or minus 3,000 rpm. This vibration motor boasts a total displacement amplitude of 1.5 millimeters peak-to-peak (p-p), and it operates over a frequency range of 10 to 55 Hertz (Hz). And the tactor was located at the centre of the forehead based on the standard 10–20 electrode system (denoted as 'Fp', which refers to the frontal pole), a location that has shown relatively high sensitivity to vibration (Part 2.3).

4.3. Design & Methodology

This experiment utilized a 3×6 repeated-measures design. The independent variables of this experiment were 3 warning modalities (auditory, vibrotactile, and a combination of acoustic and vibrotactile), and six types of hazardous scenarios shown in Figure 3. All variables were within-participants. Each type of alarming stimulus was repeated 6 times in a pseudo-random order. Dependent variables were reaction times and emotional responses (arousal and valence scales).

4.3.1 Participants

Twenty-four participants, aged between 19 and 27 (mean age of 23.4, SD = 1.81), 12 males and 12 females, took part in this experiment. All participants were right-handed, reported normal levels of auditory and tactile perception, and had a normal or corrected-to-normal vision. Four of these participants stated they had some immersive VR experiences in the past; no one reported suffering from simulator sickness. Participants were informed about the experiment and the technical equipment before the experiment; no participants reported having chronic diseases, cardiac problems, or other physical or mental illnesses that would prevent them from experiencing simulator exposure. Participants were reminded that they could stop their participation at any time. Further, all 24 participants were able to complete the VR experiment, which lasted for approximately 60 minutes; they received gift cards as compensation for participating.

4.3.2 Apparatus and material

Figure 5. Environmental Setup

Experiments were conducted in a spacious and bright test room, including an play area of 7m × 7m where participants can interact with virtual objects (see Figure 5). Direct sunlight was blocked in the experimental environment as it may affect the VR experience and even damage the headset. Thus, only indoor light sources were used. A head-mounted display (HMD) from HTC Vive Pro 2.0, with 5K resolution and 120˚ field of view, was used to provide an immersive visual experience. Its hand controllers enabled users to interface with the environment. Headphones embedded in this HMD were used to deliver verbal instructions and background sounds. Two base stations were equipped with this HMD, which were placed in diagonally opposite corners at a height of 200 cm. The virtual reality application was run on a PC with an Intel Core i7-6700K processor and NVIDIA GTX1080 Graphic card.

The vibrotactile motor (positioned at the Fp area of the head) and buzzer used to present warning signals were attached to a Velcro belt that can be worn around the head, and the response button of the hand can be fastened around the user's arm. The PC generated warning messages and sent them to the ESP32 microcontroller wirelessly for onward transmission to electronic elements, and it was programmed to record the reaction time by calculating the time between the stimulus presentation and the button press. A Sony digital camcorder was set up on a tripod to document this experiment.

4.3.3. Procedure

The experimental session comprised two tasks; the primary task required participants to carry out the simulated measurement work in the virtual construction site. The secondary task is a reaction task to hazard, which requires participants to react to a warning stimulus by pressing the button fastened on the left arm as quickly as possible.

The experimental protocol was approved by the research ethics review committee. Upon arriving at the experiment room, participants were informed about the purpose, potential risks, and procedures of the experiment, as well as their right to withdraw from the research. Then, they were asked to sign the consent form.

The complete experiment consists of a practice phase, a formal experiment phase, and an interview phase. In the practice phase, participants were instructed to wear the head-mounted devices and hold the hand controllers. They need to practice using the virtual levelling instrument for measurement under the guidance of the main test. Participants were asked to simultaneously perform the primary task and pay attention to three types of warning signals randomly presented during the experiment (sound, vibration, and their combination). They were encouraged to practice pressing the button with the right hand to respond immediately when they perceived the stimulus. Participants could try out and learn the required operations without strict time pressure until they were familiar with the VR system and could perform the experimental tasks accurately without difficulties. The practice session lasted for approximately 20 min, and participants were then given a ten-minute rest.

In the formal experimental phase, participants should walk along the designated route in the VE; they need to move the levelling instrument to benchmark locations close to the deep pit and conduct the measurement task. There were 12 spots that needed to be measured, and the participants could not jump over any of them. Eighteen hazard scenarios were arranged in a fixed order. An alarm would be triggered to the participant when entering a specified danger zone. In total, each participant received 18 signals (3 warning types × six repeats) in a pseudo-random order. The response time is automatically recorded by the simulation system, and the sequence of the stimulus conditions has been balanced. It took about 30 minutes to complete the simulated tasks.

After the experimental session, participants removed all the wearable devices. They had to rate three alarm signal modes each on arousal and valence scales. A 5-point Likert Scale (calm-alarming, very pleasant-unpleasant) was provided, as Figure 8 shows. Additionally, we redefined the label from exciting to alarming to achieve neutral valence and avoid inconsistent interpretations. The experiment concluded with a simple interview with the participants, which aimed to understand their feelings towards different warning modalities and the acceptance of vibrotactile alerts.

4.4. Data analysis

The response time and affective rating were measured. For analyzing reaction time data, trials that fell three standard deviations above or below the mean response time for each participant were discarded, which might represent a failure to perceive the stimulus or accidentally pressing the button. Three participants who gave seven outliers of all data points were identified and removed from all other data analyses, leaving a resulting data set of 21 participants (N=378 data points, 18 stimuli × 21 participants).

Data analysis was performed using the SPSS 24.0 statistical software. A 3 × 6 repeated measures analysis of variance (ANOVA) test was utilized to analyze the reaction time. The assumption that the RTs followed a normal distribution was checked by the Shapiro-Wilk test, and the homogeneity of variance was checked by the Levene test. The level of alpha (α) was set at 0.05 for analyses of the main and interaction effects, post-hoc pairwise comparisons were computed, and the Levene test checked the homogeneity of variance.

4.5. Results

4.5.1. Response Time

Table.1. Mean and SD of reaction times between the warnings depending on the scenario

Condition	Scenario 1 (ms)		Scenario 2 (ms)		Scenario 3 (ms)		Scenario 4 (ms)		Scenario 5 (ms)		Scenario 6 (ms)		Overall (ms)	
	MN	SD	MN	SD	MN	SD	MN	SD	MN	SD	MN	SD	MN	SD
Audio	3270	1413	2389	896	2882	1454	2337	1200	2452	1260	2428	1567	2626	195
Vibrotactile	2084	803	1889	574	1840	753	2025	636	1770	576	1792	599	1900	109
A&V	1673	420	1674	549	1745	609	1854	757	1838	734	1748	513	1755	108

Table 1 shows the average response times under different scenarios. For all experimental conditions, the distribution of the response times follows a normal distribution, as confirmed by QQ plots and a Shapiro-Wilk test. The assumption that the variances were equal across groups was verified using the Levene test (the P-values were higher than 0.05).

Based on the results of the two-factor (warning mode × hazard scenario) ANOVA with repeated measures, Mauchly's test revealed that the assumption of sphericity for the response times of different warning display modes had been violated ($\chi2(2) = 18.528$, $p < 0.05$). The degrees of freedom were modified using Greenhouse-Geisser epsilons ($\varepsilon = 0.616$). Based on the multivariate analysis of variance examined the within-subjects effects, the main effect of warning mode was significant ($F(2, 19) = 21.246$, $p < 0.001$, $\eta p^2 =$ **0.691**), but the main effect of the hazard scenario was not significant ($F(5, 16) = 1.793$, $p = 0.171$, $\eta p^2 =$ **0.359**). The interaction between warning mode and hazard scenario was significant ($F(10, 11) = 7.012$, $p = 0.002$, $\eta p^2 =$ **0.864**). These results preliminarily show that the mode of warning presentation did have a significant impact on the response time, while the effect of hazardous scenarios was not significant.

The post-hoc pairwise comparisons with Bonferroni correction for warning mode was plotted in the boxplots of Figure 6. In these plots, the mean is indicated by black diamonds, and the boxes represent the median, upper, and lower quartiles. While the whiskers represent the maximum and

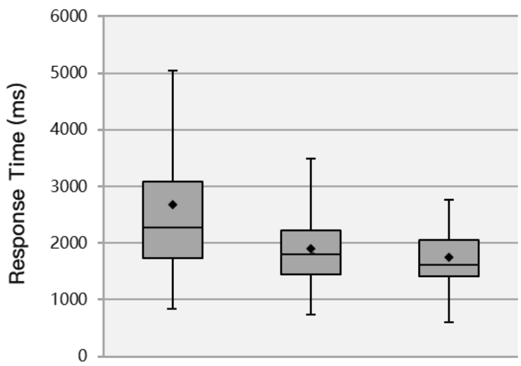


Figure 6. The response time of 3 different warning patterns, with diamond representing the mean.

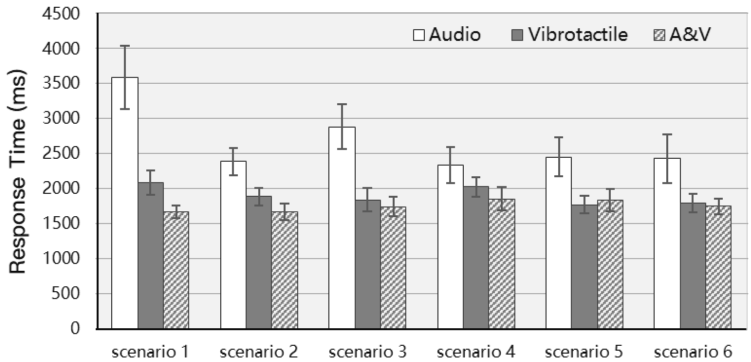


Figure 7. The response time of 3 different warning patterns under different scenarios.

