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Effectiveness of Directional Vibrotactile Cuing on a Building-Clearing Task

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ABSTRACT
This paper presents empirical results to support the use of vibrotactile cues as a means of improving user performance on a spatial task. In a building-clearing exercise, directional vibrotactile cues were employed to alert subjects to areas of the building that they had not yet cleared, but were currently exposed to. Compared with performing the task without vibrotactile cues, subjects were exposed to uncleared areas a smaller percentage of time, and cleared more of the overall space, when given the added vibrotactile stimulus. The average length of each exposure was also significantly less when vibrotactile cues were present.

ACM Classification: H.5.2 [User Interfaces]: Haptic I/O; H.1.2 [User/Machine Systems]: Human factors; I.3.6 [Methodology and Techniques]: Interaction techniques.

Keywords: tactile & haptic UIs; virtual reality; user study; vibrotactile.

INTRODUCTION
As part of a longer-term program to study the use of virtual reality (VR) systems for training applications, we have been studying the introduction of haptic cues into VR systems. The use of haptic cues in virtual reality training systems can take on many forms. Haptic cues can be used to ***provide a sense of virtual contact*** between the person and objects he/she interacts with. Thus, if a user attempts to open a virtual door, actuators on the hand can be triggered at the time and location of the contact to provide a better sense of the nature of the contact. Alternatively, haptic cues can be used as training aids to ***improve the situational awareness*** of participants, alerting them to such things as a path to follow when searching for victims in a fire, or the location of teammates in a team-based scenario. Haptics can also be used to ***compensate for shortcomings of current technology***, such as directional vibration cues used to alert a user to visual information currently outside the field of view of a visual display. Finally, haptic feedback can be used to ***increase the overall realism*** of a simulation by improving the user experience, making it closer to the experience being simulated.

The main motivation for our work is a desire to understand the usefulness of haptic sensory substitution and augmentation in HCI. This paper presents results from a study we conducted into the effectiveness of applying directional vibrotactile cues for improving the situational awareness of soldiers in a simulated building-clearing exercise. The haptic cues being studied are simple vibrotactile cues used to convey information about exposure to uncleared regions of a building. In order to get at the question of cue effectiveness, we have greatly simplified the task. Once we can establish that there is a positive effect, we can conduct further studies using a more-realistic training environment.

Although the task is presented in a military context, it is quite similar to other searching tasks such as search and rescue and fire fighting. Furthermore, this work also finds application in the field of teleoperation. Typical remote-manipulation environments present data from sensors using purely visual means, taxing the visual channel of the operator, while the other senses go underutilized. By mapping appropriate data to directional vibrotactile cues, we can better balance the load placed on any single channel, possibly reducing errors, while increasing overall capacity.

PREVIOUS WORK
The type of haptic cues we describe here have successfully been used by ourselves and others to both draw the user's attention to an area of interest, and to improve spatial awareness.

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Tactile Cuing for Spatial Attention

A tactile cue at one location has been shown to improve the individual's ability to discriminate visual stimuli at that location [16, 13]. When tactile cues were presented prior to intermingled visual and auditory targets, and subjects were required to indicate target elevation (up or down), responses for both target modalities were faster when presented on the same side as the tactile cue [16]. The authors concluded that tactile cues might produce "cross-modal orienting that affects audition and vision." When tactile stimuli were presented to one finger concurrent with visual stimuli presented to the left or right visual half-field, functional MRI indicated that such simultaneous visual and tactile stimuli enhanced visual cortex activity when the two modalities of stimuli were on the same side [13]. This result seems to support the possible efficacy of increasing spatial awareness by combining tactile and visual cues.

Tactile Cuing for Spatial Awareness

There are a variety of ways to provide tactile cuing. For a number of reasons, including low cost, portability, relative ease of mounting on different parts of the body, and modest power requirements, we have been concentrating on the use of vibrotactile tactors. Tactors are devices that provide some form of tactile sensation. A number of other researchers have recently been exploring the use of similar devices for providing feedback for human-computer interaction. Tan *et al.* [17] combined input from pressure sensors mounted on the seat of an office chair with output in the form of tactors embedded in the back of the seat to create an input device with haptic feedback. They integrated this system into a driving simulator, used a classification system of the pressure sensors to determine when the driver intended to change lanes, and then gave attentional cues to the driver with vibrotactile pulses about danger based on dynamic traffic patterns.

Though the torso has not been found to be the best body location for high-resolution vibrotactile feedback [20], those parts that are more perceptive to vibrotactile stimuli, such as the hands, are typically involved in other tasks, whereas the surface of the torso is relatively unused. Geldard provides an excellent motivation for how touch cues can be used to enhance communication [4]. Rupert [15] developed a system using a vest with tactors sewn into it to allow pilots to better judge the down-vector when performing aerial maneuvers that alter the pilot's vestibular system, causing possibly-fatal errors in judgment. He found that feedback to the torso could be effective in improving a pilot's spatial awareness.

