Perceived Urgency of Tactile Warnings

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***Abstract*— Tactile warning systems present a viable alternative when the visual and auditory modalities encounter information overload. We modified the Patterson four-step design approach for auditory warning design, adapting it to tactile warning design. Using these approaches for a tactile warning design, we identified key design parameters, which could influence the perceived urgency of tactile warnings, namely spatial location and the number of activated vibrotactors. Using a tactile grid we developed a set of tactile designs varying in activation type, layout, and activation level. The different vibrotactor designs were evaluated using the perceived urgency scale. The results showed that the number of activated vibrotactors was a key design parameter influencing the perception of urgency. This study showed that perceived urgency is a concept that can be applied to tactile warnings and that tactile warnings can be systematically designed to convey appropriate levels of perceived urgency.**

Keywords - vibrotactor; tactile interface; warning design

I. INTRODUCTION

Warnings are designed to cue potential hazards. However, one challenge in many of today's work environments is the effectiveness of warnings may be reduced because of the presence of too much information in the visual and auditory modalities, which are heavily used in most interface designs. One possible solution is to present warnings to the sense of touch, however, this has only recently become of interest in warning design studies. In these studies, tactile displays, which use vibrotactors (small transducers that provide tactile feedback to human skin), were placed on various body locations, including the wrists [1], the waist [2] and the torso [3] [4].

Another challenge for presenting warning information is that people often misjudge or are unaware of the severity of hazards. Such misjudgment may lead to incorrect assessment of the risks. One solution for this problem is to design warnings that match the correct levels of perceived urgency to the severity of the risk. This approach has been implemented in auditory warning design [5] [6]. A subjective rating technique was applied in the experiments: participants were first presented with the auditory warning stimuli, and they were asked to rate the level of urgency for each stimulus. The results showed a unique feature that acoustic parameters of auditory stimuli have some effects to the levels of perceived urgency [7] [9] [8]. On the other hand, studies on parameters of tactile signals have provided many recommendations on manipulating tactile signals. Jones et al. suggested the best range of frequencies for the tactile sense which is critical for a detection or localization task [9]. Brown et al. indicated that introducing complex rhythms and waveforms are more effective in designing effective tactile signals than adjusting parameters such as frequency and duration [10]. Results of these studies showed that manipulating parameters of tactile stimuli convey some differences in the performance for tasks. However, there is little research on how these parameters can individually or systematically effect perceived urgency on tactile interfaces. One tactile parameter, pulse rate, has only been recently observed to have some effects to perceived urgency [11]. To our knowledge, however, no other parameters of tactile stimuli have been examined.

A unique feature of tactile warnings is that they can be presented to different parts of the body. Many studies have built tactile interfaces to provide spatial and localization information via the skin [12] [13] [1]. Thus, the spatial variance of vibrotactors became one of the motivations of this study, as it can be an important factor that affects perceived urgency. The study was also inspired by a systematic approach presented by Burns et al. [14] for using cues to map information with the tactile modality. The approach demonstrated that the types of information that can be properly presented to the tactile modality are limited. For example, the tactile modality can be used to encode one or two dimensional analogical information (such as deviation of a plane), but it is not a suitable modality to utilize continuous information (such as speed).

In this study we developed a tactile display by attaching a grid of vibrotactors on the back of a vest worn by participants. After that, we developed the tactile stimuli. To explore how the spatial variance affects perceived urgency, three parameters of tactile stimuli - activation type, layout type and activation level – were identified and examined in an experiment. Similar to the design of experiments for auditory warnings, participants were presented with the tactile stimuli, and each participant conducted a subjective rating task to examine the level of perceived urgency of each stimulus. Other possible attributes of the tactile stimuli, including participant's preference, annoyance and understandability were also tested through a questionnaire after the completion of the rating task.

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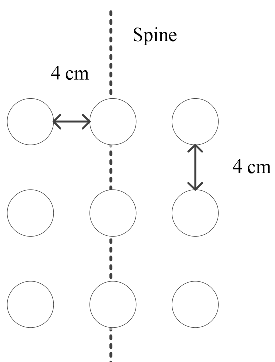
II. METHOD

A. Participants

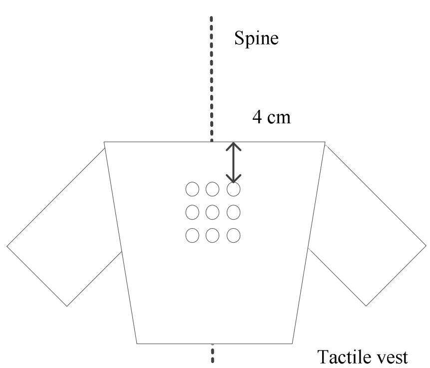
Ten participants (6 males, 4 females) were recruited from the University of Waterloo. Participants were either undergraduate or graduate students. All procedure and material of this experiment received ethical clearance by University of Waterloo Office of Research Ethics. Each participant read and signed a consent form before the start of the experiment.