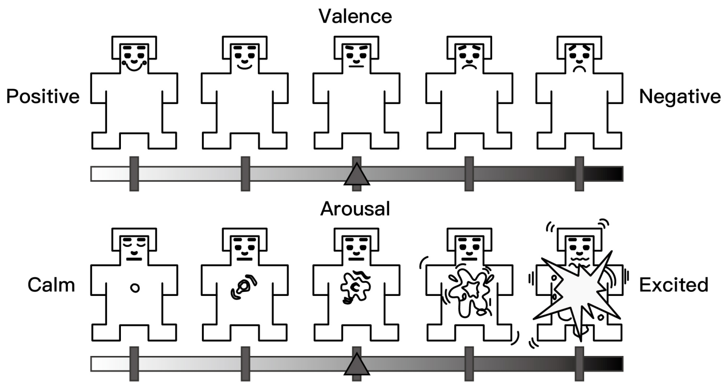


Figure 8. The 5-point arousal/valence scales used to rate the emotional

minimum values. The audio cue conditions provided statistically significant longer reaction times when compared with vibrotactile cues ($p=0.001$, **d = 0.539**) and audio-vibrotactile cue conditions ($p < 0.001$, **d = 0.694**), respectively. But no significant difference was found between the vibrotactile cues alone and audio-vibrotactile cues ($p=0.191$, **d = 0.214**). The means show that participants responded faster to audio-vibrotactile warning signals (M = 1755ms, SD = 108ms), followed by the vibrotactile signals (M = 1900ms, SD = 109 ms), with the audio signals (M = 2626ms, SD = 195ms) being the slowest.

From the post-hoc pairwise comparisons for the "mode*scenario" interaction, as shown in Figure 7, statistically significant differences in reaction times were observed across the three cue conditions within the scenario 1 (façade scaffolding). The bimodality (audio + vibrotactile) was significantly faster in comparison to the audio signals ($p = 0.001$) and the vibrotactile signals ($p = 0.037$), and the vibrotactile group was significantly faster than the auditory group ($p = 0.014$). In scenarios 2, 3, and 5 (pit edges without safety fence, electrical equipment, and area underneath the tower crane hook), the auditory group was significantly longer than the vibrotactile group and the audio-vibrotactile group ($p < 0.05$). However, no statistically significant differences were observed between the other two modes, both of which contained tactile cues. There was no significant difference among the three warning presentation modes in scenarios 4 and 6 (moving excavators and dump trucks).

4.5.2. Affective Ratings

The results of the subjective assessment are shown in Table 2. A Friedman test confirmed a statistically significant difference between the three types of alerts for the arousal ratings, $\chi2(2) = 29.757$, $P < 0.001$, W=0.647, and significant differences were also found for the valence ratings, $\chi2(2) = 35.135$, $P < 0.001$, W=0.764.

Table.2. The subjective arousal and valence ratings of 3 warning conditions

Condition	Arousal		Valence	
Audio / Vibrotactile	Z = -2.875	P = 0.012	Z = -3.686	P = 0.001
Audio / A&V	Z = -4.866	P < 0.001	Z = -5.160	P < 0.001
Vibrotactile / A&V	Z = -1.990	P = 0.140	Z = -1.474	P = 0.421

Results of post-hoc pairwise comparisons with Bonferroni correction are presented in Table 3. In terms of perceived alertness, there was a significant difference between the audio alarm and vibrotactile alarm ($P = 0.012$) and between the audio alarm and the audio-vibrotactile signals ($P < 0.001$), but not between the vibration and the bimodal alarm ($P = 0.140$). The bimodal stimulation was most alerting assessed by the participants (M = 4.85), followed by the vibrotactile

Table.3. Post-hoc pairwise comparisons of arousal and valence scores

Condition	Arousal		Valence	
	MN	SD	MN	SD
Audio	3.43	1.04	3.41	0.77
Vibrotactile	4.51	0.46	4.54	0.42
A&V	4.85	0.28	4.88	0.26
Test statistic	$\chi 2(2) = 29.757$		$\chi 2(2) = 35.135$	
Asymptotic P value	P < 0.001		P < 0.001	

(M = 4.51) and audio signals (M = 3.43). In terms of the valence ratings, the audio-vibrotactile (M = 4.88) and the vibrotactile alarm (M = 4.54) were more unpleasant and differed significantly from the sound (M = 3.41), P ≤ 0.001.

4.5.3. Analysis of interview

To obtain the participants' feedback, we conducted brief semi-structured interviews with each participant separately. Questions were prepared relating to their views of the three different warning modes, including each alarm type's advantages, disadvantages, and application prospects. Most participants perceived signals containing visual cues to be more urgent than the audio cues alone; they thought that the latter might be susceptible to being masked by the noise, and required additional attention. From five of these participants, the sound alerts, which were shrill and piercing, tended to be more alarming than the tactile stimulus. And they stated that the vibration alone was insufficient to evoke negative emotions. The majority of the participants showed their acceptance of the vibrotactile alarm as an additional communication pathway that can compensate for conventional warning systems.

4.6. Discussion

4.6.1. The role of vibration

One of the most important criteria for the evaluation of the warning method is the reaction times, which need to be as short as possible in critical real hazardous situations. In this test, the use of tactile cues provided significantly faster reaction times than the traditional alarm sound and brought significantly higher affective ratings than auditory. Based on insights from interviews with participants, this is probably due to the fact that the sound alerts may suffer from noise interruption. The participants may be unaware of audio signals when they were focused on their task, as the negative effect of visual workload on task-unrelated auditory stimuli had been demonstrated (Raveh & Lavie, 2015).

Moreover, adding a vibrotactile signal to an auditory signal gave the shortest response times, as it had consistently high ratings in arousal and valence scales. Interestingly, there were no significant differences in either response time or affective ratings between only using vibrations compared to using the bimodality (audio and vibrotactile modality). This indicated that the addition of tactile cues plays a crucial role in improving physical response and awareness of people to potential threats; it can be used as a promising alternative or supplementary sensory system when traditional warning cues are unlikely to succeed. Previous investigations have also demonstrated the potential of using tactile warnings in construction environments (Cho & Park, 2018), although these studies were not based on comparison with auditory or visual warnings. Jones and Sarter (2008) stressed the unique benefits associated with the presentation of tactile signals in terms of alerting the users more inconspicuously and unobtrusively than visual or auditory options. Due to the considerable potential in improving spatial and situational cognizance, tactile display technologies have been applied not only in construction scenarios but also in military and aerospace systems (Ngo, Pierce, & Spence, 2012), healthcare environments (Alirezaee et al., 2020) and automobile interfaces (Hogema et al., 2009).

It is also noteworthy that there were differences in the reaction times in terms of testing scenarios in a virtual environment. Unlike other scenario data, no significant difference in response time between the three warning signals was found under scenarios 4 and 6. The temporal gap between different modalities' reaction times was observed to be smaller in these two scenarios with dynamically moving vehicles (excavators and dump trucks, respectively). The influence of testing scenarios on reaction times has already been investigated by (Mueller et al., 2018), which concluded that the less critical the situation, the longer the reaction times. Previous research has also shown that high perceptual load would lead to reduced detection sensitivity in hearing and vision (Raveh & Lavie, 2015). Therefore, whether the test scenarios with different hazardous items have a direct effect on tactile perception should be examined in further studies.

4.6.2. VR as an valid experimental tool

Previous studies showed that the difference in reaction times between the auditory and the vibrotactile modalities is, in general, around 150~200 ms (Murata & Kuroda, 2015; Halabi et al., 2019), which is fairly small in comparison to the response times measured in this experiment (around 720 ms). One possible explanation is that these experiments were tested in lab settings wherein participants did not carry a full workload or be exposed to large and rapid threats. Thus, the ability of participants to perceive warning cues was not interfered with as in the field environment (Ryu et al., 2010). Although the best way to study human behaviours under dangerous situations is to replicate a real-life experimental scene, this would put people at risk and may bring physical danger to the subject. Sakhakarmi, Park, and Singh (2021) conducted a series of field trials to examine the tactile-based wearable system for improving construction workers' hazard perception, but their participants were static and not involved in any construction activities.

Therefore, to narrow the gap between the lab and field-based settings, this paper utilized virtual reality displays to re-enact the hazardous situations of construction sites in a risk-free setting, in which participants engaged in virtual measurement projects would be repeatedly exposed to struck-by hazards and warning signals. A dual-task paradigm was used in Experiment 1 to maintain the cognitive load on participants; incident data was collected, including timestamped locations when participants were in a danger zone and participants' pressing the button. Results of post-experience analysis have demonstrated that different sensory channels were comparable, as the main effect of warning modality was statistically significant (Section 4.5). According to participants' questionnaires in the pilot test, the virtual environment was convincing, and the presence level was qualified. No participants experienced simulator sickness, discomfort, or any issues related to safety during the main test. These findings from this study have demonstrated that not only in the area of safety training (Gupta & Varghese, 2020), VR can also be used as an experimental tool to collect data acquired from subjects' physical responses to hazards and to study human behaviour in harsh environments.

5. Experiment 2：Designing Tactile warning signals for Workers on Construction Sites

5.1. Objectives

This experiment manipulated three parameters of vibration to create seven tactors that were used to communicate warnings, including intensity of stimulation, pulse duration, and intervals between pulses. The resulting tactors were evaluated under both sedentary and exercise conditions to identify which pattern can induce high levels of alertness in individuals and to research how exertion conditions impacted participants' situational awareness.

5.2. Design of the tactile patterns

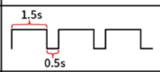
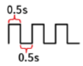
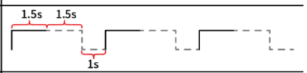
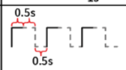
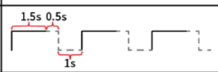
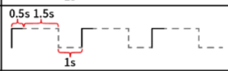
Number	Duration of Strong Pulse	Duration of Weak Pulse	Interval	Vibrotactile Patterns
P1	Infinite	0	0	
P2	1.5 s	0	0.5 s	
P3	0.5 s	0	0.5 s	
P4	1.5 s	1.5 s	1 s	
P5	0.5 s	0.5 s	0.5 s	
P6	1.5 s	0.5 s	1 s	
P7	0.5 s	1.5 s	1 s	

Figure 9. Seven Vibrotactile Patterns.