In similar work performed in the Netherlands, Veen and Erp [19] studied the impact of G-forces on both the mechanical workings of vibrotactile devices, and on reaction times to vibrotactile stimuli displayed on either the right or left side of the torso. They showed that after initial familiarization with the environment, subjects had fairly stable response times and accuracy levels, even up to 6G of force. There was also no apparent difference in performance with and without a pressure suit.

The same group in the Netherlands has performed several additional significant studies in an attempt to understand the spatial characteristics of vibrotactile perception on the torso [2]. They proposed using the vibrotactile channel as a way of augmenting the reduced visual peripheral field common in virtual environments (VEs). They found that sensitivity for vibrotactile stimuli was greater on the front of the torso than on the back, and that sensitivity decreases the further the stimulus point is from the sagittal plane (the plane dividing the left and right halves of the body).

In follow-on studies, they tested the ability of subjects to judge the location of a vibrotactile stimulus presented at different locations on a circle of tactors placed around the mid-section of the torso [1, 3]. They confirmed their earlier findings about increased sensitivity near the sagittal plane, and found a standard deviation of 4° near the sagittal plane for estimating stimulus location around the torso. They propose the existence of two internal reference points, approximately 8cm apart, one on each side of the torso, that are used for estimating direction.

Still more work from this group compared vibrotactile feedback on the back and on the hand in relation to visual performance [21]. In a forced-choice discrimination task, subjects had to decide which of two successive gaps in vibration, each defined by two pulses, was longer. The gaps ranged from 56ms to 2,000ms, and five different treatments were defined. In three treatments, both the reference and comparison gaps were fed through the same channel: visual (V-V), vibrotactile on the back (B-B), or vibrotactile on the finger (T-T). The remaining treatments were V-T and V-B. Thus, both unimodal and bimodal discrimination could be measured. Some of their treatments also varied the uncertainty about the length of the reference interval. They found that discrimination thresholds varied substantially with increased uncertainty, from 19% to 140%. Treatment effects only showed a trend in performance, with V-V being better than V-B. Multimodal discrimination showed higher thresholds than expected, suggesting added confusion when multiple channels are used.

Kume *et al.* [8] introduced vibrotactile stimulation on the sole of the foot, and developed a slipper-like interface. They put two tactors on each sole and made use of phantom sensations elicited by these tactors. They measured the characteristics of the phantom sensation psychophysically, and found that the location, movement, and rotation of objects could be perceived.

Yano *et al.* [23] developed a suit-type vibrotactile display with 12 tactors attached to the forehead (1), the palms (2), elbows (2), knees (2), thighs (2), abdomen (1), and back (one on the left side and one on the right). They examined the effectiveness of using this vibrotactile display for tasks that required the user to walk around a virtual corridor visually presented in a CAVE-like display. They showed that presentation of tactile cues was effective for imparting collision stimuli to the user's body when colliding with walls.

In our own work, we have looked at determining the limits of perception of the human back in terms of vibration intensity and location discrimination [11], as a means for directing the user's gaze for predominantly visual search tasks [12], and as a way of conveying information by way of strokes for writing letters [22].

From this survey, it is clear that the torso holds some potential for effective vibrotactile cuing. We now present work we have done in an attempt to better understand the nature of the torso as a region for displaying vibrotactile cues. The area we concentrate on is the use of visual and vibrotactile cuing, both in isolation and combination, on a building-clearing task.

EMPIRICAL STUDY

The overall goal of this research is to determine the effectiveness of vibrotactile cuing as a training aid for searching inside of a building and similar tasks. For this study, we concentrate on determining the relative effectiveness of vibrotactile cuing in a single, simple task. Accordingly, we have greatly simplified the environment to remove potential confounding variables. We use a desktop display, rather than a fully immersive environment, control our avatar with a joystick, and allow movement in only two dimensions. We view the current study as the first in a series into the effectiveness of directional vibrotactile cues in both mobile and stationary applications. As the current task in a real environment involves physical movement, later experiments will introduce more traditional VR locomotion techniques, such as walking in place [18], or treadmill walking [6]. Later studies will add more aspects of actual building clearing, but here we focus on a subset of the skills necessary for successful completion of the task, namely exposure minimization.

Subjects were given the task of searching a virtual building with five rooms on one side of a hallway (see Figure 3 and Figure 7). The goal was to minimize exposure of the subject to possible unseen sources of danger while maximizing the speed and effectiveness of the search. We define *exposure* as the user being within the field of view of uncleared space, *i.e.*, space that the subject has not yet viewed. Since the location of any potential threat is not known *a priori*, we assume that any position that has not been seen could conceal a threat. Subjects were instructed to move through the space looking for simple 3D geometric objects (*targets*) while remembering to minimize their exposure to possible attacks. The subject indicated that a target had been located by squeezing the trigger on the joystick.