B. Apparatus

Nine EAI C-2 vibrotactors were embedded in a nylon vest wore by participants. To fit the variety of user sizes, three sizes of vests (small, medium and large) were offered to build the tactile display. The vibrotactors were attached on the vest by Velcro in a three-by-three square grid. To provide a vertical reference axis, the three vibrotactors in the middle column were positioned on the spine (Fig. 1-a). Both vertical and horizontal distances between adjacent tactors were set as 4 cm to ensure that participants could differentiate adjacent tactors [3]. The grid was initially placed 4 cm below the shoulder (upper edge of the vest), but it can be repositioned vertically along the spine to fit each participant (Fig. 1-b).



a) Tactor gird



b) Default position of the tactor grid

Figure 1. Tactile display

The experiment was conducted in a normal office environment at University of Waterloo (Fig. 2). We arranged all experimental sessions during quiet hours to minimize the disturbance of extraneous sounds. The experimental information was presented by a 22-inch liquid crystal display monitor. Each vibrotactor was connected to a Tactor Control Unit (also provided by EAI). The monitor and the Tactor Control Unit were connected to a computer under the experimental table. A computer program was developed by Trellis Consulting to generate tactile stimuli.

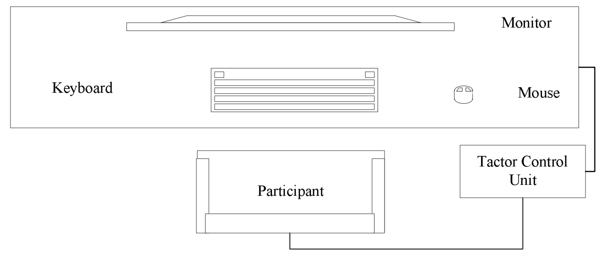


Figure 2. Experimental setup (overhead view)

C. Stimuli

We followed the four-step cycle for auditory stimuli design developed by Patterson [8]. The original design cycle begins with a sound level, a fundamental attribute of an auditory signal. We started our work of designing tactile stimuli from the fundamental vibration level. First, a fundamental vibration frequency was set. Past studies have suggested that the optimal fundamental vibration frequency should be set between 150 hertz to 300 hertz [15]. In addition, in order for the signal to be detectable, human sensitivity to detect tactile signals should move in an upward parabola such that the frequency descends from 150 hertz to 250 hertz and ascends from 250 hertz to 300 hertz [16]. In this experiment the fundamental vibration frequency was set as 250 hertz in all the tactile stimuli. A frequency of 250 hertz is also in the optimal frequency range of pacinian corpuscles which are the vibration-sensitive mechanoreceptors of the skin [17].

The second attribute of the fundamental vibration level was the duration of each tactile stimulus. The activation duration was designed for 180 milliseconds with a 20 milliseconds gap at the beginning of each tactile stimulus. The activation duration follows the suggestion by Kaaresoja and Linjama [18] who reported that vibration durations longer than 200 milliseconds become annoying. Also, Van Erp and Self [12] suggested that if a consistent vibration is presented for more than 200 milliseconds, then pressure adaptation may occur. Pressure adaptation reduces the sensitivity of the skin after a consistent vibration at the same location [19]. The 20 milliseconds gap was inserted to avoid pressure adaption.

The activation level was designed to have three levels and matched the vertical locations of the vibrotactors – Level 1 (close to the waist), Level 2 and Level 3 (close to the shoulder). The first hypothesis of this study was that increasing activation levels will result in increased levels of perceived urgency in each tactile design. If so, the levels of activation can be used to map onto the participants' psychological interpretation of perceived urgency with higher levels representing more urgent situations [14].

The second hypothesis was that more activated vibrotactors should produce higher perceived urgency. We developed two activation types that we called Target and Full Bar. Fig. 3 shows an example of the two activation types at Level 2. In a Target design, the urgency was encoded by the vertical location of tactile activation. Activation of higher level vibrotactors represented greater urgency. The Full Bar design was different to the Target design, however, all the vibrotactors below (if any) were also activated in addition to the target vibrotactor. Therefore, in this design perceived urgency was represented by both the vertical location of topmost vibrotactors being activated and the number of activated vibrotactors.