The values selected for duration, interval, and intensity of tactile warning signals were based on our pilot study. In pilots, temporal attributes were constrained from 0.5s to 3s based on previous studies on tactile design (Lins et al., 2018), and the intensity of the stimulus was controlled by adjusting the duty cycle of the PWM (Pulse Width Modulation) signal that activated the motors. Different combinations of these tactile parameters were presented to participants, who were then asked to make a preference judgement on each stimulus. Participants showed a preference for patterns with a duration of 0.5s or 1.5s, and they preferred that the intervals between pulses be shorter (0.5s and 1s) when being used as an alert. The PWM values were set at 255 and 150 to create a strength contrast between strong and weak pulses.

For our study, the stimulus set used in the main experiment consisted of 7 representative patterns (Figure 9). These warning patterns were rendered in pulse durations of 0.5s and 1.5s and intervals of 0.5s and 1s. The varying proportion of relatively weak vibrations of the total vibratory cycle from the fourth to the seventh pattern, which used low PWM signals (150), was represented by the gray dashed line. As for the black solid lines, they represented high PWM values and, thus the relatively strong vibratory intensity. The first pattern (P1) provides strong continuous vibrations, and the second pattern (P2) consists of high intensity and relatively long durations compared to the third pattern (P3). The fourth pattern (P4) is a long-period mode combined with weak and strong pulses, while the fifth pattern (P5) is a short-period one. The strong pulses were longer than weak pulses in the pattern 6 (P6), while the proportion of weak pulses was higher in the pattern 7 (P7).

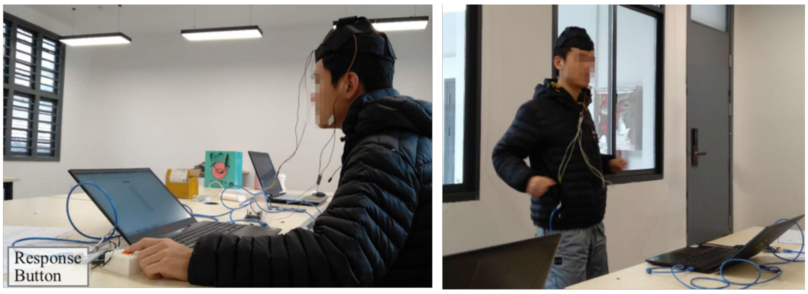
5.3. Design & Methodology

The independent variables of this experiment were vibrotactile patterns and exertion conditions (sitting stationary and doing physical exercise). The dependent variables were the response time and subjective ratings on affective scales (arousal and valence). A within-subjects design was selected for this study to increase the statistical power of any observed effects and to remove the individual differences between conditions. The order of vibrotactile patterns was pseudo-randomized between participants to reduce possible order effects; each pattern was presented twice in one condition.

5.3.1 Participants

Fourteen participants, aged between 18 and 20 (mean 18.5, SD = 0.7), seven males and eight females, were recruited from a university student population. All these subjects did not participate in Experiment 1. All participants reported normal levels of auditory perception and vision and were right-handed, and none reported any deficiencies in tactile perception. Participants received course credit for their participation.

5.3.2 Apparatus and material



(a) (b)

Figure 10. Two exertion conditions.

Experiments were conducted in a spacious and quiet test room. The same head-worn tactile prototype was used as in the first experiment, including a tactile motor and a microcontroller board, which were controlled by the laptop. The PC generated commands for the microcontroller transmitting signals to vibrotactile actuators. For the sedentary conditions, participants were seated at a standard desk in an office chair, as seen in Figure 10(a). A button, which was placed on the desk positioned in front of participants, was used as input for reaction to vibrotactile stimuli patterns. The response time was logged by the PC, measuring the time between when tactile stimuli were provided and when the participant pressed the button. For the exercise conditions, another laptop was used to present exercise instructional videos that participants were instructed to watch, learn, and follow, as seen in Figure 10(b).

5.3.3 Procedure

Before the experiment was initiated, participants reviewed and signed the consent form about the purpose of the study and the experimental procedure. Then, participants were asked to wear the vibration system, and the position of a single tactile actuator was the same as in Experiment 1 (at the centre of the forehead).

During the experiment, participants were required to press the button using the non-dominant hand as quickly as possible when they felt a vibrating sensation in the head. The reaction time for each stimulation was recorded by the PC for later analysis. All participants performed the experimental tasks in two conditions, i.e., static sitting and performing and exercise. The tactile patterns were presented and evaluated under these two conditions to better understand their

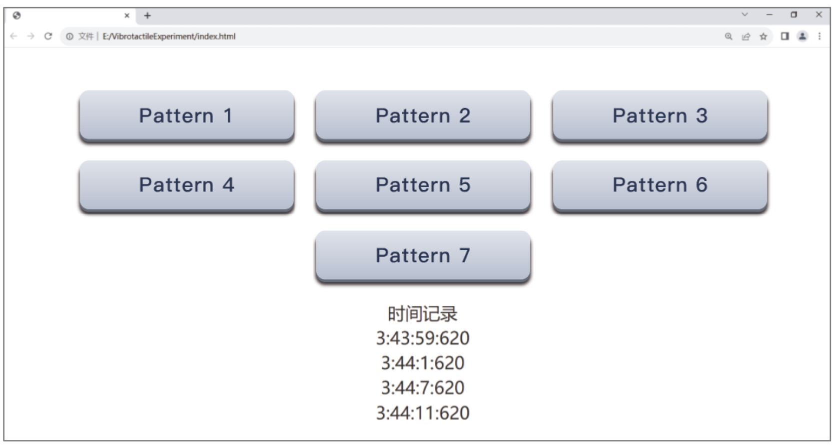


Figure 11. The graphic user interface of the Experiment 2.

potential for promoting alertness when participants were distracted. In the static condition, participants were required to sit in the office chair and put their hands on the desk. In the motion condition, the participants were instructed to perform the exercise by following the workout video, including exercises such as arm lifts, leg raises, and jumping. Each participant performed 28 trials (2 exertion conditions x 7 different vibrotactile patterns x 2 repeats) in a pseudo-random order. The inter-trial interval randomly ranged from 5 to 10 s.

After each motion condition, the participants were asked to rate seven patterns each on affective scales (calm/alarming, pleasant/unpleasant). The 5-point Likert arousal/valence scale was used to evaluate each pattern, with 1 as the most calm/pleasant and 5 as the most alarming/unpleasant. Participants were provided with a customed graphic user interface (GUI) shown in Figure 11, which enabled them to repeat the vibration pattern by clicking the corresponding button using the mouse.

5.4. Results

5.4.1 Response Time

The data of interest were participants' response time and subjective ratings for tactile patterns. For analyzing data, an alpha value of 0.05 was chosen as the level of significance.

A Shapiro-Wilk test and the QQ-plots showed that the reaction time data were normally distributed. We employed a two-way repeated measure ANOVA to test response time with two factors: exertion condition and vibration pattern. Mauchly's test indicated that the assumption of sphericity was not violated ($\chi2(20) = 40.681$, $p > 0.05$). Levene's test showed that the assumption of homogeneity of variance was met ($p > 0.05$ for all the dependent variables).

Repeated measures ANOVA showed that the main effect of exertion condition was significant ($F\ (1,\ 13) = 7.121$, $p = 0.019$, $\eta p^2 = 0.354$), but the main effect of vibration patterns was not significant ($F\ (6,\ 8) = 1.379$, $p = 0.328$, $\eta p^2 = 0.508$), the interaction between exertion condition and vibration pattern was not significant ($F\ (6,\ 8) = 0.755$, $p = 0.623$, $\eta p^2 = 0.362$). We measured the response time of reacting to warning signals in participants under workout conditions and compared these values with sitting in an office chair. The data is plotted in a standard box plot (see Figure 12). Mean reaction time from a total of 392 trials was 2894 ms (SD = 729 ms). As can be seen in Figure 12, for each vibrotactile pattern, reaction times were faster in the static condition (M = 2710 ms, SD = 732 ms) than in the motion condition (M = 3079 ms, SD = 681 ms).

The results showed that the pattern with short vibrations and short intervals (pattern 3) provided the fastest reaction times in both static (M = 2634 ms, SD = 907 ms) and exercising conditions (M = 2875 ms, SD = 675 ms). Similar results were observed using the continuous vibration (pattern 1), and the pattern combined long strong pulses with brief weak pluses (pattern 6),

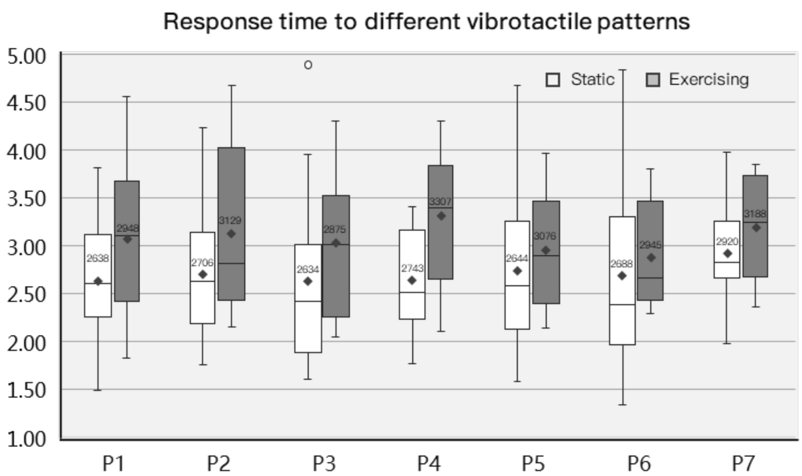


Figure 12. Response time to different vibrotactile patterns.

resulting in an average response time for the static condition of 2638 ms ± 637 ms, 2688 ms ± 984 ms, and for the exercising condition of 2948 ms ± 788 ms, 2945 ms ± 532 ms, respectively. Then followed by the pattern with long vibrations and short intervals (pattern 2) and the pattern with short-period strong pulses and weak pulses (pattern 5). Reaction times were slow when the long-period pattern combined with strong and weak pulses (pattern 4) and the pattern with short, strong vibrations and long weak pulses (pattern 7) were presented, which might be explained by the long duration of weak pulses (of 1500 ms).

