International Journal of Industrial Ergonomics 46 (2015) 76–84

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

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

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A R T I C L E I N F O

Article history:
Received 1 May 2014
Received in revised form
21 November 2014
Accepted 14 December 2014
Available online 21 January 2015

Keywords:
Vibrotactile
Navigation
Frequency
Duration
Amplitude

A B S T R A C T

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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http://dx.doi.org/10.1016/j.ergon.2014.12.008
0169-8141/

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), telemanipulation 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 revealed constant and good discrimination capacities for strong stimulus conditions but discrete and bad capacities for weak stimulus conditions. Sherrick and Craig (1982) found that the frequency range of skin is from 10 Hz to 1000 Hz, but this usable range is limited from 10 Hz to 400 Hz (Cholewiak and Wollowitz, 1992). Verrillo and Gescheider (1992) also found that the maximum sensitivity is 250 Hz. Frequency research has been important to the analysis of vibrotactile signals.

Duration refers to the length of a vibration. Gescheider and his colleagues (1994) investigated the effect of signal duration on vibrotactile intensity discrimination and found that vibrotactile intensity measured by the continuous pedestal method were found to decrease substantially as a function of increases in stimulus duration over a range of 12–1000 ms. In contrast, vibrotactile intensity measured by the gated pedestal method were only slightly affected by changes in stimulus duration. These findings suggested that, at suprathreshold levels of stimulation, the effects of temporal summation tend to be canceled by the effects of adaptation. Geldard (1957) has investigated the duration in tactile interface and specified the range of durations to be from 0.1 s to 2 s. However, it is possible for duration to interact with amplitude. For example, Sherrick and Craig (1982) found that short intense signals could be confused with longer and lower intensity signals. Previous research involving duration has provided present researchers with guidelines for administering and evaluates vibrotactile signals.

Pattern (i.e. rhythm) of vibrotactile feedback has also been investigated as a parameter of vibrotactile message. It could be useful to combine vibration and gaps with different durations to form temporal patterns. These patterns are similar to rhythms found in music. To this end, the terms pattern and rhythm can be used interchangeably. For instance, Jones et al. (2009) evaluated the effectiveness of vibrotactile display mounted on either the forearm or the back. They found that simple navigational and instructional commands presented tactually on the arm or back can be accurately identified. Meanwhile, the ability to identify tactile patterns clearly depended on the characteristics of the other patterns being presented. Salzer and his colleagues (2012) have examined the vibrotactile alerting system in a cockpit and found that the four-tactor display mode and the compatible response mode produced the most accurate results. Studies suggest that combining vibrations and gaps with different durations to form temporal patterns could be useful.

Spatial location refers to the location of vibrotactile stimulation. Since tactile sensitivity varies at different locations on a user's body, it has to be carefully considered to select location. The fingertips are commonly considered to be the most sensitive to small amplitudes (Craig and Sherrick, 1982). It was necessary to investigate the use of the forearm (Verrillo and Gescheider, 1992) or the torso (Weinstein, 1968) in order to make use of vibrotactile practically. Here, researchers were motivated to develop a system using a vest with tactors in pilot decision-making study, since the frequent use of arms and hands in other tasks leaves the torso is comparatively unused (Weinstein, 1968). It was found that feedback to the torso could be effective in improving pilots' spatial awareness. From the study review, it is clear that the torso has potential for effective vibrotactile feedback.

2.3. Limits of vibrotactile feedback

Although there are several known benefits to the use of vibrotactile feedback, more research is still required to investigate the effect of vibrotactile feedback as a primary information modality in enhancing the user's spatial orientation in a navigation task. The use of vibrotactile feedback has not been widely accepted by mainstream applications. While the use of vibrotactile display in sensory substitution is quite established, most of the vibrotactile messages used in the existing commercial applications have been very simple, generally encoding only one dimension of information such as incoming calls on a mobile phone or upcoming appointments in a personal digital assistant (PDA). The use of more complex signals would enable more information to be presented to users and could be imperative for encoding more dimensions of information. In the example of vibrotactile use in mobile phones and PDAs, a user would identify who was calling by multi dimensions of vibrating signal; however, the vibration signal alone would allow a user to simply be alerted of an incoming call.