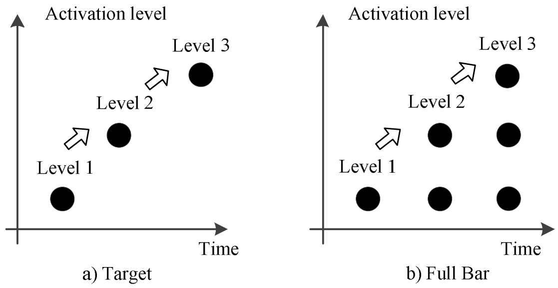


Figure 3. Example of two activation types

The number of activated vibrotactors was also manipulated by varying the layout of the tactors. Fig. 4 shows two layout designs which were examined in the experiment. In the One Column design, only the middle column of vibrotactors was used, while in the Two Column design only the left and right column of vibrotactors were used. We hypothesized that the Two Column design should convey greater urgency mapping, because more tactors are activated in each warning.

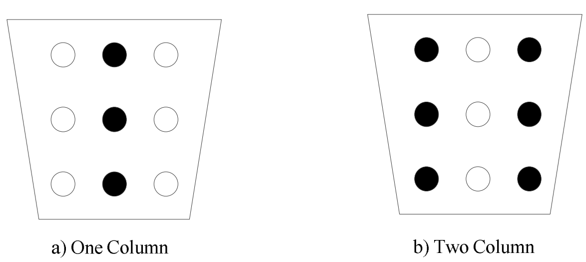


Figure 4. Layout types

Table 1 shows the 12 combinations of tactile stimuli that were developed. Each combination of activation type × layout type was defined as a “design”. During the experiment, each stimulus was replicated five times. Thus, each participant was presented with 60 trials in this experiment.

TABLE 1. DESIGN PARAMETERS OF THE TACTILE DISPLAY

Activation type (2)	**Layout type (2)**	**Activation level (3)**
Target	One Column	Level 1
Full Bar	Two Column	Level 2
		Level 3

In summary, we evaluated the following hypotheses:

- Higher activation levels should result in increased levels of perceived urgency in each tactile design.
- More activated vibrotactors should result in higher perceived urgency.

III. PROCEDURE

Prior to running in the study, participants were instructed to wear a T-shirt to ensure a good contact between the vibrotactors and the skin. They were also asked to try all three sizes of vests and pick the most suitable size from small, medium and large. All participants wore a medium-sized vest without adjusting the position of the vibrotactors.

The experiment started with a training session to familiarize participants with the tactile stimuli used in the experiment. During the training session, participants were asked whether they could feel each stimulus. If not, the experimenter repositioned the grid of vibrotactors. However, all participants reported no concerns sensing the vibrotactors.

The urgency rating session began after the completion of the training session. Participants rated the degree of urgency for each trial according to how their perception of the tactile display. An urgency rating scale, based on auditory urgency scales [20] [7], was displayed on a monitor ranging from 1 to 100. Participants were given the instructions as shown in Fig. 5. No cues of the tactile stimuli being presented was showed on the monitor.

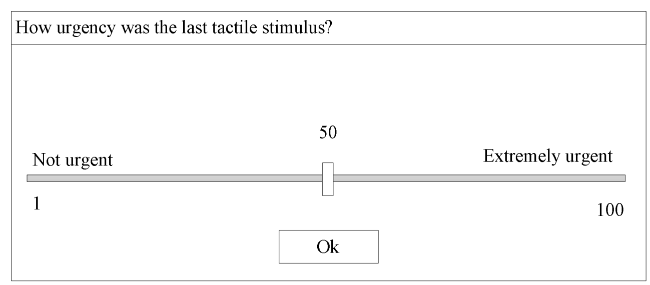


Figure 5. Prompt window for urgency rating task.

After each trial, participants were asked to drag a rating slider to their perceived urgency on the numerical scale. After the completion of the urgency rating task, participants were asked to answer a questionnaire. Participants were asked, respectively, for their overall preference, understandability and perceived annoyance of the four designs.

IV. RESULTS

Urgency rating scores were recorded by the experimental program and exported to a log file after the completion of each participant. We calculated the mean urgency rating of five replicates per tactile stimulus [20] [7].

