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Navigation by vibration: Effects of vibrotactile feedback on a navigation task

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ABSTRACT

In the background of spatial orientation in a navigation task, this study investigated the effect of frequency, duration and amplitude of vibrotactile feedback when it provided primary information modality. Multiple levels of each parameter were designed for an experiment conducted with 18 participants. Their performance was evaluated via number of errors, task completion time, annoyance level, and user preference. Result showed that medium level of frequency and duration was more preferred and can produce better performance. However, optimal amplitude level varied by individuals and also interacted with frequency. The paper summarized a set of design guidelines, which could be used to the design of future user interface with vibrotactile feedback. The study should provide great empirical data and meaningful insight for the design of vibrotactile feedback for future applications.

Relevance to industry: The paper evaluated the vibrotactile interfaces and summarized a set of design guidelines, which could help to speed up the commercialization and industrial application of vibrotactile user interface.

1. Introduction

The processes underlying the transfer of information (to human recipients) have often been limited, but the use of vibrotactile feedback offers advantageous potentials, especially in navigation tasks. Visual presentation is often the primary method of information delivery in most computer-based systems; however, visual display can be unsuitable in certain cases. For example, a traffic scene, as viewed from a vehicle system, can place pressure on the driver's visual sensory channel and result in an overloading of cognitive capacities (Van Erp and Van Veen, 2004). Non-visual information may be required in cases that lack visual display. For instance, communication with the visually impaired regularly requires the use of non-visual information. Auditory display has been widely used and investigated as an alternate modality (Blattner et al., 1989).

Vibrotactile is one type of haptic feedback that can be used in most applications, providing either secondary or primary modality information. Research has shown that vibrotactile feedback can be used for texture discrimination (Martinez et al., 2011), musical timbre discrimination (Russo et al., 2012), hovering a helicopter (Raj et al., 2000). However, most research about the use of vibrotactile systems employs vibrotactile display/feedback as a secondary information channel in specific applications and tests whether it is applicable and if the user performance is enhanced. More research is required to investigate the effect of vibrotactile feedback as primary modality information on enhancing the user's spatial orientation. The application of vibrotactile feedback as a primary information modality is beneficial in situations lacking visual and/or auditory stimuli/feedback or for people with disabilities. The main purpose of this study was to examine and evaluate the effects of different vibrotactile feedback on user performance in a navigation task.

2. Related work

Tactile displays that enhance real, physical environments are becoming increasingly common. Researchers have investigated the effectiveness of vibrotactile display in a range of applications, such as sensory substitution (Jones and Sarter, 2008; Maclean, 2009; Sklar and Sarter, 1999), navigation systems (Altini et al., 2011; Lindeman et al., 2005; Van Erp and Van Veen, 2001; Van Erp and Van Veen, 2004; Vichare et al., 2009; Yang et al., 2010), warning

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systems (Ho et al., 2005), posture awareness systems (Johnson et al., 2010; Van der Linden et al., 2011), in-vehicle systems (Ryu et al., 2010a,b), mobile devices (Park et al., 2011), tele-manipulation system (Pongrac, 2006), and in the exploration of virtual environments (Jones and Sarter, 2008). Vibrotactile display systems have also been developed in rehabilitation for those with impairments (Alahakone and Senanayake, 2009), successfully employed in applications such as brain–computer interfaces (Chatterjee et al., 2007; Cincotti et al., 2007), a wearable tactile display system (Ross and Blasch, 2000) to a mobile museum guide system for the visually impaired (Ghiani et al., 2008), and even applied to prosthetic limbs (Stepp et al., 2012).

Vibrotactile navigation systems have been developed and investigated to aid in navigation for a variety of fields including car drivers, pilots, and people with visual impairments. Van Erp and Van Veen (2001) designed vibrotactile icons for an in-vehicle navigation system using vibrotactile devices mounted in a car seat. In addition, Van Erp and Van Veen (2003) have investigated the use of a vibrotactile vest to provide navigation information for airplane pilots. It was found that tactile display would be particularly useful when pilots are in harsh conditions, and tactile information might be more readily received. In addition to aiding navigation in vehicles, vibrotactile feedback has also been used to help blind or visually impaired people to navigate. Tactile feedback offers a number of benefits, as demonstrated by its success in a number of applications and fields.