In spite of the advantages mentioned above, most research in this area has focused on either the application of vibrotactile display/feedback as a secondary modality or on the basic mechanism of vibrotactile. Not enough research has been conducted to investigate the effect of the vibrotactile feedback as primary modality on the user performance in human–computer interaction background. There is also a lack of vibrotactile design basis for blind people to transform information effectively. This study was aimed at determining the effect of vibrotactile feedback (duration, frequency, amplitude and their interactions) on a navigation task with the hopes of identifying an optimal design of vibrotactile feedback with an empirical basis. Particularly, we expected to find how various vibrotactile types can influence stimulus-response compatibility and affect spatial orientation. From the previous review, it is clear that the torso has potential for effective vibrotactile feedback. Therefore, this study developed a simple belt with tactors sewn into it to allow users to be informed navigation information. In response to growing research and development of vibrotactile displays, our research aimed to effectively build upon prior studies in order to determine which form(s) of vibrotactile feedback work most efficiently as a primary modality.

3. Methods

3.1. Participants

Eighteen participants (10 male, 8 female) with a mean age of 24.2 years (SD = 5.7) were recruited from a local University, based on the sample size calculation from the pilot test. Participants received course credits for their participation. The experiment was approved by the Institutional Review Board. All of the participants received and signed the consent form prior to the experiment.

3.2. Apparatus

The experimental system used to provide vibrotactile feedback consisted of a tactor controller, Eval 2.0 (Engineering Acoustics, Inc.), which controlled four C2 Tactors attached on an elastic belt worn around the chest over the shirt and provided a strong, pointlike sensation easily felt and localized. When an electrical signal is applied, the tactors oscillate perpendicular to the skin, while the surrounding skin surface is “shielded” with a passive housing. Each tactor weighs 17 g, with a height measuring 0.31″ and a diameter of 1.2″. The exposed material is anodized aluminum and polyurethane. The skin contactor has a diameter of 0.3″ and is preloaded onto the skin (see Fig. 1).

Four C-2 Tactors were used in the study to represent 4 directions (left, right, up, and down) in the navigation task. The experiment system ran on a Dell Computer with Windows 7, and was developed based on the Tactor SDK (Engineering Acoustics, Inc.).

Fig. 1. C2-tactor from EAI.

3.3. Experiment design

3.3.1. Independent variables

3.3.1.1. Duration. Duration defines how long a vibrotactile signal lasts. In other words, the duration is the time from onset to the termination of the stimulus. Geldard (1960) stated that duration of less than 0.1 s would feel like nudges while 2.0 s was considered to be a limit beyond signal coding. For the design of navigation information, since each tactor delivers only one bit (0 or 1), it is better to focus on accurate transmission. Thus, duration of vibrotactile signal was selected between 250 ms and 2500 ms, which are slightly longer than Geldard's criteria. Mid-level was selected from the middle of the range. There were 3 levels of vibrotactile duration (on time) in the study. The inter-stimulus-interval (off time) was kept constant (200 ms).

- Long duration (D_1): 2500 ms;
- Medium duration (D_2): 1000 ms;
- Short duration (D_3): 250 ms.

In the training session, participants would be exposed to the three levels of vibrotactile duration and the difference was explained.

3.3.1.2. Amplitude. Amplitude defines the strength or intensity of the vibrotactile stimuli. There were 2 levels of amplitude in the study. The amplitude level was set up by choosing the gain value in the system. The big amplitude was selected by the largest gain which the tactor can produce. The small amplitude was determined by the minimum gain which pilot testers were able to perceive with 50 Hz. Thus, the amplitude levels were set up as below:

- Big amplitude (A_1): 24 dB;
- Small amplitude (A_2): 6 dB.

In the training session, participants would be exposed to the two levels of amplitude and the difference was explained.

3.3.1.3. Frequency. Frequency defines the rate of vibration in the system. Since only sinusoidal stimuli were available, frequency is also the number of cycles of sinusoidal stimuli occurred in 1 s (Hz). There were 3 levels of frequency in the study. The high frequency was determined by the maximum value the tactor could produce. Due to the tactor controller's limitation, 50 Hz is the lowest frequency which the system can generate under the experimental condition. The medium frequency was the middle value in the range of frequency the system can generate.

- High frequency (F_1): 349 Hz (highest frequency in the system);
- Medium frequency (F_2): 200 Hz;
- Low frequency (F_3): 50 Hz.

In the training session, participants were exposed to the three levels of frequency and the difference was explained.

3.3.2. Dependent variables

3.3.2.1. Task completion time (milliseconds). Task completion time is the time taken from the starting point to the finish of the task by the participant. The completion of the task in this experiment was marked by the time point at which the participant said, “done”.