Hardware and Software Setup

The experiment was performed on a PC with dual 1.7GHz Xeon processors running Windows XP. The monoscopic graphics were generated by a 3Dlabs Wildcat II 5110 graphics card, and were displayed on a 21" CRT. Movement was controlled using a Logitech USB Extreme 3D Pro joystick. To support the delivery of vibrotactile cues, we have designed the TactaBoard system [10]. This system incorporates the control of a large number of different types of feedback devices into a single, unified interface (Figure 1).

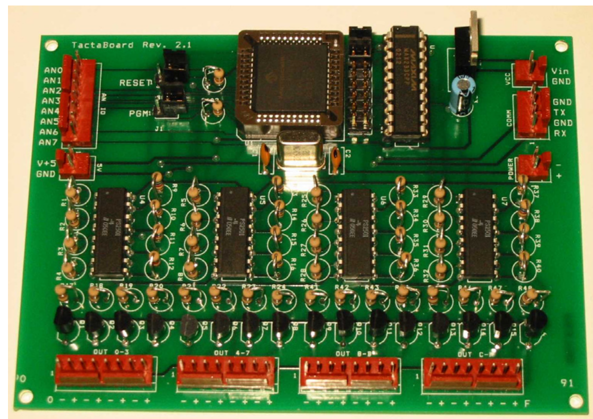

Figure 1: The TactaBoard.

In addition, the system can be run completely from battery power, and can use a wireless connection to provide control from the host computer running the simulation software. Our current version supports the independent control of 16 outputs on a single controller board using a standard serial port. This solution is general in the sense that it supports feedback cues when performing direct manipulation of purely virtual objects, by mounting the tactors directly on the person, as well as when the environment is explored with physical props by mounting the tactors on the prop. In the current work, the tactors are used to present directional cues.

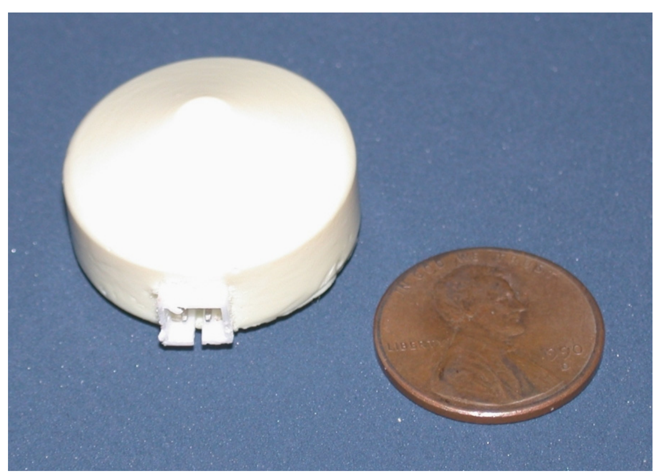

Figure 2: Ruggedized tactor.

The vibrotactile stimuli were delivered using tactors placed at eight, evenly spaced compass points around the torso of the subject. The tactors were positioned individually for each subject, and held in place by pressure using a neoprene belt, forming a TactaBelt. The tactors were ruggedized versions of the Tokyo Parts Industrial Co., Ltd., Model No. FM37E, and have an operating voltage range of 2.5-3.8V at 40mA (Figure 2). They have a frequency of 142Hz at 3.0V, and have a vibration quantity of 0.85G. The stimulus frequency for our experiments, determined from previous work [11, 12], was set to 130Hz.

The visual environment was created using the OpenInventor implementation by TGS. Simple collision detection was done to keep subjects from penetrating walls. No visible avatar of the user was provided, that is, the camera view is the same as the subject's view. A snapshot of the environment is shown in Figure 3.

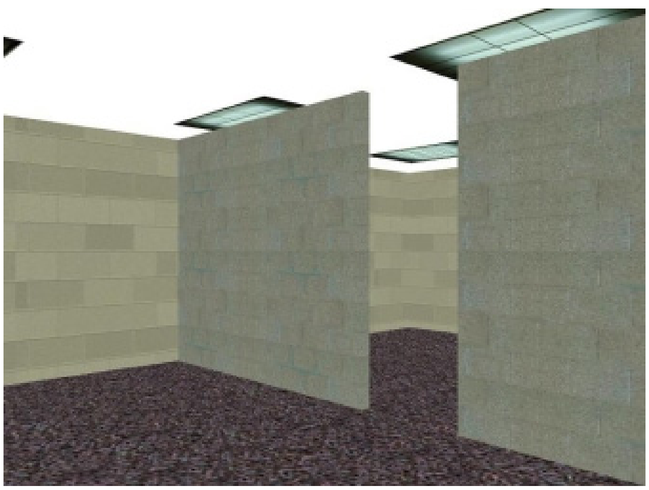

Figure 3: Screen capture of virtual environment.