2.1. Benefits of vibrotactile feedback

Vibrotactile technology has the benefit of discretion and privacy to the user, and it does not disturb other people (Brewster and King, 2005). This concealment might be particularly useful when the user wishes to receive information in an environment where audio alerts would be unacceptable. Another advantage to using vibrotactile feedback is that it leaves the auditory senses free for other tasks. This can be greatly advantageous for blind people who rely on environmental noise for safe navigation. In addition, vibrotactile signals can be sensed in noisy environments, when an auditory message might not be heard. Aside from its intuitive, easy-to-learn nature (Tan et al., 2001), vibrotactile feedback has been supported by studies of its efficiency. Vibrotactile feedback can be designed and adjusted so that it can be perceived in varying situations (Ryu et al., 2010a,b), something that often proves advantageous. By measuring the spectral characteristics of internal vibrations in a vehicle, they designed sinusoidal vibrations with highest discriminability. Then, they evaluated the learnability and replaced those with low learnability with patterned signals that can improve the learnability. Their result showed the high potential of vibrotactile feedback to be used for the communicative transfer during a driving task.

If spatial information was transmitted only through the auditory channel, it could be attenuated or distorted by external noise. Thus, vibrotactile display can be an appropriate choice in these situations for navigation tasks. Vibrotactile feedback lessens the pressure on the other senses, making it an advantageous mode of feedback for demanding or multiple tasks. For example, Brewster and King (2005) investigated the use of tactile information in presenting progress information and found that progress indicators in tactile form can be more effective than their standard visual counterparts, emphasizing that using tactile senses to receive secondary information strengthens visual attention on a main task. In a strenuous outdoor environment, a tactile navigation device outperformed visual displays in situations of high cognitive and visual workloads (Elliott et al., 2010). In comparison to other senses, tactile feedback has been found to be equally or more effective than both auditory and visual modes of feedback. Zheng and Morrell (2013) found vibrotactile and visual feedback to be similarly effective in guiding seated postures. In a comparison of visual and haptic feedback in a virtual environment, Koritnik and colleagues (2010) found the haptic modality to be more successful than visual in terms of participant performance. In a study comparing feedback in a point task (using a mouse-like device), tactile feedback allowed subjects to use a wider area of the target and more quickly select targets compared to both auditory and visual feedback (Akamatsu et al., 1995). Vibrotactile feedback has been found to be beneficial in comparison to or in cooperation with alternate forms of feedback.

2.2. Determinants of vibrotactile feedback

It is important to understand the parameters of vibration in order for vibrotactile display to effectively transmit multi-dimensions of information. These limitations can be manipulated to encode information, and it is important to consider both the capabilities and restrictions of the sense of touch in the perception of these parameters. In the early stages of vibrotactile research, Geldard (1960) discussed the potential of mechanical vibrations for communicating information. He proposed that the main parameters of vibration are intensity (amplitude), frequency, signal (waveform) duration, rhythm, and spatial location. Today, these variables are accurate representations of perceived differences of vibrations.

Intensity refers to the square of the amplitude of the signal. However, the terms intensity and amplitude are often used interchangeably when referring to the strength of sound signal (Soderquist, 2002). In the present study, the term “amplitude” is predominately used. Intensity is a parameter that has been examined by numerous researchers. For example, Gescheider and his colleagues (1971) investigated absolute thresholds in vibrotactile signal detection. They found that measures of detection probability, reaction time, and sensation magnitude were functions of signal intensity only for vibration amplitudes greater than 1 micron. Gescheider and his colleagues (1969) found that the probability of subjects' reporting the presence of a signal was influenced by signal probability and signal intensity. Mean reaction time for reporting the presence of a signal decreased as a function of signal intensity and signal probability whereas mean reaction time for reporting the absence of a signal increased as a function of signal intensity and signal probability. Researchers have also studied the effect of vibrotactile feedback in relation to amplitude and frequency. Kyung and Kwon (2006) have investigated the correlation between the perceived roughness and frequency and amplitude of vibrotactile stimuli. Their results showed that the perceived roughness is proportionally intensified as logarithms of frequency or logarithms of amplitude increase and that amplitude and frequency could complement each other. Lieberman and Breazeal (2007) link the control of amplitude and frequency together and found that their invented system, the System Tactile Interaction for Kinesthetic Learning (TIKL), has high statistical significance for helping humans learn motor skills through real-time tactile feedback. The amplitude of vibrotactile sensation may change when the tactor size (Verrillo and Gescheider, 1992) or the spatial location (Geldard, 1960) changes. Previous research of amplitude has guided the research and development of vibrotactile displays.

Frequency refers to the rate of vibration, and many researchers have investigated it before. For example, Verrillo (1966) found that absolute vibrotactile thresholds were a function of stimulus frequency and contractor area on the hairy skin of the volar forearm. Mahns and his colleagues (2006) revealed a striking similarity in vibrotactile frequency discrimination in hairy and glabrous skin despite marked differences in detection thresholds for the two sites. Kuroki and his colleagues (2012) investigated the human capacity for vibrotactile frequency discrimination. The results