3.3.2.2. Number of errors. Number of errors defines the number of wrongly perceived vibrotactile feedback in each trial. For example, if the participant drew two movements in wrong directions, their number of errors would be 2.

3.3.2.3. User's annoyance. The annoyance was evaluated by a 1–7 Likert scale rated by participants after each of their trials (Likert, 1932). The annoyance level is meant to measure participants' irritation or distraction as a result of the provided vibrotactile feedback. Larger numbers represent a higher annoyance level, while smaller numbers convey lower annoyance levels.

3.3.2.4. User preference. Users' preference of each independent variable was measured by the post-experiment questionnaire and represented the participant's favorite condition.

3.3.3. Experiment task design

3.3.3.1. Screening task. The screening task was designed to measure participant's vibrotactile working memory capability. Participants received a sequence of vibrotactile stimuli expressing different directions. The number of stimuli in each sequence varied from 2 to 6. After the sequence of stimuli was presented, participants were required to navigate on gridded paper with pencil. Each stimulus was designed to represent one specific movement in the grid paper with explicit direction. For example, if the number of stimuli in a sequence was 5, and the participant correctly perceived the stimuli, he/she would draw a navigation path with 5 continuous pointed segments in the grid paper. One example screening task was R-U-R-D, which indicated a sequence of four vibrotactile stimuli – right first, then up, then right, and finally down (see Fig. 2). The screening task contained fifteen trials with 3 trials for each specific number (an integer between 2 and 6) of stimuli. The 3 trials with the same number of stimuli portrayed different navigation paths, and were assumed to be homogeneous. In the screening task, the number of stimuli in the trials increased from 2 to 6. The largest number of vibrotactile stimuli that the participant could recall was determined as his/her vibrotactile working memory capacity. For example, if a participant could correctly recall 4-stimulus-trial and proceeded to make mistakes in 5-stimulus-trial, his/her vibrotactile working memory capacity would be 4.

Two main principles were followed when designing the navigation paths:

(1) Neighboring movements will not cancel each other.
(2) Neighboring movements will not be the same.

For example, L–R–U–R does not follow the principle (1), because the first movement, L, and the second movement, R, will cancel each other, making it difficult for experimenters to evaluate.

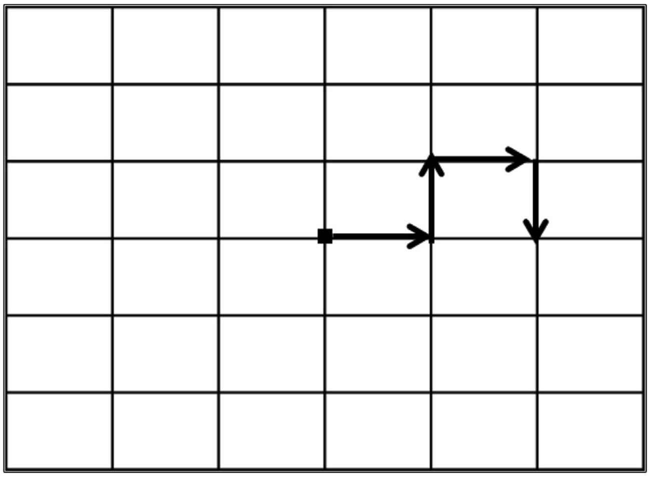

Fig. 2. Grid and direction presentation (R–U–R–D).

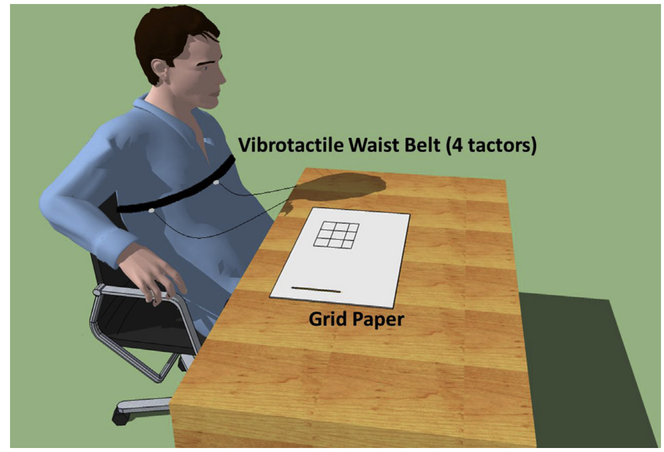

Fig. 3. Experiment setup.