Movement Control

Displacement of the joystick in any direction from the center initiated rate-controlled user movement in that direction, proportional to the magnitude of the displacement from center. Maximum travel speed was 1.5m/sec. Rotation of the joystick initiated rate-controlled rotation of the user's view, with a maximum rotational velocity of 180°/sec. Though subjects were not actually walking around in the environment, letting them control their own movement follows the notion of *active touching* discussed by Heller *et al.* [5].

Clearing Algorithm

We define a subject as exposed if he/she is currently visible from any space that has not yet been cleared. Space is defined as "cleared" if the subject has viewed that space. To facilitate exposure computation at runtime, we have made some simplifying assumptions. First, we assume that walls are the only occluders, so we do not consider other objects, such as the geometric shapes and pedestals (see below). Second, the space is static, *i.e.*, nothing moves, so we can compute occlusion based on a fixed building layout. Third, all potential enemies must be standing on the floor, so we can reduce the problem to 2-D space. Finally, we define locations within the space, called *hotspots* that represent locations that an enemy could occupy. A hotspot is considered cleared when a subject views it, thus, clearing the space is performed by clearing the hotspots. For this experiment, one hotspot was placed in each corner of every room, with the exception of the hallway. The thought was that it is difficult to actually clear an entire room without looking into each corner, and looking in every corner is difficult to do without sweeping all of the room.

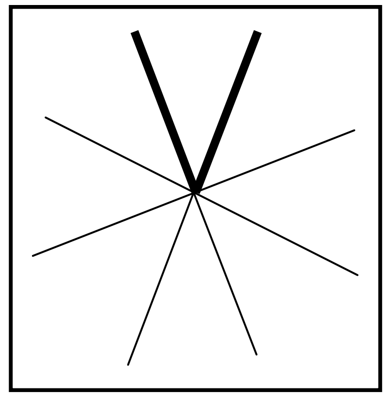

Figure 4: Marking and clearing frusta. The current view frustum is always N **(demarcated by bold lines).**

Based on these assumptions, at the beginning of each trial we set all hotspots to "uncleared," and run the following algorithm at each time step (please refer to Figure 4):

1. If the view frustum has not changed since the last time step, then do nothing.
2. Otherwise, unset all bits in an eight-bit bitfield, one bit for each of the compass directions.
3. Mark any hotspots within the current view frustum as "cleared."
4. For each of the seven remaining compass directions, compute a frustum demarcated by the adjacent compass directions, and set the corresponding bit for this compass direction if there are any uncleared hotspots within it.
5. For each bit that is set (unset) in the bitfield, turn the corresponding tactor on (off).

Our assumptions make the computation of exposure to hotspots a simple 2D visibility test with static objects.

Experimental Design

The experiment followed a single factor, two level, within subjects design, counter balanced for treatment presentation order. The factor levels were the presence (V) or absence (N) of vibrotactile cues.

Protocol

Subjects first completed an IRB-approved human subject consent form, and provided anonymous demographic information. A preliminary study was given to each subject before beginning the actual experiment. This pretest had several purposes:

1. to familiarize each subject with the vibrotactile cues,
2. to provide baseline data for each subject's performance in recognition of relative direction from a vibrotactile cue, and
3. to screen subjects for poor vibrotactile acuity.

The subject wore a TactaBelt with one tactor for each of eight compass-point directions. Assuming the front of the subject is N, the directions were N, NE, E, SE, S, SW, W, and NW. The subject was seated in front of a computer monitor. On the monitor, the eight directions were displayed as square, labeled buttons in a circular pattern with N at the top (Figure 5). Subjects were instructed to imagine themselves in the center of the pattern. Given a one-second, 130Hz stimulus, the subject was asked to indicate a point in the same relative direction from the center of the diagram as he/she sensed the vibration to be coming from. Each subject was given 32 trials to perform, the first eight of which went in order around the circle, beginning with N. The remaining 24 trials were in pseudo-random order.

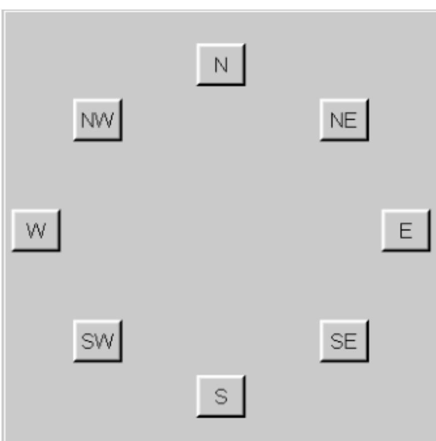

Figure 5: The eight cardinal points displayed in the pretest.