5.4.2 Affective Ratings

The results of the arousal and valence ratings are shown in the box plots below, Figure 13 and Figure 14. The Friedman test revealed that there was a significant difference between the valence ratings of the patterns with $\chi2(6) = 18.541$, $p = 0.005$, W=0.221. However, there was no significant difference in the arousal ratings, $\chi2(6) = 10.939$, $p = 0.09$, W=0.130.

The constant vibration (pattern 1) was perceived as the most unpleasant (M = 4.14, SD = 0.95), and its arousal scores were also rated at a high level (M = 3.79, SD = 0.89). As is shown in the post-hoc analysis using the Wilcoxon signed-rank test with Bonferroni correction, for the valence scales, there was a significant difference between the pattern 1 and pattern 3 (p=0.046), pattern 1 and pattern 5 (p=0.025), and between pattern 1 and pattern 7 (p=0.030). The short-period pattern with strong vibrations (pattern 3) was the most alarming (M = 3.86, SD = 1.03), while its valence rating was low (M = 2.71, SD = 0.83).

Patterns with a high proportion of long and strong pulses (pattern 2 and pattern 6) were also perceived as relatively unpleasant, with the same mean valence ratings of 3.21 ± 0.97. And these two patterns elicited high arousal ratings of 3.79 ± 0.89 and 3.57 ± 1.02. As can be seen in Figure 14, the arousal ratings of patterns with long weak vibrations (pattern 7 and pattern 4) were lower than ratings for other patterns, with the average scores of 2.71 ± 1.38 and 3.28 ± 0.83, respectively.

At the end of the entire experiment, participants were asked about their feelings of the 7 tactile patterns. Ten of the participants perceived the patterns with several strong vibrations (pattern 2

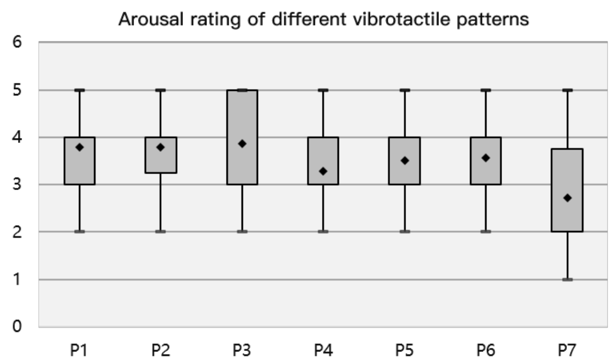


Figure 13. Arousal rating of different vibrotactile patterns.

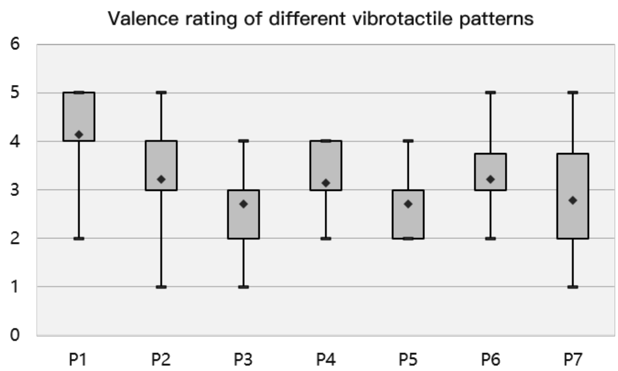


Figure 14. Valence rating of different vibrotactile patterns.

and pattern 3) to be very urgent, but they did not perceive the pattern 3 as annoying because it felt like mobile phone vibration alerts. Four participants indicated that the long continuous pattern (pattern 1) was alarming but non-rhythmic without intervals. Six participants reported that the four patterns consisting of strong pulses and weak pulses (patterns 4, 5, 6, and 7) were not easy to distinguish. While two participants suggested the pattern 6 as the warning alert and one suggested the pattern 7, which indicated individual differences between humans in tactile perception.

5.5. Discussion

5.5.1 Impact of exertion conditions on sensory awareness

Results of Experiment 2 showed that the average response time was longer when the audio signal was presented in exercise conditions (M = 3079 ms, SD = 681 ms) compared with the static condition (M = 2710 ms, SD = 732 ms). This finding indicates that increased physical exertion associated with motion and activity would negatively influence the time taken to respond to stimuli and cognitive workload, probably due to visual and cognitive distractions during the workout.

Related tactile research (Wolf & Kuber, 2018) also found that higher exertion introduced more errors and higher participants' self-reported cognitive workload, and there were masking effects in tactile perceptual performance related to realistic physical and cognitive activity (walking and routine mobile phone tasks). Dim and Ren (2017) investigated differences between vibration perception in the lab setting and in the actual mobile settings and found that participants sometimes missed the vibration while walking in the real-world mobile environment. A similar effect was not observed in our experiment, perhaps because the vibration on the head was unlikely to be affected by the motion. These insights support the conclusion that effective tactile design, especially for warning alerts, should account for the probable deleterious impact of higher exertion on concurrent cognitive workload and tactile perception.

5.5.2 Vibrotactile pattern design for alarms

Experimental results in this study also demonstrated that the designed vibrotactile patterns could be perceived in a short time (M = 2894 ms, SD = 729 ms). However, different patterns varying in pulse durations, intervals, and vibration intensities, induced different responses (reaction times and affective ratings). More specifically, there is a link between response speed and subjective arousal scales: people responded faster to strong vibrations, which they perceived to be more alarming with relatively high arousal ratings, e.g., pattern 3 and pattern 2. From the results of patterns consisting of strong and weak pulses (patterns 4,5,6, and 7), the increase in the duration time of the weak pulses resulted in increased reaction times and decreased subjective level of perceived alarm. Additionally, the duration of strong vibrations seemed to influence valence data, as continuous vibrations (pattern 1) and longer vibrations with short intervals (pattern 3 and pattern 2) were considered more unpleasant. Previous studies also confirmed the impact of tactile parameters on participants' responses. For example, Saket et al. (2013) indicated that more intense vibrotactile alerts provide higher perceived urgency. Baldwin and Lewis (2014) found that the perceived urgency of tactile warnings was a function of the inter-pulse interval(IPI), and reducing the IPI might help to increase the urgency of signals.

For communicating hazard information using the tactile-based wearable system, the vibration signals should be designed to represent specific hazard scenarios to some degree, so that workers could be aware of the hazardous level of potential risks and take corresponding measures to avoid such risks. Based on these findings, in order to create vibrotactile warning signals, which are not only effective but also alarming and unpleasant for alerting people in harsh environments, our results suggest utilizing the pattern 2, pattern 3 and 6 as these patterns implied faster reaction times and higher arousal ratings. Although the long continuous vibrations (pattern 1) have the fastest reaction times, it was considered as smooth and nonrhythmic by the participants, therefore it may not be suitable for transmitting warning information.

Although the authoring tools discussed in Section 2.2 enable the generation of various more complex vibration patterns, we chose to use only one motor and design relatively simple patterns align with our research goal of creating patterns for safety alerts. Because patterns used for hazard response should be easily memorized and learned by construction workers, allowing them to accurately define the level of danger in emergency situations. However, multiple motors that can produce complex vibration patterns and rhythms may not be suitable for hazard response as they could potentially increase the cognitive load on the users.

6. Experiment 3：Validating Communicability of the Identified Basic Unit Signals

6.1. Objectives

Vibrotactile pattern	Duration of Strong Pulse	Duration of Weak Pulse	Interval	Rhythm Diagram	Mapped Hazard Levels
P3	0.5s	0	0.5s		High
P2	1.5s	0	0.5s		Medium
P6	1.5s	0.5s	1s		Low

Figure 15. Arousal rating of different vibrotactile patterns.

A follow-up study was conducted to validate whether the selected vibrotactile patterns could be used effectively to deliver information on hazard levels (low, medium, and high) to individuals and to investigate whether individuals could distinguish three different types of tactile warnings and take action immediately. The evaluation of participants' abilities to differentiate vibrotactile patterns was conducted at two different time points (20 minutes and 24 hours after pattern presentation) to assess participants' memory performance.

6.2. Mapping of the tactile patterns with hazard levels

Based on the structure of construction sites, dangerous regions can be divided into core of hazardous areas, hazardous areas, and warning areas, which involve different degrees of risk. Accordingly, for communication of the hazard level, we established a mapping relationship between the perceived urgency of the tactile warning and the level of situational urgency. The vibration signal profiles were defined based on Experiment 2; three vibrotactile patterns were used to indicate low, medium, and high hazard levels, respectively. Figure 15 illustrates a pictorial view of the vibration signal profiles with different hazard levels.

Pattern 3, which provided fast reaction times and relatively high arousal scales, was used to signify situations of high urgency, such as approaching the area of façade scaffolding. Pattern 2 was used to signify medium urgency, which was perceived as relatively unpleasant, alarming, and urgent by participants, indicating conditions such as approaching the edges of the pit. Pattern 6 signified the low urgency, such as areas near the electrical equipment, as it elicited relatively fast responses in individuals.

