Human-Computer Interaction -- INTERACT'03
M. Rauterberg et al. (Eds.)
Published by IOS Press, (c) IFIP, 2003, pp. 89-96

Effective Vibrotactile Cueing in a Visual Search Task

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Abstract: This paper presents results from work we have done into the combination of visual and vibrotactile cues for improving user interaction in virtual environments. Using a custom-designed control system, the intensity of a large number of low-cost vibrational devices can be independently controlled. Our current task is to determine the parameters and design-space for providing this type of cueing to support effective HCI. In a visual search task, user performance was compared over three levels of visual cues and four levels of vibrotactile cue types, in an attempt to narrow the visual search field for locating a letter from a random display of letters. Our results confirm the work of others, showing that users perform significantly faster when given visual cues, and that in the absence of visual cues, vibrotactile cues significantly improve performance. We also found that the waveform of the vibrotactile cue does not seem to make a difference in performance.

Keywords: Multi-modal, vibrotactile, empirical study, HCI.

1 Introduction

In an attempt to better utilize the high-bandwidth capacity of the human sensing systems, we are employing cues to multiple sensory channels for more effective HCI. Many information display systems put a large burden on the visual channel, mainly because of its dominance over other modalities in terms of resolution, end-to-end lag time, and ease of information delivery. Even with these benefits, however, there is a limit to the amount of information that can be quickly and accurately cognitively digested.

This paper presents work we are currently doing on using the haptic channel, through vibrotactile cues, as a means of augmenting the processing capabilities of humans. Introducing the DARPA program on Augmented Cognition, Schmorrow describes augmented cognition as potentially valuable for "complex human-machine interactive environments" that are subject to failure during rapid, stressful, and complex situations such as during military operations (Schmorrow, 2002). He continues by stating that not enough is known about how different sensory channels interact, and that GUIs currently are organized by the visual modality alone.

A sub-area of research for these complex environments is in facilitating visual attention by means of signals in other sensory modalities, such as touch or audition. The following points are true of this area:

1. It is often difficult to direct visual attention rapidly toward appropriate areas of space in information-crowded environments.
2. There has been substantial progress in understanding the brain functions responsible for visual attention.
3. Vision as a sensory input channel may become overloaded by the numerous parallel sources of information present in both graphical user interfaces and the natural environment, so that supplementing vision by the use of other sensory modalities offers an appealing solution.
4. There is growing interest and a growing research literature in tactile and auditory cueing of visual attention.

2 Previous Work

Our approach to using the haptic channel draws on contributions from the fields of cognitive psychology and neuroscience, as well as from previous work aimed at effectively delivering vibrotactile feedback. We begin by considering the nature of visual attention.

2.1 Brain Mechanisms of Visual Attention

Brain mechanisms of visual attention have been studied via functional magnetic resonance imaging (MRI) of the brain in human subjects, supplemented by information from neurological disorders and neurophysiological research (Kastner & Ungerleider, 2000). These authors start with the observation that a typical scene contains multiple objects that compete for attention. The visual system has a limited processing ability. Therefore, in general, an observer will direct attention to only one of the objects presented.

In a functional MRI study (Kastner *et al.*, 1998), the subject looked at a fixation point while four complex images were displayed in the right upper quadrant, either simultaneously or sequentially. Simultaneous display of the images evoked less brain activity compared with sequential display, suggesting a suppressive or inhibitory sensory interaction in the simultaneous condition. The influence of spatially directed attention was studied by instructing the subjects to covertly attend to one of the complex images (the one closest to the fixation point) and count its occurrences. Results suggested that spatially directed attention enhanced brain responses to the attended location, when competing stimuli were presented at the same time, by counteracting the suppression elicited by the competing stimuli.

As a more general illustration, consider three objects, labeled A, B, and C, presented in a person's field of view, with object A closest to the center and the others further to the side. Each object activates a different group of nerve cells in the visual cortex. Suppose that the person has been instructed to attend to the location of object A, so that it can be considered the target stimulus, while objects B and C can be considered non-target or distracter stimuli. The resulting top-down biasing signals might increase the level of activity and/or the number of nerve cells responding to object A, which are otherwise suppressed by the distracters B and C.

The attention-related activity described may be closely related to working memory (Kastner & Ungerleider, 2000). Furthermore, the authors present evidence that spatial working memory may share neural pathways with spatially directed attention. In the example given above, directing attention to the target object A over a period of time requires that instructions to do so are stored in working memory. As another example, selecting one person's image from a crowd of others, as in the "Where's Waldo" books, requires that features of the target image (rather than simply location) be stored in working memory while the complex scene is scanned.