Pretest Findings

The twenty-nine subjects who performed the pretest averaged 3.7 errors in 32 attempts with standard deviation (s.d.) 3.82, median and mode were both 2. Figure 6 shows the number of subjects (vertical) at each error level. Apparently, the subjects who committed 13 and 16 errors are outliers. The TactaBelt was actually configured incorrectly for the subject with 13 errors (the positions of 2 tactors were reversed). When this was discovered, and corrected prior to the actual experiment, we decided that this subject is not truly an outlier. We concluded that the other subject is in fact an outlier and must be excluded from the analysis, leaving a total of 28 subjects whose data is used in subsequent analyses. In all cases, with the exception of the two apparent outliers, no errors were greater than one octant, suggesting that directional cuing was accurate. This is consistent with previous results discussed above.

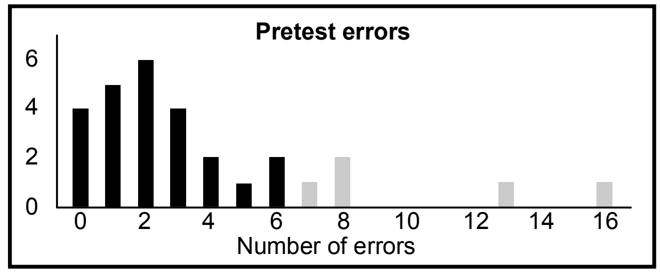

Figure 6: Number of subjects by error level.

Exposure Experiment

Following the pretest, subjects were asked to carefully read a detailed description of the experimental task, complete with a list of the measures that were being used to assess performance. Subjects were told that they should explore the space, looking for enemies that might be hiding within the space, similar to a first-person shooter game. We chose this scenario to simplify the explanation of the task, building on a well-known gaming genre. They were also told that there would be some geometric objects, with various shapes and colors, distributed throughout the space, and that when they encountered such an object, they should squeeze the trigger of the joystick. We placed the objects in the environment to provide landmarks to the subject, and had them squeeze the trigger to acknowledge sight of each one. Following each trial, subjects were asked to draw the space they had just encountered, including the location, shape, and color of each object. They were told to explore the environment using any techniques they wanted, but that they should move carefully so as not to be caught by an enemy.

Each subject was randomly assigned to either the vibro/non-vibro (VN) or non-vibro/vibro (NV) treatment-ordering group. Before each treatment, a training session was given with a different, but similar environment to the test environment to ensure that the basics of moving through the environment were mastered. The vibrotactile cues present in the training sessions matched those of the subsequent treatment.

Building Layout

The layout of the space for the experiment is shown in Figure 7. The space consisted of a long hallway with a width of 2.5m, and five rooms off to one side, each with a width of 5m. Rooms 1 and 4 were 13m long, room 2 was 10m long, and rooms 3 and 5 were 7m long. All doors were 0.8m wide. Four geometric shapes, each with different visual properties, were placed on pedestals in four of the rooms. Referring to the figure, shape ***a*** was an orange cone, shape ***b*** was a green sphere, shape ***c*** was a blue cube, and shape ***d*** was a red sphere.

The two treatments used the same room layout, but subjects started at one end of the hallway for the V treatment, and the other end for the N treatment, denoted in the figure by ***V*** and ***N***, respectively. Each subject started facing down the hallway, with their back 1.5m from the wall. At the far end of the initial corridor, a yellow bouncing ball was placed, and subjects were instructed to move to this location and press a button on the joystick base after completing the trial.

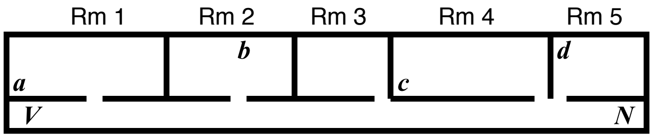

Figure 7: Layout of the space.

Data Collection

A wealth of data was collected during each treatment, including the time and direction of all exposures, trigger pulls, and timing information. In addition, all samples from the joystick were captured, allowing each session to be re-played and analyzed. Performance measures included:

1. Time to complete trial,
2. Total time exposed,
3. Average length of time per exposure,
4. Number of exposures,
5. Total time not exposed,
6. Average time between exposures,
7. Percent of time exposed, and
8. Amount of building "cleared".

In addition, subjects were instructed that they would need to draw a map of the environment upon completing each treatment. This was done to assess how well they remembered the layout, but also to motivate them into careful exploration.

Subject Demographics

A total of twenty-nine subjects (graduate and undergraduate engineering students) took part in the experiment, twenty-four males and five females. Of these, data from twenty-eight was used; the other subject (a male) was considered an outlier because of erratic performance on the pretest (see below). The average age of these subjects was twenty-five years, four months. Twenty-three of the subjects were right-handed, and five were left-handed (all males). All subjects chose to use their right hand for controlling the joystick. In terms of experience with computer games, four subjects (three males, one female) reported no previous gaming experience, nineteen (fifteen males, four females) reported casual gaming usage, and six (all males) reported being regular gamers. Nineteen subjects (thirteen males, five females) reported having average orientation skills, and nine (all males) reported having strong orientation skills.