6.3. Design & Methodology

The independent variables of this experiment were three vibrotactile patterns (pattern 3, pattern 2 and pattern 6) that indicated different hazard levels and two testing time points (20 min and 24 h later), which were within-participants. The dependent variables were the error rate and response times. The response time measured in Experiment 3 was choice reaction time (CRT). The error rate was defined as the number of incorrect responses divided by the total number of choice reactions. To reduce possible learning effect and sequence effect, the stimuli were presented in a completely counterbalanced design.

6.3.1 Participants

Figure 16. Experimental Setup of the Study 3.

Sixteen able-bodied students (ten males and six females) with an average age of 23.38 years (SD=1.15) participated in this study. All these subjects did not participate Experiment 1 or Experiment 2. All participants reported normal levels of auditory and tactile perception and having normal or corrected-to-normal vision. All of them were right-handed. Participants received gift cards for their participation.

6.3.2 Apparatus and material

In the context of designing haptic warning signals for construction workers, we developed a "Tactile safety helmet" to deliver tactile patterns to the user, which was composed of a vibrotactile actuator fitted to the inside headband and a microcontroller unit. The tactile helmet was connected to a laptop controlled by the experimenter, which automatically logged the types of stimuli generated by the PC and the time alerts were sent out. As shown in Figure 16, three response buttons of the hand were placed on the desk in front of the participants, using markers of different colors (red, orange, and yellow, respectively) to correspond to different levels of urgency (high, medium, and low urgency from left to right, respectively). Another laptop, connected with response buttons, was used to record reaction times and participants' choices on patterns. Both computers were configured to synchronize their system clocks with a Network Time Protocol (NTP) server to ensure synchronicity. To mask the audio produced by the vibration motors, white noise was delivered via wireless earphones (X2 true wireless earbuds, Edifier, Shenzhen, China) at a comfortable volume to mask the tactor noise.

6.3.3 Procedure

Before the experiment, participants provided informed consent about the purposes, rewards, and procedures of the experiment. Then, they were introduced to the tactile parameter terms related to the three types of alerts in Figure 14, and the test conductor explained the relationship of correspondence between the vibrotactile pattern and the level of urgency.

During the training, participants were asked to wear tactile helmets and experience these patterns to help them familiarize themselves with the vibration patterns corresponding to different hazard levels. They were required to perform a judgment task of three hazard levels (high, medium, and low) by pressing the corresponding button for each transmitted tactile signal. In addition to remembering the exact meaning of each vibrotactile pattern, pre-instructions also required participants to react as soon as possible when they perceived the transmitted information.

Once participants could differentiate between vibration patterns and select the buttons correctly, they were asked to attend two test sessions. The first session was tested 20 min after the training. The second test session was carried out 24 hours after the first session. During the tests, participants received vibration signals containing information related to the level of hazard. On receiving signals, the participants made choice responses by pressing the button, as pre-instructed during the practice phase. In total, each participant performed 24 trials (2 testing points x 3 types of haptic patterns × 4 repeats) in a random order. After completing all trials, each participant was also asked for any impressions of the vibrotactile patterns and ease or difficulty in identifying the corresponding hazard level of the signals.

6.4. Data analysis

The two primary metrics used in this study include the error rate and reaction time. The error rate analysis was conducted using the Chi-Square test, which detected differences between groups since the data were not normally distributed. Response times below or above three standard deviations from the average were discarded from the analysis. A two-way repeated measures ANOVA (analysis of variance) was used to analyze the effects of vibrotactile patterns and testing time points on response times. Trials on which participants responded incorrectly were discarded from the ANOVA test.

6.5. Results

6.5.1 Rate of error in tactile parameter identification

Table.4. Error rate and response times in correct trials of three different patterns

Tactile Patterns	Error Rate (%)			Response Time in Correct Trials (ms)		
	20min later	24h later	Two time points	20min later	24h later	Two time points
Pattern 3	3.17%	6.78%	4.92%	3044 ± 1542	2419 ± 1261	2753 ± 1447
Pattern 2	4.69%	11.29%	7.94%	5137 ± 2772	4313 ± 1939	4631 ± 1894
Pattern 6	1.54%	3.39%	2.41%	4935 ± 2816	4168 ± 2697	4584 ± 2778
In Total	3.12%	7.22%	/	4290 ± 2312	3601 ± 2226	3979 ± 2296

Based on the aggregated data for error rate, the average accuracy for all participants was 94.89%, with 19 incorrect identifications out of 372 signals. As the parametric assumptions for the error rate were violated, a Friedman test was conducted to analyze the error rate of different vibration patterns. The results revealed that there was no significant difference between the three patterns, $\chi 2(2) = 3.263$, $p = 0.196$, $W = 0.102$. As can be seen from Table 4, the incorrect rate of the vibrotactile pattern 2 (signifying the medium level) was relatively higher than the other two patterns, with 7.94% incorrect perceptions. The average error rate of the pattern 3 and pattern 6 over the two test sessions was 4.92% and 2.41%, respectively.

Participants could identify three different rhythms with a relatively low error rate of 3.12% in the first test session, while they made more errors in identifying the level of urgency during the second test session, with the average error rate reaching 7.22%. A Wilcoxon Signed-Rank Test indicated that there was no significant difference in the error rate between the two different time points, Z = -1.807, P = 0.071, with an effect size r = -0.467. Based on individual assessment of the tests, eight errors occurred as participants incorrectly pressed the "the low level of urgency" button when the pattern 2 (signifying the medium urgency level) was presented. Similarly, two errors occurred because participants incorrectly selected "the medium level of urgency" when the pattern 6 (signifying the low urgency level) was transmitted. This means that the majority of inaccuracies in the judgement were between pattern 2 and pattern 6. Additionally, there were three signals of the pattern 3 (signifying the high urgency level) were misperceived as "the low level of urgency", 3 signals of the pattern 2 were misperceived as "the high level of urgency", and one signal from the pattern 6 was incorrectly perceived as "the high level of urgency."

6.5.2 Choice reaction times

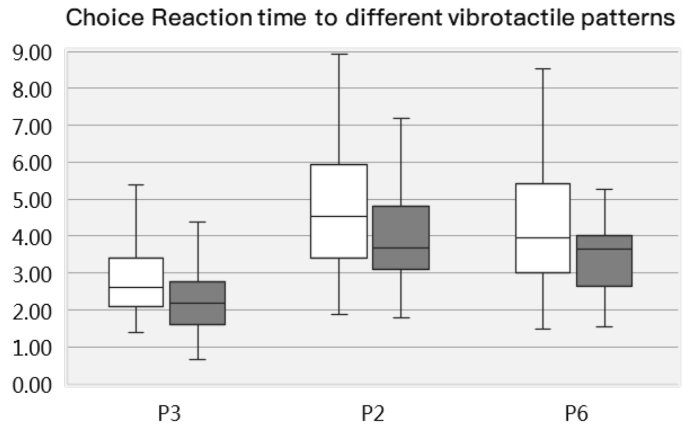


Figure 17. Choice Reaction time to different vibrotactile

Based on the aggregated data (Table 4) for reaction time, the mean choice reaction time from all trials was 4001 ms (SD = 2749 ms), and the mean reaction time of the correct responses was 3979 ms (SD = 2296 ms). Based on the results of the two-factor ANOVA with repeated measures, there was a significant main effect on choice reaction time for testing time points ($F(1, 63) = 8.897$, $p = 0.004$, $\eta p^2 = 0.124$). The main effect of the vibrotactile pattern was significant ($F(2, 62) = 80.563$, $p < 0.001$, $\eta p^2 = 0.722$), but the interaction between vibrotactile pattern and situation was not significant ($F(2, 62) = 0.149$, $p = 0.862$, $\eta p^2 = 0.005$).

Post hoc testing using the Bonferroni correction indicated that the response time for identifying the level of urgency in the second test session (M = 3601 ms, SD = 2226 ms) was significantly faster than the first test session (M = 4290 ms, SD = 2312 ms) after a 24-hour interval, $p < 0.01$. Post hoc tests also showed that there was a significant difference in reaction time between the pattern 3 and the pattern 2 ($p < 0.001$, d = 0.900), and between the pattern 3 and pattern 6 ($p < 0.001$, d = 0.714), but no significant differences between the pattern 2 and pattern 6 ($p > 0.05$, d = 0.019). As can be seen in Figure 17, reaction times were fastest when presented the pattern 3 (M = 2753 ms, SD = 1447 ms), followed by the response time for recognizing the pattern 6 (M = 4584 ms, SD = 2777 ms) and the pattern 2 (M = 4631 ms, SD = 1894 ms).

6.5.3 Analysis of interview

Most of the participants (11/16) reported that the three different types of vibrotactile patterns were easy to distinguish, and they were able to identify the hazardous information conveyed by the tactile warnings easily in most cases. However, only two participants stated that they might forget some details of these patterns and their corresponding hazard levels, which did not agree with the results of error rates (six participants made more errors on the second day).

In addition, nine participants reported that sometimes they may be confused between pattern 6 and pattern 3, because the beginnings of these two patterns were perceived as very similar, and they thought the pattern 2 was the easiest to distinguish with the shortest period. Five participants stated that the pattern 6 led to more accurate identification because it had weak vibration pulses which created an intensity contrast.

6.6. Discussion

6.6.1 The effectiveness of the designed vibrotactile patterns mapped to different hazardous levels

The test results demonstrated that 94.89% of the signals transmitted with the wearable system could be well-perceived and identified by the test participants. This indicated that the set of three selected vibrotactile patterns is reliable for communicating different hazard levels with a head-mounted tactile display. And it is worth mentioning that the average choice response time of all trials (M = 4001 ms, SD = 2749 ms) was longer than CRTs of correct trials (M = 3979 ms, SD = 2296 ms), probably because it may take more time for participants to make a judgement when they have confusion about the presented signals.