This relationship between visual attention and working memory implies a potential competition among visual attention and other cognitive tasks for limited working memory capacity. Additional (redundant) sensory cues may reduce the demands of visual attention on working memory. This potential opportunity provides our motivation for exploring haptic cueing as a possible improvement in visual search performance.

2.2 Tactile Cueing for Covert Spatial Attention

A tactile cue at one location has been shown to improve the individual’s ability to discriminate visual stimuli at that location (Spence *et al.*, 1998; Macaluso *et al.*, 2000). 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 (Spence *et al.*, 1998). 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 (Macaluso *et al.*, 2000). This result seems to support the possible efficacy of redundant tactile cueing.

2.3 Tactile Cueing for Spatial Awareness

There are a variety of ways to provide tactile cueing. 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[1]. A number of other researchers have recently been exploring the use of similar devices for providing feedback for human-computer interaction. Tan *et al.* (1997) 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 back has not been found to be the best body location for high-resolution vibrotactile feedback (Weinstein, 1968), those parts that are more perceptive to vibrotactile stimuli, such as the hands, are typically involved in other tasks, whereas the surface of the back is relatively unused. Rupert (2000) 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 (2000), 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 (Erp, 2000a). 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 larger on the front of the torso than on the back, and that sensitivity decreases the further the stimulus point is from the sagittal (median or midline) plane.

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 (Erp & Werkhoven, 1999; Erp, 2000b). 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 (Werkhoven & Erp, 1998). 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.* (1998) 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.* (1998) 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.

From this survey, it is clear that the torso holds some potential for effective vibrotactile cueing. 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

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[1] Tactors are devices that provide some form of tactile sensation.

concentrate on is the use of visual and vibrotactile cueing, both in isolation and combination, on a visual search task.

3 Vibrotactile Cueing Approach

To support the delivery of vibrotactile cues, we have designed the TactaBoard system (Lindeman & Cutler, 2003). This system incorporates the control of a large number of different types of feedback devices into a single, unified interface (Figure 1).

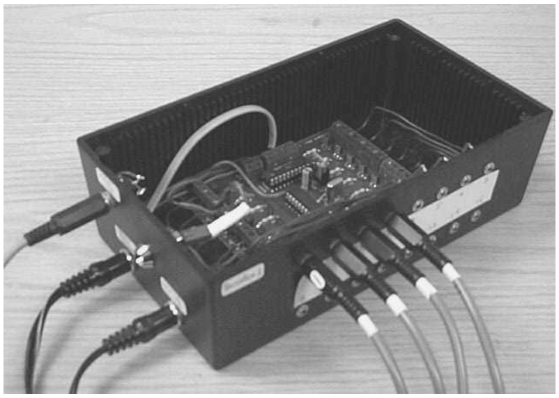

Figure 1: The TactaBoard inside a box

Using standard 2.5mm phono connectors, we can quickly reconfigure the system for use with various types and numbers of tactors. We have experimented with different deployment form-factors, such as a stylus, glove, sleeve, and the office chair used in the current studies. Each one of these form-factors used the same TactaBoard, only requiring the correct tactors to be plugged in. The power supply for the tactors is separate from the power for the circuit board, which allows output devices with fairly substantial power requirements to be supported.

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. Future versions will allow multiple boards to be daisy-chained together, providing a scalable solution.

4 Experiment: Visual Search Task

This experiment looked at the influence of visual and vibrotactile cueing on a visual search task. It measured the ability of subjects to locate a target letter from a display of randomly organized letters on a computer screen. There were three main goals of this work. The first was to see if augmenting the visual processing of information with complementary vibrotactile attentional cues could improve performance on a visual search task. Though visual dominance is generally well accepted, we wanted to look more closely at the affect of vibrotactile feedback on performance of a visually-oriented task (Werkhoven & Erp, 1998). Second, we wanted to compare different types of visual cues in terms of their influence on performance. Finally, we wanted to discover whether some types of vibrotactile stimuli were more effective than others in enhancing performance.

4.1 Participants

Twenty-one researchers from our lab, ranging in age from 20 to 39, volunteered for participation in a one-hour experimental session. All subjects reported using their right hand for controlling the mouse in their everyday lives, and all had normal or corrected-to-normal vision. None of the subjects had any prior knowledge of our work before taking part in the study. Eight of the subjects were from Japan, five from France, three from Canada, and one each from Australia, China, Sri Lanka, Thailand, and the U.S. Fourteen were male and seven female.

4.2 Experimental Apparatus

The experiment was conducted using software running on a standard PC. Vibrotactile feedback was controlled using the TactaBoard system described above, which was connected to the PC using a standard serial port. User input was made using solely the mouse.