U–U–L–D does not follow principle (2), because the first movement and the second movement are the same. The principle (2) guarantees random and realistic stimuli delivery.

3.3.3.2. Experimental task. Participants performed the same task as the screening task in their experimental sessions. The experiment task differed from the screening task in that participants were only presented a sequence of 4 vibrotactile stimuli in each, single trial of the study. For the four-stimulus navigation, there were 32 different designs ($4 \times 2 \times 2 \times 2$), based on the two principles. Eighteen different navigation paths were randomly selected for each participant in the experiment. When a sequence of stimuli concluded, participants were required to navigate the directions provided by the stimuli onto the grid paper with pencil. Like the screening task, the main focus of the experimental task is to provide participants with navigation directions through vibrotactile feedback in order to analyze their behavior and performance in the task.

3.3.4. Experiment design

A $3 \times 3 \times 2$ factorial design with three within-subject factors was used, resulting in a total of 18 conditions. The 18 chosen navigation tasks were randomly assigned to each condition and repeated once for each participant.

3.4. Procedure

Once the participant arrived at the lab, the experimenters briefly explained the study and then asked them to read and sign the consent form. All of the participants' questions concerning the experiment were clearly and promptly answered. Then, the participant was required to finish the demographic questionnaire.

In the experiment, the participant was seated in a comfortable chair in a quiet laboratory. A belt was used to surround the chest of the participant in order to mount the tactors (see Fig. 3). The belt was made very tight around the body over the shirt but produced no discomfort. Four tactors were put inside of the belt and arranged in left, right, middle front and middle back of the chest, representing the direction left, right, up and down in the grid table.

The participant was asked not to make any body movements when the vibrotactile feedback was being displayed, and to perceive the vibrotactile signal in a relaxed manner. The experimenter operated the experiment system through a computer. There were no interferences or hints during the experiment. Before the experiment, a training session was conducted to make sure that the participant was familiar with the vibrotactile feedback. Then, a screening test was conducted to measure the participant's vibrotactile working memory capacity. The screening test included 15 trials with the number of vibrotactile feedback varying from 2 to 6. A 5 min break was provided after the screening test. The experiment session was composed of 36 trials, with 4 vibrotactile feedback in each trial. Rest was provided every 10 trials and whenever required by the participant. In both screening test and the following experiment session, the trials were completely randomized to avoid the sequence effect. Participants were required to perform the same type of navigation task in screening test and the experiment session. In other words, participants need navigate in a grid paper based on the vibrotactile feedback they received.

After the experiment, the participant was required to complete one paper-based questionnaire to choose his/her favorite conditions and make comments on the vibrotactile system. Example questions are: "Which frequency level do you prefer most? Please give comments to improve the vibrotactile system." In sum, each participant was required to perform 51 trials of navigation task. The whole experiment lasted less than 45 min.

3.5. Data analysis

Normality and constant variance consumptions were assessed for each dependent variables by Shapiro–Wilk test and Brown–Forsythe test, respectively. Then, parametric ANOVAs and rank-based ANOVAs were performed to find the effect of the independent variables. Tukey's HSD test was used for post-hoc analysis.

4. Results

Based on the results from the screening task, all participants had vibrotactile working memory greater than or equal to 4. So, all the data was included in the analysis. Shapiro–Wilk test showed that normality assumption was violated. However, parametric ANOVAs and rank-based ANOVAs showed identical result. Based on Montgomery (2009), results were reported based on the parametric ANOVAs. In order to determine difference in the user preference to the usage conditions, a one-way Chi-Square test for equal proportions was conducted. Table 1 summarized the significant effects for performance measurements.

Table 1
Significant effects for performance parameters.

Parameter	Effect	*F*-value	*p*-Value
Number of errors	Duration	$F_{2,34} = 7.98$	0.0014
	Frequency	$F_{2,34} = 80.18$	<0.0001
	Amplitude	$F_{1,17} = 35.30$	<0.0001
	Frequency*Amplitude	$F_{2,34} = 11.53$	0.0002
Completion Time	Duration	$F_{2,34} = 6.18$	0.0051
	Frequency	$F_{2,34} = 46.83$	<0.0001
	Amplitude	$F_{1,17} = 38.93$	<0.0001
	Frequency*Amplitude	$F_{2,34} = 29.05$	<0.0001
Annoyance	Duration	$F_{2,34} = 8.79$	0.0008
	Frequency	$F_{2,34} = 20.44$	<0.0001
	Amplitude	$F_{1,17} = 21.82$	0.0002
	Frequency*Amplitude	$F_{2,34} = 3.85$	0.0312
	Frequency*Duration	$F_{4,68} = 4.86$	0.0017