A repeated measures analysis of variance (ANOVA) was conducted on normalized mean rating as a function of activation type (Target vs. Full Bar), layout (One Column vs. Two Column) and level of activation (Level 1 vs. Level 2 vs. Level 3). Two statistically significant interactions were observed: an activation type × layout type interaction, $F(1,9) = 6.416, p = 0.032$ (Fig. 6), and an activation level × layout type interaction, $F(2,18) = 30.526, p < 0.001$ (Fig. 7). No other significant interactions were found.

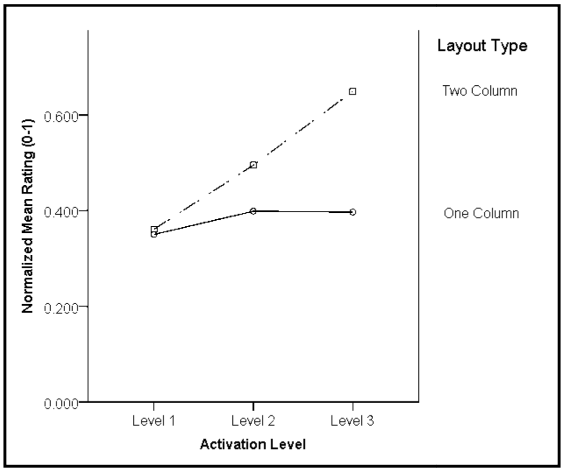


Figure 6. The activation level × layout type interaction

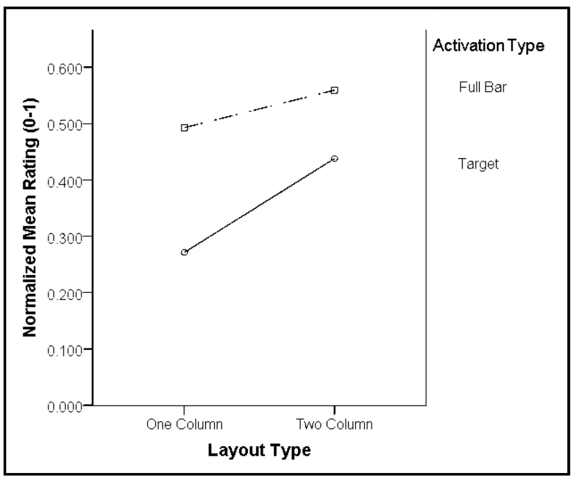


Figure 7. The activation type × layout type interaction

Table 2 shows the normalized mean rating of each stimulus (activation type × layout type × activation level) in the experiment.

TABLE 2. NORMALIZED MEAN RATING OF ACTIVATION TYPE × LAYOUT TYPE × ACTIVATION LEVEL

Combination	M	SD
Target One Column Level 1	0.245	0.164
Target One Column Level 2	0.293	0.158
Target One Column Level 3	0.276	0.188
Full Bar One Column Level 1	0.456	0.124
Full Bar One Column Level 2	0.505	0.128
Full Bar One Column Level 3	0.518	0.139
Target Two Column Level 1	0.267	0.157
Target Two Column Level 2	0.480	0.127
Target Two Column Level 3	0.549	0.133
Full Bar Two Column Level 1	0.442	0.113
Full Bar Two Column Level 2	0.511	0.142
Full Bar Two Column Level 3	0.750	0.133

Results of the questionnaire showed that there was a statistically significant association between design and preference, $\chi^2 = 21.867, p < .0005$. Descriptive statistics in Table 3 show that most participants preferred the Full Bar Two Column design.

TABLE 3. PREFERENCE IN DESIGN

Design	Preference
Target One Column	0%
Target Two Column	10%
Full Bar One Column	10%
Full Bar Two Column	80%

Participants were asked to circle the most preferred activation type. A Pearson Chi-square test on preference in design showed that no statistically significant association was found between activation type and preference, $\chi^2 = 0.800, p = 0.371$. From Table 4 we know that the preference for Target and Full Bar was almost equally divided.

TABLE 4. PREFERENCE IN ACTIVATION TYPE

Design	Preference
Target	40%
Full Bar	60%

The said question was asked for participant's preference in two layout types. Results of a Pearson Chi-square test performed on preference in layout type showed, there was a statistically significant interaction between design and preference, $\chi^2 = 12.800, p < 0.0005$. Descriptive statistics showed almost all participants preferred the Two Column design (Table 5).

TABLE 5. PREFERENCE IN FOR LAYOUT TYPE

Design	Preference
One Column	10%
Two Column	90%

The next metric was perceived understandability of the four designs. Participants were asked to circle the design which seemed easiest to understand. A Pearson Chi-square test showed that there was a significant association between design and perceived understandability, $\chi2(1) = 22.933, p < 0.0005$. Table 6 reports that most participants believed that the Full Bar Two Column was easiest to understand.