Subjects were seated throughout the entire session. A 3-by-3 array of tactors was affixed to an office chair, with a spacing of 6cm between the centers of each pair of neighboring tactors (Figure 2).

Figure 2: Office chair with 3-by-3 array of tactors

The tactors in the lowest row were affixed such that they touched the back of the subject just above the belt line. The center column of tactors touched the subject along the spine. Care was taken to insure that subjects wore light clothing for the experimental session, and most wore dress shirts or "T" shirts. Only the top row of tactors was used in this experiment.

The tactors used in this setup were DC motors with an eccentric mass. They are manufactured by Tokyo Parts Industrial Co., Ltd., Model No. FM23A, and have an operating voltage range of 0.8-1.6V at 30mA. They have a standard speed of 5,000 RPM at 1.3V, and have a vibration quantity of 1.0G. Each of these disk-shaped tactors measures 18mm in diameter and is 3mm thick. We operated the motors at 1.5V for this experiment, but modulated the signal sent to the tactors using the TactaBoard. The visual display of letters was divided vertically into three panels each containing eight randomly selected letters, taken from the letters A through X, without replacement (Figure 3).

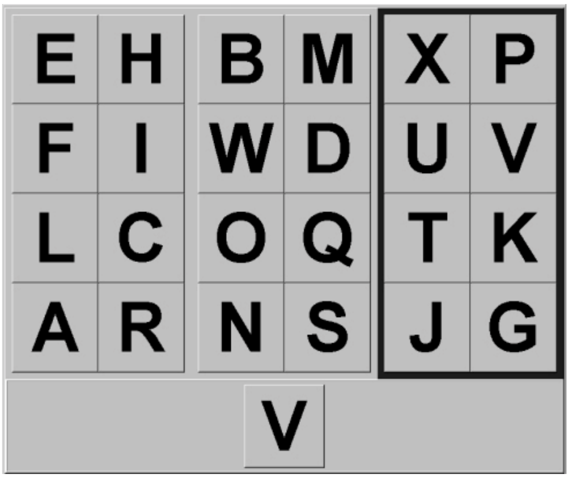

Figure 3: Visual search task interface
(with outlined panel)

Cues provided the subject with information designed to speed the processes of locating the letter, by indicating which of the three panels the target letter appeared in, thereby potentially reducing the visual search space.

4.3 Experimental Design

In a within-subjects design, subjects performed the identical task seven times, each time with different levels of visual and vibrotactile cues. The experiment was designed to allow for the collected data to be compared along at least two different axes: one visual and one vibrotactile (Table 1).

		Vibrotactile Cue Levels			
		None	*Square*	*Saw-tooth*	*Triangle*
Visual Cue Levels	*None*	X	X		
	Single		X		
	Multi	X	X	X	X

Table 1: Experimental Treatments
(X indicates treatments explored)

There were three levels of visual cues. In the case of "None," subjects were not given any additional visual cue, other than the display of the letters. In the "Single" case, an outline of the panel containing the target letter was shown for one second in blue at the start of the trial. The "Multi" case used red for outlining the left panel, green for the center panel, and blue for the right panel.

Vibrotactile cueing was given in the form of a vibrotactile stimulus for one second at the onset of the trial. The location of the stimulus coincided with the panel containing the target letter (*e.g.*, the tactor on the left was triggered if the target letter appeared in the left panel). There were four levels of vibrotactile cueing used in the experiment. In the "None" case, no vibrotactile stimulus was given. In the "Square" case, a one second square-wave pulse at 92Hz was given at the onset of the trial. In the "Sawtooth" treatment, a one-second stimulus that started at 35Hz and linearly increased to 101Hz in 13 equal increments was presented. In the "Triangle" treatment, a one-second stimulus that started at 35Hz, linearly increased to 101Hz, and then linearly decreased to 35Hz, all in 13 even increments, was presented.

4.4 Procedure

At the beginning of the experiment, the subject was seated in a height-adjustable office chair, approximately 60cm from the monitor, and asked to adjust the height of the chair to a comfortable level for viewing the screen and manipulating the mouse. The subject was then read a script explaining that the experiment was measuring the speed and accuracy with which they could locate and click on a target letter from among a random layout of letters. Subjects were instructed that during the experiment they would be given a target letter, and would have to search the display for the corresponding letter from among the random letters. They were also told that they would perform the experiment seven times, each time with varying types and amounts of cues to assist them in the task. Each treatment consisted of 50 trials where data was recorded. There were seven counter-balanced orderings for the treatments, and each subject was randomly assigned to perform the treatments in one of these orders.