RESULTS

From the data we collected during the experiment, we were able to extract the performance measures shown in Table 1. We analyzed the data for significant differences in mean performance using the Within Subjects General Linear Model section of the SPSS statistical analysis package. For those measures with significance above the .05 level, we also calculated η^2 as a measure of effect size, that is its value is interpreted as the percentage of variation due to different levels of the factor.

Measure	N	V	All
Total Time per Trial*	90,606 (24,723)	105,781 (31,263)	98,193 (28,957)
Total Time Exposed	22,306 (10,077)	21,630 (8,758)	21,968 (9,360)
Average Length of an Exposure**	1,988 (570)	1,613 (531)	1,800 (578)
Number of Exposures*	11.2 (3.9)	13.9 (5.0)	12.5 (4.6)
Total time not Exposed*	68,299 (22,707)	84,151 (27,033)	76,225 (25,996)
Average Time Between Exposures	7,122 (4,469)	6,741 (2,839)	6,931 (3,715)
Percent of Trial Time Exposed*	25.0% (10.3)	20.7% (7.2)	22.8% (9.1)
Total Hotspots Cleared**	18.0 (1.9)	19.5 (1.2)	18.8 (1.8)

Table 1: Mean performance (standard deviation).
***measures significantly different at the .05 level.**
****measures significantly different at the .01 level.**
Times are given in milliseconds.

Total Time per Trial. Total time is the time from the subject's first movement with the joystick until the button signifying completion was pressed. We can see that subjects spent an average of almost 15 seconds longer completing the vibrotactile (V) treatment. This difference is significant at the .05 level (F 5.25, η^2 .17, df 1, 26). There was no interaction effect with treatment order.

Total Time Exposed. This is the total time during which the subject was exposed by being visible from at least one hotspot. The V treatment has shorter exposure however the difference is not statistically significant.

Average Length of an Exposure. When each treatment began, the subject was not exposed to any hotspots. While moving through the space, subjects became exposed to hotspots, cleared the hotspots by viewing them (became "unexposed"), then moved into view of another hotspot becoming exposed again. Thus, the subject alternated between exposure and unexposure. We call each period of exposure an exposure incident. Average exposure is the average duration of an exposure incident. The overall difference between V and N treatments is about 375 ms, V being shorter, and this is significant at the .01 level (F 8.16, η^2 .24, df 1, 26).

Number of Exposures. The average exposure time is clearly related to the number of exposures. We can see that the V treatment averaged about 2.7 more exposure incidents than the N treatment. The number of exposures is significant at the .05 level (F 5.58, η^2 .177, df 1,26)

Total Time not Exposed. This measures the total time during each trial that a subject was not exposed to any hotspot. Subjects averaged about 16 seconds longer unexposed in the V trial. It is interesting that this measure is significant at the .05 level (F 7.03, η^2 .21, df 1, 26) while the total time exposed is not. This apparent contradiction is probably caused by the significantly longer average length of V trials.

Average Time Between Exposures. Subjects averaged a 380 ms shorter interval between exposure incidents in V, but the difference is not significant.

Percentage of Trial Time Exposed. Recalling that the V treatment trials were longer on average, we looked at percentage of total time that a subject was exposed. On average, the N percentage was higher than the V percentage, and the difference was significant at the .05 level (F 6.54, η^2 .20, df 1, 26).

Total Hotspots Cleared. When each trial began, the environment included 20 hotspots. Recall that when a subject viewed the location of a hotspot, we considered it cleared. On average, subjects cleared 1.5 more hotspots in the V treatment. Although this may seem to be a small difference, it is significant at the .01 level (F 14.47, η^2 .36, df 1, 26). There was also a significant interaction effect (F 4.94, η^2 .20, df 1, 26) with treatment presentation order.

Demographics. There were no significant interaction effects between any of the demographic variables and the main effect.

DISCUSSION

We observed significant main effects in both effectiveness of the clearing task and in minimizing exposure. Looking at clearing effectiveness first, we see that the difference in performance is significant, although the absolute difference of 1.5 is relatively small. However, it may make more sense to look at clearing in terms of the space left uncleared. This is particularly true, for example, in search and rescue operations where overlooking an unconscious survivor is a real possibility. If we think of the difference as the probability that we will miss on average 2 potential survivors rather than 0.5, the magnitude of the difference seems more important. In addition, when we look at individual performances, we find that nine of the subjects performed identically in both treatments, clearing all 20 hotspots; 16 subjects cleared more in the V treatment while only three cleared more in the non-vibro treatment. This seems to strengthen the result, but there is also the issue of the significant interaction effect with treatment presentation order. Looking at values of η^2 we can see that while the main effect accounts for 36% of variance, the interaction effect is also strong, accounting for 20%. We should look at this interaction in more detail.