4.1. Number of errors

Results showed that duration had a significant effect on number of errors ($F_{2,\ 34} = 7.98$, $p = 0.0014$) with a small effect size of 0.013. Tukey's HSD test indicated that participants had significantly more errors in short duration ($M = 1.38$, Std Dev $= 1.63$) than medium duration ($M = 0.99$, Std Dev $= 1.46$) and long duration ($M = 1.00$, Std Dev $= 1.56$) at $p < 0.05$, while the number of errors were not significantly different in medium and long duration. The main effect of frequency ($F_{2,\ 34} = 80.18$, $p < 0.0001$) and amplitude ($F_{1,\ 17} = 35.30$, $p < 0.0001$) were also significant with pretty big effect size (0.367 and 0.088). Tukey's HSD test showed that participants had significantly more errors in low frequency ($M = 2.46$, Std Dev $= 1.62$) than medium ($M = 0.40$, Std Dev $= 0.85$) and high frequency ($M = 0.51$, Std Dev $= 1.15$) at $p < 0.05$, while the number of errors were not significantly different in medium and high frequency. Participants also had significantly fewer errors in big amplitude ($M = 0.66$, Std Dev $= 1.24$) than small amplitude ($M = 1.59$, Std Dev $= 1.71$) at $p < 0.05$.

A significant interaction effect between frequency and amplitude was found ($F_{2,\ 34} = 11.53$, $p = 0.0002$) with a small effect size of 0.027. As showed in Fig. 4, the number of errors decreased as frequency increased from low to medium, then increased as frequency increased from medium to high. But the rate of change (slope of the line) was different at the two amplitude levels, especially when frequency changed from low to medium level.

4.2. Task completion time (milliseconds)

Result showed that duration has a significant effect on task completion time ($F_{2,\ 34} = 6.18$, $p = 0.0051$) with a very small effect size of 0.009. Tukey's HSD test showed that participants had significantly shorter completion time in medium duration ($M = 11{,}567$, Std Dev $= 11{,}438$) and long duration (M $= 12{,}053$, Std Dev $= 13{,}376$) than short duration ($M = 14{,}340$, Std Dev $= 12{,}833$) at $p < 0.05$; the medium and long duration were not significantly different. Frequency ($F_{2,\ 34} = 46.83$, $p < 0.0001$) and amplitude ($F_{1,\ 17} = 38.93$, $p < 0.0001$) were also found to have significant effect with pretty big effect size (0.269 and 0.069). Tukey's HSD test indicated that participants had significantly shorter completion time in medium frequency ($M = 7314$, Std Dev $= 5304$) and high frequency ($M = 8780$, Std Dev $= 8777$) than low frequency ($M = 21{,}866$, Std Dev $= 15{,}643$) at $p < 0.05$; while the medium and high frequency were not significantly different. Tukey's HSD test of amplitude also showed that participants had significantly shorter completion time in big amplitude ($M = 9350$, Std Dev $= 9416$) than small amplitude ($M = 15{,}957$, Std Dev $= 14{,}429$) at $p < 0.05$.

A significant interaction effect between frequency and amplitude was found ($F_{2,\ 34} = 29.05$, $p < 0.0001$) with medium effect size of 0.059. As Fig. 5 showed, the task completion time decreased as frequency increased from low to medium level, then increased as frequency increased from medium to high level. However, the rate of change (slope of the line) was different among the two amplitude levels. For example, the task completion time had bigger decreasing rate with small amplitude than big amplitude when frequency changed from low to medium level.

4.3. Annoyance

Result found significant effect of frequency ($F_{2,\ 34} = 20.44$, $p < 0.0001$), duration ($F_{2,\ 34} = 8.79$, $p < 0.0001$) and amplitude ($F_{1,\ 17} = 21.82$, $p = 0.0002$) with effect size of 0.182, 0.029 and 0.045, respectively. Tukey's HSD test of frequency showed that the annoyance level was significantly lower in low frequency ($M = 1.78$, Std Dev $= 1.46$) than medium ($M = 3.30$, Std Dev $= 1.64$) and high frequency ($M = 3.44$, Std Dev $= 1.67$) at $p < 0.05$, while the medium and high frequency were not significantly different. Meanwhile, the annoyance level was significantly higher in long duration ($M = 3.26$, Std Dev $= 2.00$) than short ($M = 2.67$, Std Dev $= 1.65$) and medium duration ($M = 2.58$, Std Dev $= 1.53$) at $p < 0.05$, but there were no significant difference between short and medium duration. Participants also felt significantly less annoyed in small amplitude ($M = 2.46$, Std Dev $= 1.66$) than big amplitude ($M = 3.21$, Std Dev $= 1.79$) at $p < 0.05$.