Although the three tactile patterns could easily be learned in the absence of workload and within a short-time training, the increased error data after a 24-hour interval showed that participants' memory of tactile alerts and their meaning would decline over time. Interestingly, inconsistent with the worse accuracy, participants seemed more confident with their decisions in the second testing point with a significantly faster choice response time. One possible explanation is due to the learning effect as the participants become familiar with the repeated signals. However, the misperceptions would also be reinforced without prompt correction.

Given the limits on the human capacity for processing and learning tactile information, optimizing participants' identification performance of tactors (response speed and accuracy) requires that tactile signals remain distinguishable (Poupyrev, Maruyama, & Rekimoto, 2002). In this experiment, in terms of self-reported views gathered regarding the three vibrotactile patterns composed of three parameters (pulse duration, intervals, and vibration intensities), the majority of participants reported that the perception of vibrotactile patterns seemed largely depend on temporal cues. This may be why participants' confusion between the alerts of pattern 2 and pattern 6 contributed to most of the misperceptions (10/19), as these two patterns have nearly the same beginnings (1.5s strong vibration). However, several participants felt that changes in intensities were more noticeable than temporal parameters, and they reported that the pattern with changing intensities (pattern 6) seemed much easier to distinguish from other patterns because the strength contrast between the strong pulse (PWM = 255) and weak pulse (PWM = 150) was noticeable.

6.6.2. Tactile warning signals design guidelines

This experiment aimed to design tactile warning signals that can convey meaningful hazardous information (that is, workers ideally need to be able to identify the meaning conveyed by the tactile warnings easily). It is clear that vibration duration, intervals, and intensity would be useful parameters to vary in a tactile display; all can be manipulated as variables to encode information. However, since participants' perception of vibrotactile patterns appears to largely depend on temporal cues (duration and inter-pulse interval), this suggests that noticeable difference should be designed at the onset of vibration. Otherwise, if different vibrotactile patterns were designed to have similar parameters at the beginning, participants cannot make judgement immediately with no delay, like pattern 6 and pattern 2. Our results also suggest that tactons encoded with changing intensity are recommended. More specifically, although the stimuli with high intensity would be perceived as stronger and rated as more alarming, strong and weak vibrations can be combined to create patterns with relatively higher contrast, which could be reliably distinguished from other patterns by participants.

Additionally, designers should be aware that it is essential to train the workers to learn the tactile-based language, which can familiarize them with the meaning of different vibration signal profiles so that users can promptly react to the transmitted signals when the warning alarms are used in realistic scenarios. Further, it should be noted that the effectiveness of tactile alerts would decline over time, not only due to the declined memory, but the habituation to warning alarms in participants when they are exposed to a stimulus for longer would also impact deleteriously on tactile perception (Kim N et al., 2023).

Sakhakarmi, Park, and Singh (2021) identified three pieces of information to represent a potential collision scenario: the approximate location of the hazard, hazard levels, and types of construction equipment, using a tactile waist belt with ten vibration motors. And the average accuracy for their participants was around 95%. Inspired by these findings, in our study, further research is required to explore the feasibility of communicating more collision-related hazard information to workers through the vibration on the head.

7. Discussion and Conclusions

This work compares audio, haptic modalities and their combinations for presenting warning signals in the virtual construction environment. The results demonstrated that the addition of tactile cues statistically improved performance compared to non-tactile cues with regard to reaction time and affective ratings. The Experiment 1 also demonstrated the validity of using the HMD immersive displays as an experimental tool to measure subjects' physical responses to hazards.

Then, we investigated how the use of the three-parameter (duration, interval, and intensity) tactile coding patterns impacted participants' responses. Based on the results, the pattern 2, pattern 3 and pattern 6 would be suitable for transmitting warning signals as they imply faster reaction times and higher arousal ratings. The effectiveness of the three vibrotactile patterns for communicating hazardous levels to a tactile helmet prototype was evaluated, as measured through the identification error rate and choice response time. Overall, the recognition accuracy for the three patterns was high within a short time (M = 3979 ms), which demonstrates that the tactile motor can be indexed to indicate particular information. Our results provide new evidence that wearable haptic displays have promise as an intuitive means of displaying warning signals and can improve risk awareness in simulated harsh construction environments. In the context of tactile signal design for the head, existing research is invaluable; this work also supplied guidance regarding the effective design of tactile cues for interaction at the head.

However, we also found some experimental limitations in the study. Although key components of construction sites, including visually hazardous scenarios, noises, and measuring the work processes, were simulated in the VE, it may be unable to fully replicate the realistic sensory experience as the inherent vibrations in a construction workplace were not modeled in the VR setup. And it must be acknowledged that the absence of active machinery and the associated environmental vibrations may affect the experimental results, as a tactile stimulus can be masked by another stimulus (Verrillo et al., 1983). Thus, there is a need to investigate the effectiveness of vibrotactile system in alerting construction workers under conditions where multiple sources of vibration might interfere with the perception of intended warning. Our further experiments will simulate environmental vibrations to achieve a higher level of immersiveness and fidelity by applying additional VR simulation techniques. For example, Wegscheider (2014) endeavored to create realistic vehicle elements and immersive driving experience. Their virtual reality forklift simulator utilized six degrees of freedom motion feedback and 3D visual feedback, thereby generating whole body vibration. Jung et al. (2021) developed a computer-controlled vibration floor and integrated it into their VR system. This floor can provide an average vibration of M = 1.15g, closely resembling the vibration intensity in real moving vehicles. Soave et al. (2020) provided whole-body vibration to participants through the vibration chair with built-in Actuators.

What might provide additional evidence to support the practicality of vibrotactile alerts under real operational conditions was their applications in vehicles. Similar to the construction site, the driving space is also an environment characterized by external vibrations and a high audiovisual workload, encompassing the vehicle motion, engine vibrations, uneven road surfaces, and vehicle horns, which could potentially interfere with the efficacy of alert systems. Although research on vibrotactile signals tested in real construction settings remains quite limited, they have been evaluated multiple times in real driving conditions, demonstrating their potential to significantly reduce driver reaction times. For instance, Petermeijer et al. (2015) conducted a literature survey to review research that demonstrated the effect of haptic driver support systems, and found that 10 of the 70 empirical studies were conducted in real vehicles.

Since our results were obtained in a lab setting, e.g., in the anticipated control environment, it should be viewed with caution in considering their application to field environments. For instance, in a harsh construction environment with many potential risks and distractions, repeated tactile alarms could be more distracting, as suggested by Experiment 2. To further explore the practical applicability of the vibrotactile warning system, we conducted a preliminary field test using the helmet prototype embedded with tactors. 3 construction workers were recruited, and they were required to walk freely around the construction site and respond instantly whenever they perceived vibrations on their head. All participants reported clear and distinct perceptions of the vibrations. Although participants were not at work during the test, it provided initial insights into the practical application of our findings outside the lab.

On the other hand, the capability of using different signal profiles to deliver multiple types of information, such as distance, speed, and types of hazardous objects, has not been investigated in this study. Therefore, future studies will focus on exploring the feasibility of communicating complex hazard scenarios using vibration signals as an information delivery mechanism to further heighten levels of situational awareness among workers. Follow-on studies from this work would endeavor to develop a comprehensive safety system by integrating this communication system with hazard detection systems, which aims to improve the safety of construction workers at a working scale.

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References

Enya, A., Dempsey, S., & Pillay, M. (2019). High reliability organisation (HRO) principles of collective mindfulness: an opportunity to improve construction safety management. In Advances in Safety Management and Human Factors: Proceedings of the AHFE 2018 International Conference on Safety Management and Human Factors, July 21-25, 2018, Loews Sapphire Falls Resort at

Universal Studios, Orlando, Florida, USA 9 (pp. 3-13). Springer International Publishing. https://doi.org/10.1007/978-3-319-94589-7_1

China Central Television. (2022, May 22). Lifeline weekend special program "Emergency Moment" 20220522 [Video]. CCTV. https://tv.cctv.com/2022/05/22/VIDEzcRJB6SMF3jc6yOqYnhU220522.shtml

U.S. Occupational Safety and Health Administration. (2020). National Census of Fatal Occupational Injuries in 2020. Retrieved June 12, 2023, from https://www.osha.gov/data/commonstats.

Chi, S., & Han, S. (2013). Analyses of systems theory for construction accident prevention with specific reference to OSHA accident reports. International journal of project management, 31(7), 1027-1041. https://doi.org/10.1016/j.ijproman.2012.12.004

Alsharef, A., Albert, A., Awolusi, I., & Jaselskis, E. (2023). Severe injuries among construction workers: Insights from OSHA's new severe injury reporting program. Safety science, 163, 106126. https://doi.org/10.1016/j.ssci.2023.106126

Shen, X., Marks, E., Pradhananga, N., & Cheng, T. (2016). Hazardous proximity zone design for heavy construction excavation equipment. Journal of Construction Engineering and Management, 142(6), 05016001. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001108

Son, H., Seong, H., Choi, H., & Kim, C. (2019). Real-time vision-based warning system for prevention of collisions between workers and heavy equipment. Journal of Computing in Civil Engineering, 33(5), 04019029. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000845

Zhao, T., Xu, K., & Zhou, W. (2018). Graded Management of Hazardous Area in Construction Site. Industrial Safety and Environmental Protection, 11,43-46. [In Chinese]

Soltanmohammadlou, N., Sadeghi, S., Hon, C. K., & Mokhtarpour-Khanghah, F. (2019). Real-time locating systems and safety in construction sites: A literature review. Safety science, 117, 229-242. https://doi.org/10.1016/j.ssci.2019.04.025

Park, J., Kim, K., & Cho, Y. K. (2017). Framework of automated construction-safety monitoring using cloud-enabled BIM and BLE mobile tracking sensors. Journal of Construction Engineering and Management, 143(2), 05016019. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001223

Kanan, R., Elhassan, O., & Bensalem, R. (2018). An IoT-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies. Automation in Construction, 88, 73-86. https://doi.org/10.1016/j.autcon.2017.12.033

Sakhakarmi, S., Park, J., & Singh, A. (2021). Tactile-based wearable system for improved hazard perception of worker and equipment collision. Automation in Construction, 125, 103613. https://doi.org/10.1016/j.autcon.2021.103613

Basil, M. D. (1994). Multiple resource theory I: Application to television viewing. Communication research, 21(2), 177-207. https://doi.org/10.1177/009365094021002003

Wickens, C. D. (2008). Multiple resources and mental workload. Human factors, 50(3), 449-455. https://doi.org/10.1518/001872008X288394

Kacznaarek, K. A., & Bach-Y-Rita, P. (1995). Tactile displays. In Virtual environments and advanced interface design (pp. 349-414). Oxford University Press.