If we group the subjects in two pools, those who saw the vibro treatment first (VN) and those who saw the non-vibro treatment first (NV), we can see the interaction effect. The NV pool averaged 17.5 cleared hotspots on their first trial while they all cleared all 20 on the second trial (when vibrotactile feedback was added). The VN pool averaged 19.1 on their first trial using vibrotactile cues. When the vibrotactile cues were removed for the second trial, their performance went down to 18.5. It seems that subjects in the NV pool were aided both by the addition of the vibrotactile cue and by a practice effect in their second trial. Those in the VN pool may have suffered from the loss of the cue on their second trial.

The vibrotactile cuing also seems to have been effective in reducing subjects' exposure to uncleared space. Although the total time during which subjects were exposed was only slightly (676ms) shorter for the V treatment, the duration of V trials averaged more than 15 seconds longer than N trials. These differences resulted in the V trials spending almost 16 seconds longer while not exposed. Therefore, subjects during the V trials were exposed for significantly lower percentages, 25.0 vs. 20.7, a difference of 4.3. Partly as a result of this lower percentage of exposure, the average length of an exposure incident was also significantly lower for the V treatment, especially in first trial. This is a fairly large effect, accounting for about 24% of the variability. The time difference, about 375ms, is an important difference in terms of reaction time.

The overall performance differences appear to be the result of subjects exhibiting different behavior, or modified searching styles, in the two treatments. When in a V trial, subjects in general moved through the space more slowly, searched more completely, and minimized the duration of exposure incidents. We can see some evidence of different behaviors by graphically retracing each trial in a plan view as shown in Figure 8.

For all three subjects, the vibrotactile (V) trial is on the left. For V trials, the subjects started at the end of the hall nearest the bottom of the figure while for N trials subjects started at the top. The direction in which the subject was looking at each timestamp is indicated by the acute point of an isosceles triangle, and the triangles change from red to blue (light to dark) over the course of a trace to show the passage of time. We can see that in the leftmost V trial, the subject traversed the hallway and the first three rooms at least twice. This subject had the largest difference, almost three times, in total trial time between V and N trials. The traces in the center represent the subject with the second largest time difference, although this subject shows no backtracking in the V trial, but completely missed the second room in the N trial. In contrast, the subject on the right shows very similar behavior in both trials and had almost no difference in total trial time. When we looked at the traces for all 28 subjects, we saw that most of the difference in total trial time was caused by these two behaviors: backtracking and missing rooms.

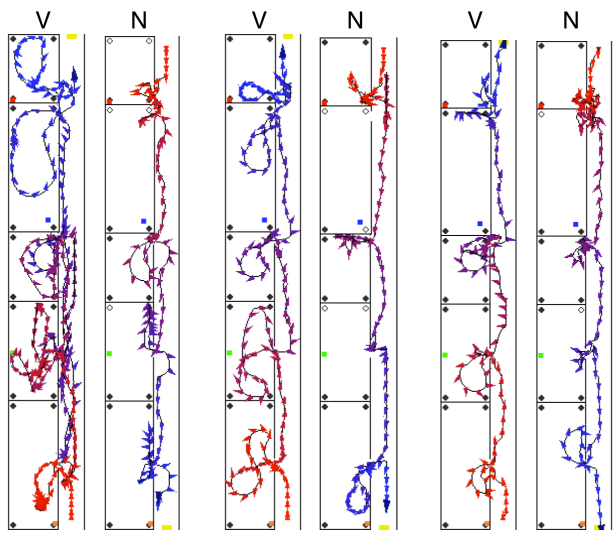

Figure 8: Traces of movement behaviors exhibited by three different subjects.

CONCLUSIONS AND FUTURE WORK

This study has established that a torso-mounted vibrotactile display can provide effective cuing for searching in a virtual environment. Subjects were significantly more effective in both space clearing and avoiding exposure. We feel this is a promising start, but much remains to be done to fully exploit the potential of vibrotactile cuing.

Follow-on Studies

Observation and the pretest results suggest that the directionality of the cue was important, but without further study this is merely anecdotal. Although we can vary the intensity of the stimulus, we used a single intensity level for all stimuli in this initial study to avoid an overly complex design. Lee *et al.* present results of a study on the use of auditory and haptic cues in graded and single-stage warning systems for drivers during braking events [9]. They showed that graded cues provided benefits over single-stage cues, as the former elicited more cautionary driving behavior. In the future, we plan to test the usefulness of varying intensity of the stimulus (*e.g.*, "you're getting warmer") and applying directional vs. non-directional cuing.