Significant interaction effects were also found between duration and frequency ($F_{4,\ 68} = 4.86$, $p = 0.0017$), frequency and amplitude

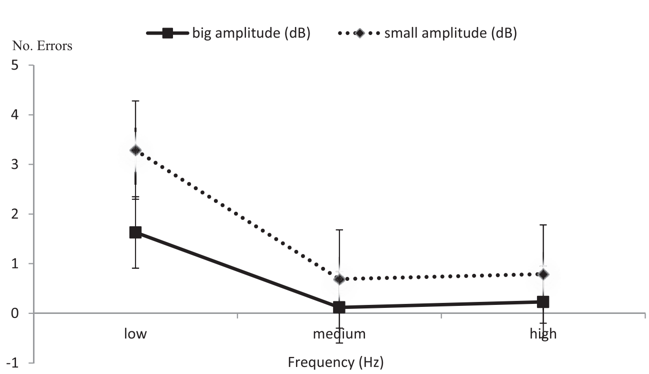

Fig. 4. Interaction effect between frequency and amplitude on number of errors. Significant interaction effect was found ($p = 0.0002$). The error bar indicated the 95% confidence interval of one standard error.

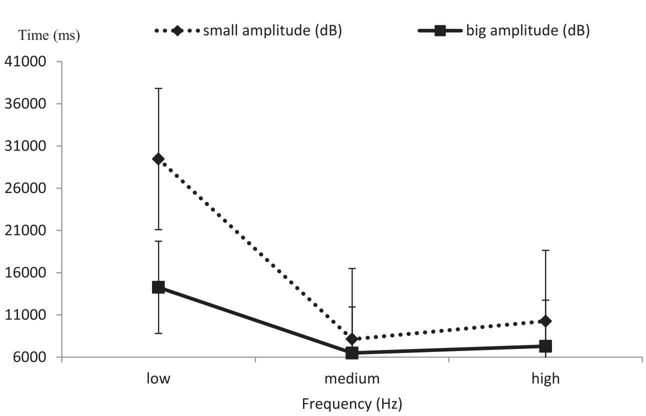

Fig. 5. Interaction effect between frequency and amplitude on task completion time. Significant interaction effect was found ($p < 0.0001$). The error bar indicated the 95% confidence interval of one standard error.

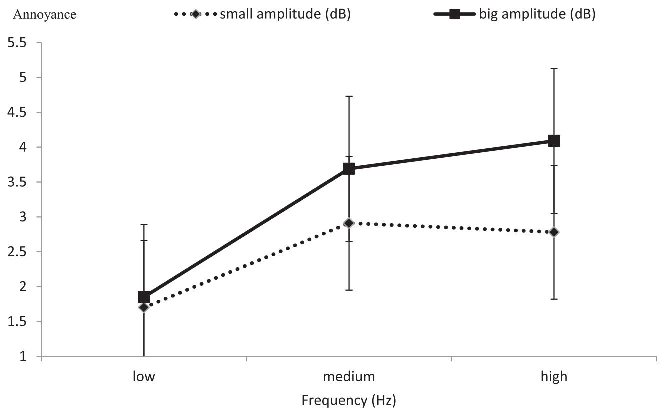

Fig. 6. Interaction effect between frequency and amplitude on annoyance. Significant interaction effect was found ($p = 0.0312$). The error bar indicated the 95% confidence interval of one standard error.

($F_{2,\ 34} = 3.85$, $p = 0.0312$) with pretty small effect size of 0.023 and 0.018. Fig. 6 showed that the annoyance level increased as frequency increased from low to medium for both amplitude levels, but the rate of change (slope of the line) was different. When frequency changed from medium to high, annoyance level increased for big amplitude, but decreased for small amplitude.

Fig. 7 showed that the annoyance level changed differently as duration time increased at different frequency levels. At high frequency level, annoyance increased as duration increased. At medium frequency level, annoyance decreased at first, then increased to a quite high level as duration increased. At low frequency, annoyance increased at first, then decreased as duration increased. However, the annoyance level was stable in the whole and much smaller than medium and high frequencies.