Van Veen, H. A. H. C., & Van Erp, J. B. (2003, July). Providing directional information with tactile torso displays. In Proceedings of EuroHaptics (Vol. 2003, pp. 471-474).

Cassinelli, A., Reynolds, C., & Ishikawa, M. (2006, October). Augmenting spatial awareness with haptic radar. In 2006 10th IEEE International Symposium on Wearable Computers (pp. 61-64). IEEE. https://doi.org/10.1109/ISWC.2006.286344

Haas, E. C., & Van Erp, J. B. (2014). Multimodal warnings to enhance risk communication and safety. Safety science, 61, 29-35. https://doi.org/10.1016/j.ssci.2013.07.011

Jones, L. A. (2011). Tactile communication systems: Optimizing the display of information. Progress in brain research, 192, 113-128. https://doi.org/10.1016/B978-0-444-53355-5.00008-7

Jones, L. A., & Sarter, N. B. (2008). Tactile displays: Guidance for their design and application. Human factors, 50(1), 90-111. https://doi.org/10.1518/001872008X250638

Dufresne, A., Martial, O., & Ramstein, C. (1995). Multimodal user interface system for blind and "visually occupied" users: Ergonomic evaluation of the haptic and auditive dimensions. Human—Computer Interaction: Interact'95, 163-168.

Palani, H. P., Fink, P. D., & Giudice, N. A. (2020). Design guidelines for schematizing and rendering haptically perceivable graphical elements on touchscreen devices. International Journal of Human–Computer Interaction, 36(15), 1393-1414. https://doi.org/10.1080/10447318.2020.1752464

Zhu, A., Cao, S., Yao, H., Jadliwala, M., & He, J. (2020). Can wearable devices facilitate a driver's brake response time in a classic car-following task?. IEEE Access, 8, 40081-40087. https://doi.org/10.1109/ACCESS.2020.2971632

Lu, S. A., Wickens, C. D., Prinet, J. C., Hutchins, S. D., Sarter, N., & Sebok, A. (2013). Supporting interruption management and multimodal interface design: Three meta-analyses of task performance as a function of interrupting task modality. Human factors, 55(4), 697-724. https://doi.org/10.1177/0018720813476298

Chai, C., Shi, J., Wu, C., Zhou, Y., Zhang, W., & Liao, J. (2022). When to use vibrotactile displays? A meta-analysis for the role of vibrotactile displays in human–computer interaction. Applied Ergonomics, 103, 103802. https://doi.org/10.1016/j.apergo.2022.103802

Murata, A., Tanaka, K., & Moriwaka, M. (2011). Basic study on effectiveness of tactile interface for warning presentation in driving environment. International Journal of Knowledge Engineering and Soft Data Paradigms, 3(1), 95-105. https://doi.org/10.1504/IJKESDP.2011.039881

Chang, W., Hwang, W., & Ji, Y. G. (2011). Haptic seat interfaces for driver information and warning systems. International Journal of Human-Computer Interaction, 27(12), 1119-1132. https://doi.org/10.1080/10447318.2011.555321

Murata, A., & Kuroda, T. (2015). Effects of auditory and tactile warning on drivers' response to hazard under noisy environment. In Engineering Psychology and Cognitive Ergonomics: 12th International Conference, EPCE 2015, Held as Part of HCI International 2015, Los Angeles, CA, USA, August 2-7, 2015, Proceedings 12 (pp. 45-53). Springer International Publishing. https://doi.org/10.1007/978-3-319-20373-7_5

Hopkins, K., Kass, S. J., Blalock, L. D., & Brill, J. C. (2017). Effectiveness of auditory and tactile crossmodal cues in a dual-task visual and auditory scenario. Ergonomics, 60(5), 692-700. https://doi.org/10.1080/00140139.2016.1198495

Lutnyk, L., Rudi, D., Meier, E., Kiefer, P., & Raubal, M. (2023). FlyBrate: Evaluating Vibrotactile Cues for Simulated Flight. International Journal of Human–Computer Interaction, 39(12), 2374-2391. https://doi.org/10.1080/10447318.2022.2075627

Calhoun, G., Draper, M., Ruff, H., Fontejon, J., & Guilfoos, B. (2003, October). Evaluation of tactile alerts for control station operation. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 47, No. 20, pp. 2118-2122). Sage CA: Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/154193120304702009

Freeman, E., Wilson, G., Vo, D. B., Ng, A., Politis, I., & Brewster, S. (2017). Multimodal feedback in HCI: haptics, non-speech audio, and their applications. In The Handbook of Multimodal-Multisensor Interfaces: Foundations, User Modeling, and Common Modality Combinations-Volume 1 (pp. 277-317). https://doi.org/10.1145/3015783.3015792

Ho, C., Reed, N., & Spence, C. (2007). Multisensory in-car warning signals for collision avoidance. Human factors, 49(6), 1107-1114. https://doi.org/10.1518/001872007X249965

Lee, J. D., McGehee, D. V., Brown, T. L., & Marshall, D. (2006). Effects of adaptive cruise control and alert modality on driver performance. Transportation research record, 1980(1), 49-56. https://doi.org/10.1177/0361198106198000108

Lavie, N. (2005). Distracted and confused?: Selective attention under load. Trends in cognitive sciences, 9(2), 75-82. http://dx.doi.org/10.1016/j.tics.2004.12.004

Meng, F., & Spence, C. (2015). Tactile warning signals for in-vehicle systems. Accident analysis & prevention, 75, 333-346. https://doi.org/10.1016/j.aap.2014.12.013

Jelonek, M., & Herrmann, T. (2019). Atentiveness for potential accidents at the construction site: virtual reality test environment with tactile warnings for behavior tests in hazardous situations. In Proceedings of Mensch und Computer 2019 (pp. 649-653). https://doi.org/10.1145/3340764.3344885

Fiala, E., Jelonek, M., & Herrmann, T. (2020, July). Using virtual reality simulations to encourage reflective learning in construction workers. In International Conference on Human-Computer Interaction (pp. 422-434). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-50506-6_29

Kim, N., & Ahn, C. R. (2020). Using a virtual reality-based experiment environment to examine risk habituation in construction safety. In Proceedings of the International Symposium on Automation and Robotics in Construction (IAARC).

Kerdegari, H. (2017). Head-mounted Sensory Augmentation System for Navigation in Low Visibility Environments (Doctoral dissertation, University of Sheffield).

Brewster, S. A., & Brown, L. M. (2004). Tactons: structured tactile messages for non-visual information display.

Pasquero, J. (2006). Survey on communication through touch. Centre for Intelligent Machines-McGill University, Tech. Rep. TR-CIM, 6, 1-28.

Enriquez, M. J., & MacLean, K. E. (2003). The hapticon editor: A tool in support of haptic communication research. Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 356–362. IEEE. https://doi.org/10.1109/HAPTIC.2003.1191310

Swindells, C., Maksakov, E., MacLean, K. E., & Chung, V. (2006). The role of prototyping tools for haptic behavior design. Proceedings of the 2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 161–168. IEEE. http://dx.doi.org/10.1109/HAPTIC.2006.1627084

Ryu, J., & Choi, S. (2008). posVibEditor: Graphical authoring tool of vibrotactile patterns. Proceedings of the 2008 IEEE International Workshop on Haptic Audio Visual Environments and Games, 120–125. IEEE. http://dx.doi.org/10.1109/HAVE.2008.4685310

Schneider, O. S., & MacLean, K. E. (2016). Studying design process and example use with Macaron, a web-based vibrotactile effect editor. Proceedings of the 2016 IEEE Haptics Symposium, 52–58. IEEE. http://dx.doi.org/10.1109/HAPTICS.2016.7463155

Terenti, M., & Vatavu, R. D. (2023). VIREO: Web-based Graphical Authoring of Vibrotactile Feedback for Interactions with Mobile and Wearable Devices. International Journal of Human–Computer Interaction, 39(20), 4162-4180. https://doi.org/10.1080/10447318.2022.2109584

Brown, L. M., & Kaaresoja, T. (2006, April). Feel who's talking: using tactons for mobile phone alerts. In CHI'06 extended abstracts on Human factors in computing systems (pp. 604-609). https://doi.org/10.1145/1125451.1125577

Azadi, M., & Jones, L. (2013, April). Identification of vibrotactile patterns: Building blocks for tactons. In 2013 World Haptics Conference (WHC) (pp. 347-352). IEEE. http://dx.doi.org/10.1109%2FWHC.2013.6548433

Cho, C., & Park, J. (2018). An embedded sensory system for worker safety: Prototype development and evaluation. Sensors, 18(4), 1200. https://doi.org/10.3390/s18041200

Baldwin, C. L., Spence, C., Bliss, J. P., Brill, J. C., Wogalter, M. S., Mayhorn, C. B., & Ferris, T. K. (2012, September). Multimodal cueing: The relative benefits of the auditory, visual, and tactile channels in complex environments. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 56, No. 1, pp. 1431-1435). Sage CA: Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/1071181312561404

Wenzel, E. M., & Godfroy-Cooper, M. (2021). The Role of Tactile Cueing in Multimodal Displays: Application in Complex Task Environments for Space Exploration.