For this study, we intentionally simplified the space and movement within it. We intend to add obstacles, such as doors and furniture, and additional sources for possible exposure, such as windows, to the space. We also want to extend the degrees of freedom of motion and allow independent head movement. Ultimately, we want to move to a fully immersive environment including mobile avatars for both enemies and team partners. Our virtual environment work in this area has largely been driven by the desire to develop better tools for training in virtual environments. As we extend the work into more-realistic and complex environments, we intend to begin assessing the effectiveness of training using longer-term studies.

Robot Control

Another area for future extension concerns the teleoperation of robots, in particular, search and rescue robots. The RoboCup Rescue Robot League [14], which sponsors a series of annual search and rescue performance contests, has stated the following vision:

> *When disaster happens, minimize risk to search and rescue personnel, while increasing victim survival rates, by fielding teams of collaborative robots that can:*
>
> - *Negotiate compromised and collapsed structures*
> - *Find victims and ascertain their conditions*
> - *Produce practical maps of the environment*
> - *Deliver sustenance and communications*
> - *Embed sensors and communication networks*
> - *Identify hazards*
> - *Provide structural shoring*
>
> *… allowing human rescuers to quickly locate and extract victims.* [7]

Rescue robots are equipped with a variety of sensors to enable them to carry out these tasks. Video cameras and proximity sensors are used to find a path through the environment. Audio, heat, and CO_2 sensors are used both to locate survivors and determine their condition. Although it is considered desirable to increase the degree of autonomous operation of these robots, for the near future a relatively high degree of operator control will be necessary. This means that the operators will need to integrate sensor data to determine the condition of survivors and to successfully navigate the space.

Currently, most rescue robots are controlled by an operator with a display (*e.g.*, a laptop) and interface devices ranging from keyboard and mouse through joysticks and other game controllers. All of the sensor data are presented visually, leading to a complex display (Figure 9). We want to investigate the use of vibrotactile cues to display some of the sensor information. For example, if a robot has a variety of proximity sensors situated around the robot's perimeter, we could map proximity data to directional tactors to aid the operator in avoiding obstacles that may entangle the robot.

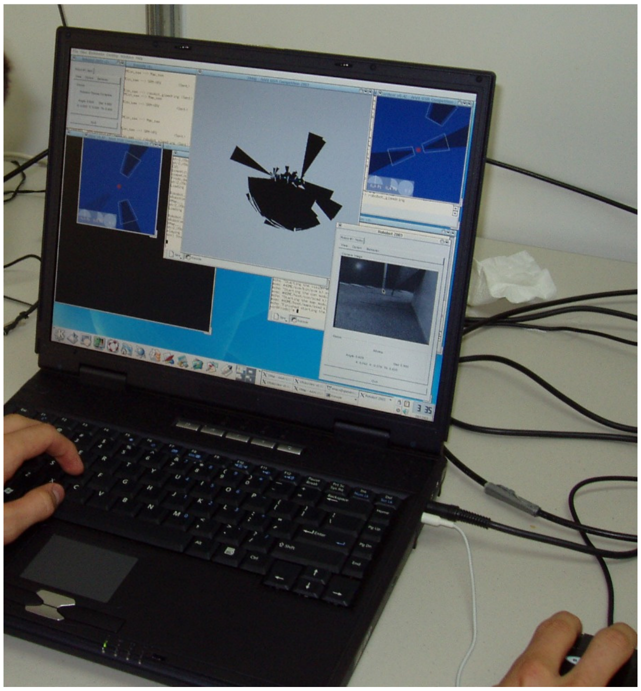

Figure 9: Operator display for an urban search and rescue robot (Courtesy of Bruce Maxwell, Swarthmore College).

Some of the same techniques may be effective as navigational aids for the blind and particularly the deaf-blind. Directional proximity sensors could be used to monitor the environment around the user, and display the information using directional cues, mapping object distance to vibration intensity. In addition, temporary visual impairment caused by smoke or fog could be mitigated by the use of similar techniques.

The low-cost and ease of integration of vibrotactile technology have made this type of haptic feedback attractive for inclusion in many HCI designs. Most of the applications, such as those used with current mobile phones and console game controllers, however, utilize only very simplistic cues, such as ON/OFF, and do not provide directional cues. Even when the application, such as a driving simulator, might benefit from the inclusion of such information, the tactors used in these devices are mounted rigidly to the device, or only a single tactor is included, precluding the use of directional cues. With simple changes in design, these devices could be modified to provide a much richer set of tools for software designers to use in their applications.

It is hoped that the results presented here will stimulate additional work by others, and also aid interface designers in deciding how best to incorporate vibrotactile cues into their systems. By easing the burden on the visual channel, distributing the load rather to the haptic or audio channels, we can better utilize human information bandwidth capacity.

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