4.4. User preference

The frequency analysis showed that 66.70% (12 of 18) of participants preferred medium frequency and 22.78% (5 of 18) preferred high frequency. Only 5.52% (1 of 18) of participants preferred low frequency. In order to determine significant statistical difference for frequency user preference, a one-way Chi-Square test for equal proportions was conducted. Results showed that participants preferred medium luminosity contrast, $\chi^2 = 10.3333$, $p = 0.0057$.

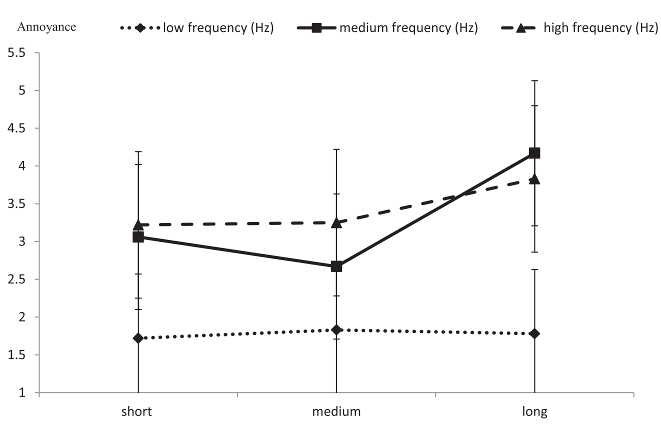

Fig. 7. Interaction effect between frequency and duration on annoyance. Significant interaction effect was found ($p = 0.0017$). The error bar indicated the 95% confidence interval of one standard error.

For duration, it showed that 66.70% (12 of 18) preferred medium duration, 16.67% (3 of 20) preferred long duration. The remaining 16.67% (3 of 20) preferred short duration. A one-way Chi–Square test for equal proportions showed that participants preferred medium duration, $\chi^2 = 9$, $p = 0.0111$. For amplitude, 94.44% (17 of 18) preferred big amplitude and only 5.56% (1 of 18) preferred small amplitude. A one-way Chi-Square test for equal proportions showed that participants preferred big amplitude, $\chi^2 = 14.2222$, $p = 0.0002$.

5. Discussion

5.1. Effect of amplitude

Our results indicated a significant effect of amplitude on task completion time, number of errors, and annoyance level. Participants were able to finish the task significantly quicker with notably fewer errors when presented with high amplitude in comparison to low amplitude. Though higher amplitudes resulted in improved completion times and fewer errors, they also produced higher levels of annoyance to the participants.

Amplitude is defined as the strength or magnitude of vibrotactile stimuli. The fact that vibrotactile stimuli of greater amplitude are easier for participants to perceive than those of smaller amplitudes is self-evident. An improved stimulus reception has the ability to reduce task completion time and number of errors. It is important to ensure that the signal does not cause pain or discomfort, but is strong enough to be detected when designing a vibrotactile display (Craig and Sherrick, 1982). Participants in this study confirmed that both amplitude levels were detectable and didn't cause any discomfort. However, the subjective magnitude, as perceived by a user, is a function of the intensity of the input signal and varies depending on users (Verrillo and Gescheider, 1992). This could be addressed by the following procedures: At first, determine the threshold for each user. Secondly, obtain the signal's intensity level based on the threshold. Finally, present the vibrotactile interface.

Vibrotactile displays can annoy users in terms of physical displeasure (i.e. creating painful sensations from generating heat) or by distracting the user, as it is difficult for users to ignore tactile stimuli that they do not wish to sense (Van Erp and Van Veen, 2001). In the study, participants felt moderately annoyed in the large amplitude condition. Users may not have been annoyed regardless of amplitude levels as a result of the short on-time duration of the tactile display, lasting less than 2 s. A time series analysis of annoyance level may strengthen an understanding of participants' changes in annoyance level. Future research should employ more levels of amplitude in order to improve task performance without sacrificing user friendliness.

5.2. Effect of duration

The results showed that duration has a significant effect on task completion time, number of errors and annoyance level. Participants were able to finish the task with significantly longer completion time and significantly more errors in short duration than medium and long duration. However, the number of errors and task completion time were not significantly different between medium and long duration, supporting the theory that the effects of temporal summation tend to be canceled by the effects of adaptation at suprathreshold levels of stimulation (Gescheider et al., 1994). Annoyance levels were significantly higher in long durations than medium and short durations; therefore, short duration was not preferable in the perspective of performance

Table 2
Design guidelines of vibrotactile feedback in navigation.