Wolf, F., & Kuber, R. (2018). Developing a head-mounted tactile prototype to support situational awareness. International Journal of Human-Computer Studies, 109, 54-67. https://doi.org/10.1016/j.ijhcs.2017.08.002

Seifi, H., & Maclean, K. E. (2013, April). A first look at individuals' affective ratings of vibrations. In 2013 World Haptics Conference (WHC) (pp. 605-610). IEEE. https://doi.org/10.1109/WHC.2013.6548477

Lins, C., Fudickar, S. J., Gerka, A., & Hein, A. (2018, March). A Wearable Vibrotactile Interface for Unfavorable Posture Awareness Warning. In ICT4AWE (pp. 178-183).

White, T. L. (2011). The perceived urgency of tactile patterns. Aberdeen Proving Ground, Md.: Army Research Laboratory.

Nnaji, C., & Awolusi, I. (2021). Critical success factors influencing wearable sensing device implementation in AEC industry. Technology in Society, 66, 101636. https://doi.org/10.1016/j.techsoc.2021.101636

Adilkhanov, A., Rubagotti, M., & Kappassov, Z. (2022). Haptic devices: Wearability-based taxonomy and literature review. IEEE Access. https://doi.org/10.1109/ACCESS.2022.3202986

Yadav, N. (2017). Warning system for outdoor construction workers using haptic communication (Doctoral dissertation). https://hdl.handle.net/1969.1/187304

Li, P., Meziane, R., Otis, M. J. D., Ezzaidi, H., & Cardou, P. (2014, October). A Smart Safety Helmet using IMU and EEG sensors for worker fatigue detection. In 2014 IEEE International Symposium on Robotic and Sensors Environments (ROSE) Proceedings (pp. 55-60). IEEE. https://doi.org/10.1109/ROSE.2014.6952983

Kerdegari, H., Kim, Y., & Prescott, T. J. (2016). Head-mounted sensory augmentation device: comparing haptic and audio modality. In Biomimetic and Biohybrid Systems: 5th International Conference, Living Machines 2016, Edinburgh, UK, July 19-22, 2016. Proceedings 5 (pp. 107-118). Springer International Publishing. https://doi.org/10.1007/978-3-319-42417-0_11

Dim, N. K., & Ren, X. (2017). Investigation of suitable body parts for wearable vibration feedback in walking navigation. International Journal of Human-Computer Studies, 97, 34-44. https://doi.org/10.1016/j.ijhcs.2016.08.002

Gilliland, K., & Schlegel, R. E. (1994). Tactile stimulation of the human head for information display. Human Factors, 36(4), 700-717. https://doi.org/10.1177/001872089403600410

Myles, K., & Kalb, J. T. (2010). Guidelines for head tactile communication. Army Research, Laboratory.

Diener, V., Beigl, M., Budde, M., & Pescara, E. (2017, September). VibrationCap: studying vibrotactile localization on the human head with an unobtrusive wearable tactile display. In Proceedings of the 2017 ACM International Symposium on Wearable Computers (pp. 82-89). https://doi.org/10.1145/3123021.3123047

Ministry of Ecology and Environment of the People's Republic of China & General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. (2011). Emission standard of environment noise for boundary of construction site (GB 12523-2011).

Suter, A. H. (2002). Construction noise: exposure, effects, and the potential for remediation; a review and analysis. AIHA journal, 63(6), 768-789. https://doi.org/10.1080/15428110208984768

Tikka, C., Verbeek, J. H., Kateman, E., Morata, T. C., Dreschler, W. A., & Ferrite, S. (2017). Interventions to prevent occupational noise - induced hearing loss. Cochrane Database of Systematic Reviews, (7). https://doi.org/10.1002/14651858.CD006396.pub4

Sanders, M.S., & McCormick, E.J. (1998). Human Factors in Engineering and Design. Industrial Robot, 25(2), 153-153. https://doi.org/10.1108/ir.1998.25.2.153.2

Halabi, O., Bahameish, M. A., Al-Naimi, L. T., & Al-Kaabi, A. K. (2019). Response times for auditory and vibrotactile directional cues in different immersive displays. International Journal of Human–Computer Interaction, 35(17), 1578-1585. https://doi.org/10.1080/10447318.2018.1555743

Dobrzynski, M. K., Mejri, S., Wischmann, S., & Floreano, D. (2012). Quantifying information transfer through a head-attached vibrotactile display: principles for design and control. IEEE Transactions on Biomedical Engineering, 59(7), 2011-2018. https://doi.org/10.1109/TBME.2012.2196433

Qian, H., Kuber, R., & Sears, A. (2011). Towards developing perceivable tactile feedback for mobile devices. International Journal of Human-Computer Studies, 69(11), 705-719. https://doi.org/10.1016/j.ijhcs.2011.06.003

Raveh, D., Lavie, N. Load-induced inattentional deafness. Atten Percept Psychophys 77, 483–492 (2015). https://doi.org/10.3758/s13414-014-0776-2

Zeng, W., Shu, L., Li, Q., Chen, S., Wang, F., & Tao, X. M. (2014). Fiber - based wearable electronics: a review of materials, fabrication, devices, and applications. Advanced materials, 26(31), 5310-5336. https://doi.org/10.1002/adma.201400633

Ngo, M. K., Pierce, R. S., & Spence, C. (2012). Using multisensory cues to facilitate air traffic management. Human factors, 54(6), 1093-1103. https://doi.org/10.1177/0018720812446623

Alirezaee, P., Weill-Duflos, A., Schlesinger, J. J., & Cooperstock, J. R. (2020, March). Exploring the effectiveness of haptic alarm displays for critical care environments. In 2020 IEEE Haptics Symposium (HAPTICS) (pp. 948-954). IEEE. https://doi.org/10.1109/HAPTICS45997.2020.ras.HAP20.156.6c3cc0bf

Hogema, J. H., De Vries, S. C., Van Erp, J. B., & Kiefer, R. J. (2009). A tactile seat for direction coding in car driving: Field evaluation. IEEE Transactions on Haptics, 2(4), 181-188. https://doi.org/10.1109/TOH.2009.35

Mueller, A., Ogrizek, M., Bier, L., & Abendroth, B. (2018). Design concept for a visual, vibrotactile and acoustic take-over request in a conditional automated vehicle during non-driving-related tasks. In 6th international conference on driver distraction and inattention, Gothenburg, Sweden. Retrieved from: http://ddi2018. org/wp-content/uploads/2018/10 S (Vol. 2).

Ryu, J., Chun, J., Park, G., Choi, S., & Han, S. H. (2010). Vibrotactile feedback for information delivery in the vehicle. IEEE Transactions on Haptics, 3(2), 138-149. https://doi.org/10.1109/TOH.2010.1

Gupta, A., & Varghese, K. (2020, October). Scenario-based construction safety training platform using virtual reality. In 37th International Symposium on Automation and Robotics in Construction, Kitakyushu, Japan.

Saket, B., Prasojo, C., Huang, Y., & Zhao, S. (2013, February). Designing an effective vibration-based notification interface for mobile phones. In Proceedings of the 2013 conference on Computer supported cooperative work (pp. 149-1504). https://doi.org/10.1145/2441776.2441946

Baldwin, C. L., & Lewis, B. A. (2014). Perceived urgency mapping across modalities within a driving context. Applied ergonomics, 45(5), 1270-1277. https://doi.org/10.1016/j.apergo.2013.05.002

Poupyrev, I., Maruyama, S., & Rekimoto, J. (2002, October). Ambient touch: designing tactile interfaces for handheld devices. In Proceedings of the 15th annual ACM symposium on User interface software and technology (pp. 51-60). https://doi.org/10.1145/571985.571993

Kim, N., Yan, N., Grégoire, L., Anderson, B. A., & Ahn, C. R. (2023). Road Construction Workers' Boredom Susceptibility, Habituation to Warning Alarms, and Accident Proneness: Virtual Reality Experiment. Journal of Construction Engineering and Management, 149(2), 04022175. https://doi.org/10.1061/JCEMD4.COENG-12818

Verrillo, R. T., Gescheider, G. A., Calman, B. G., & Van Doren, C. L. (1983). Vibrotactile masking: Effects of oneand two-site stimulation. Perception & Psychophysics, 33(4), 379-387. https://doi.org/10.3758/BF03205886

Petermeijer, S. M., Abbink, D. A., Mulder, M., & De Winter, J. C. (2015). The effect of haptic support systems on driver performance: A literature survey. IEEE transactions on haptics, 8(4), 467-479. https://doi.org/10.1109/TOH.2015.2437871

Wegscheider, P. (2014). Development and assessment of a virtual reality forklift simulator as a research tool to study whole-body vibration. The University of Western Ontario (Canada). https://ir.lib.uwo.ca/etd/2405.

Jung, S., Li, R., McKee, R., Whitton, M. C., & Lindeman, R. W. (2021). Floor-vibration vr: mitigating cybersickness using whole-body tactile stimuli in highly realistic vehicle driving experiences. IEEE Transactions on Visualization and Computer Graphics, 27(5), 2669-2680. https://doi.org/10.1109/TVCG.2021.3067773

Soave, F., Bryan-Kinns, N., & Farkhatdinov, I. (2020). A preliminary study on full-body haptic stimulation on modulating self-motion perception in virtual reality. Proceedings of the 7th

International Conference on Augmented Reality, Virtual Reality, and Computer Graphics, Part I, 461–469. https://doi.org/10.1007/978-3-030-58465-8_34

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