TABLE 6. UNDERSTANDABILITY FOR DESIGN

Design	Understandability
Target One Column	0%
Target Two Column	20%
Full Bar One Column	0%
Full Bar Two Column	80%

Participants were asked to choose which activation type was perceived to be easier to understand between the Target and Full Bar designs. A Pearson Chi-square test was conducted on understandability for activation type, $\chi2(1) = 7.200, p = 0.023$, which was statistically significant. Most participants believed the Full Bar design was easier to understand than Target, as shown in Table 7.

TABLE 7. UNDERSTANDABILITY FOR ACTIVATION TYPE

Design	Understandability
Target	20%
Full Bar	80%

Participants were asked which layout type seemed easier to understand, between the one column and two column layouts. All participants believed Two Column was easier to understand (Table 8). The result of Pearson Chi-square test was highly significant, $\chi2(1) = 20.000, p < 0.0005$.

TABLE 8. UNDERSTANDABILITY IN FOR LAYOUT TYPE

Design	Understandability
One Column	0%
Two Column	100%

Participants were asked to rank the perceived annoyance of the four designs on scale from "the least annoying" (coded as 1) to "extremely annoying" (coded as 4). Results of a Friedman test suggested that there was no significant difference in annoyance between the four designs, $\chi2(3) = 3.154$, $p = 0.369$. Table 9 shows the mean annoyance score and standard deviation per design. Finally participants were asked if any of the designs were "too annoying to use". None of the designs were rated as "too annoying to use".

TABLE 9. MEAN ANNOYANCE SCORE OF DESIGN

Design	M	SD
Target One Column	2.778	1.302
Target Two Column	3.000	0.866
Full Bar One Column	2.333	0.866
Full Bar Two Column	2.000	1.225

V. DISCUSSION

In general, ratings of perceived urgency increased with activation level. In other words, higher urgency was produced when vibrations occurred close to the shoulder when compared to that occurred in the middle of the back and close to the waist. However, an exception to this general finding is evident in the activation level × layout type interaction wherein this effect did not exist in the One Column design (Fig. 6). This finding partially supported our hypothesis that activation level can match the level of perceived urgency, in some tactile warning designs.

The analysis of activation type and layout type showed that more vibrotactors conveyed higher perceived urgency. A Full Bar design was perceived to be more urgent than a Target design. This result supported our hypothesis that more activated vibrotactors conveyed higher perceived urgency, as the Full Bar design used more vibrotactors. The effect of the layout types was consistent with this hypothesis. That is, a Two Column design produced higher perceived urgency than a One Column design. In the One Column design, only the middle column - which was positioned on the spine - of vibrotactors were used. An earlier study has suggested that the spine is a sensitive region on the back, so it can be a very strong referent for a tactile display [2]. In our case, however, it seemed that the spine did not interfere with the hypothesized relationship. The significant activation type × layout type interaction showed a possible relationship between the activation type and the number of columns. When the number of columns increases, the difference of perceived urgency between the Target design and the Full Bar design may be reduced (Fig. 7).

The major limitation of this experiment was that all the tactile stimuli were tested in the absence of realistic context, although participants were told that all the tactile stimuli were warnings. The lack of the realistic context may also result in a habituation of tactile stimuli [12]. Participants may lose awareness, so the sensitivity to detect tactile stimuli did not change over the trials. Future studies should examine the effects of warning parameters in a hazardous situation, which have been touched in the field of auditory warning design [20]. Future studies should also be conducted with a larger sample size of participants, so we may generalize the results to the overall population. Another direction for future research is to extend the current study to more tactile parameters so that more complex tactile stimuli can be evaluated, as recommended in related tactile warning studies [11] [10]. In this case, it would be interesting to see how significant the effect of the number of activated vibrotactors is compared to other parameters.

In conclusion, this study examined the effects of several important tactile parameters to perceived urgency of tactile warnings. Some promising findings on the effects of parameters were observed. Such findings should help designers to build the prototype of a tactile warning system, and the urgency mapping of this system with the severity of hazards should be considered as early as the design phase. The design of the current study has suggested a possible form of such warning system: some parameters can be combined to build certain warning designs, and one parameter is adjustable to vary the urgency of tactile warnings. However, future studies remain unfinished. Designers should be very careful to use the tactile modality as a warning display.

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