Parameter	Guideline	Description
Frequency	Medium level; Most sensitive around 250 Hz	People are more sensitive to Medium level frequency (Verrillo and Gescheider, 1992; Kuroki et al., 2012).
Duration	Medium level: less than 2 s; Shorter duration + large amplitude, or longer duration + lower amplitude	User adaptation exists, so medium level duration works more efficient. It interacts with amplitude (Geldard, 1957; Gescheider et al., 1994)
Amplitude	Varies by tactor size, spatial location and users. Also interact with duration.	Larger amplitude may be annoying, though more efficient. It should be considered together with duration in design (Verrillo and Gescheider, 1992; Geldard, 1960).

measurement, and the usage of long duration was not optimal from the user point of view.

Different from the amplitude, duration describes how long a vibrotactile stimulus lasts. There were three levels of duration in this study: short (250 ms), medium (1000 ms), and long (2500 ms). With frequency and amplitude given, a vibrotactile stimulus of longer duration can enhance the perception and reception of the participant. In other words, increases in duration can increase the total intensity of the vibrotactile feedback. The greater the intensity of the vibrotactile feedback, the more efficiently information can be delivered and enhance participants' task performance. However, vibrotactile feedback of longer duration can increase participants' annoyance levels. We found that as duration increased, participants felt more uncomfortable. This result suggested medium duration as the optimal condition by trading off between task performance and user comfortableness.

An interesting point to address was the interaction effect between duration and frequency on annoyance level. For example, Fig. 7 illustrated the consistency of annoyance level at low frequency. However, at high and medium frequency, the annoyance fluctuated at different duration level. Still, the medium duration level has proven to be the best of the three. One limit of this study is that there are only three levels of duration with specific values. To get a more general and convincing conclusion, more levels should be defined and tested.

5.3. Effect of frequency

Just as they did for amplitude and duration, the results indicated frequency's impact on task completion time, number of errors, and annoyance level. The medium frequency was able to produce the shortest task completion time and fewest errors. Participants also felt significantly less annoyed in low frequency condition than in others. Too low frequency will make the vibrotactile stimulus discrete and less efficient. Too high frequency can result in annoyance and interfere with task completion.

The number of errors varied in accordance to the frequency level from other responses. While the medium and high frequency has very similar trend, the low frequency derived much higher errors than do medium and high frequencies. These tendencies suggested that user performance, in terms of error rate, would be consistent above a certain level of frequency level. However, the extremely high level of frequency was not expected to deliver low level of errors. Thus, determining the range of frequency deriving 'good performance' may be very meaningful to designing an effective tactile display. Though the results of this study provide information important to tactile design, further research is needed to determine the optimal frequency for the navigation tasks.

5.4. General design guidelines

Results based on the amplitude come as expected. However, the resulting interaction between amplitude and frequency should be considered as remarkable. Interaction between amplitude and frequency (Rothenberg et al., 1977), and duration and perceived amplitude (Sherrick and Craig, 1982) on the perceptual threshold have previously been studied. Interaction between frequency and the other characteristics should be considered to find more meaningful result. Meanwhile, individual difference should be further discussed. For example, the research found that people with different weight might show different sensitivity to the vibrotactile stimuli.

A set of the design guidelines of vibrotactile feedback in a navigation task was summarized in Table 2, based on the result and previous research.

6. Conclusion

This study investigated the effects of vibrotactile feedback on a navigation task and provided a general design guideline for future applications. Vibrotactile duration, amplitude and frequency were manipulated to present different patterns of vibrotactile stimuli. The participants performed a navigation task with vibrotactile stimuli conveying the moving direction. The results showed that they all have significant effects on user performance (task completion, number of errors) and annoyance level. Medium level duration and medium frequency could produce better performance and less user annoyance, which could be used as a general guideline for tactile navigation systems. Optimal amplitude level was difficult to decide because of limited levels. These results should give some insight to the real-world applicability of the vibrotactile feedback as a primary modality information provider.

It is of importance to note that more studies involving those with visual impairments should be conducted to ensure that the results can be applicable to users with visual impairments. Meanwhile, limited levels of each vibrotactile parameter were examined in the present study. More levels with narrower ranges should be investigated to get more specific results. Additionally, bigger sample size of participants will make the conclusion more convincing.

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