A practice session was provided prior to each treatment, which required the subjects to perform a minimum of 20 trials, but they could perform as many as they liked before starting the actual experiment. The visual and vibrotactile cues provided during each practice session were identical to those provided during the next treatment. The subject was instructed to click on the "Start" button when ready to begin the test phase, and was reminded to work as quickly as possible, but also as accurately as possible. Each trial ended when the subject clicked on a letter (even the wrong letter), at which point the displayed letters were randomized, and a new target letter was displayed. Visual feedback was given on whether the subject clicked on the correct letter or not. The letter was highlighted in green for correct selections, and red for incorrect selections.

4.5 Results

For each trial, the trial time and whether the correct letter was selected were recorded. Trial time (in milliseconds) was measured from the moment the target letter appeared until a letter was clicked in the display. The tabulated descriptive statistics for trial time are shown in Table 2.

		Vibrotactile Cue Levels			
		None	*Square*	*Saw-tooth*	*Triangle*
Visual Cue Levels	*None*	1924 (985)	1694 (702)		
	Single		1337 (350)		
	Multi	1339 (376)	1301 (342)	1337 (424)	1308 (381)

Table 2: Descriptive Statistics for
Mean Trial Time in ms (std.dev. in parentheses)

The "None-None" treatment may be used for comparison to a random search. Analysis of variance tests were run to compare the data along the two axes, including the "None-None" treatment in both cases.

In terms of the number correct, no significant difference was found for visual cue $F(3, 4196) = 0.92$, $p > 0.1$, nor for vibrotactile cue $F(4, 5245) = 0.27$, $p > 0.1$. Accuracy for all treatments was greater than 99%.

A significant main effect was found for trial time for visual cue $F(3, 4196) = 219.73$, $p < 0.05$. A Tukey's-b test for homogeneous subsets gives the groupings as shown in Table 3. The means within each subset are statistically from the same population, while means from different subsets are statistically from the same population. In addition, a significant main effect was found for trial time for vibrotactile cue $F(4, 5245) = 246.84$, $p < 0.05$. A Tukey's-b test for homogeneous subsets gives the groupings as shown in Table 4.

	Subset		
Treatment	**1**	**2**	**3**
Multi-Square	1301.46		
Single-Square	1336.76		
None-Square		1693.51	
None-None			1924.30

Table 3: Homogeneous subsets for visual cue

	Subset	
Treatment	**1**	**2**
Multi-Square	1301.46	
Multi-Triangle	1308.05	
Multi-Sawtooth	1337.26	
Multi-None	1338.64	
None-None		1924.30

Table 4: Homogeneous subsets for vibrotactile cue

4.6 Discussion

While performance was most significantly enhanced by visual cueing, with an approximate 30% average speed advantage over no cueing, haptic cueing alone provided a significant performance increase of approximately 12%. This suggests that a vibrotactile cue can be a workable substitute when visual cueing is not practical.

Combined haptic and visual cueing, on the other hand, did not show a significant advantage over visual alone. This may be a result of the greater latency of the vibrotactile cue. The visual and vibrotactile cues were invoked simultaneously. However, while the visual cue occurred essentially instantaneously, the vibrotactile cue is subject to a delay because of the time necessary to accelerate the motor to a perceivable vibration. This latency is further increased by the slightly longer time required for the brain to receive the stimulus from the back versus the eye. It seems that for the vibrotactile cue to provide added value, it would have to physically precede the visual cue, which may or may not be reasonable for a given application.

No significant difference was detected among the various shapes of vibrotactile output waveforms. This could be explained by the experimental design, which varied the vibrotactile cue only when it was combined with visual cues. It is likely that the visual cue dominated, and any differences among the vibrotactile cue types were hidden by this dominance. Alternatively, because of the spin-up and spin-down periods inherent in the vibrotactile devices used here, the "Square" treatments were mechanically more similar to a trapezoid than a square. Thus, the output stimulus for "Square" might not be perceived as being very different from the other treatments, as evidenced by the similarity of the resulting trial-time means for "Square" and "Triangle."

5 Conclusions and Future Work

Although less effective than visual prompting, the vibrotactile cue did yield significant improvement in performance, suggesting that it may be useful in situations where visual cuing is impractical.

The location of haptic stimuli on different parts of the body is likely to produce different results. We chose the back, even though it is known to be less sensitive to localized vibration than other parts of the body, because locating the tactors in a backrest seems likely to have practical applications (*e.g.*, driver safety, command and control). Other tactor placement locations and attachment means should also be studied so that we can better predict the effect of varying them.

To this last point, it is very difficult to obtain accurate measurements of the frequency and amplitude of the tactors' vibrations. We have tried several measurement methods using a laser range finder and accelerometers (Lindeman & Cutler, 2003). We have concluded that a number of hard-to-control parameters, including body location, method of attachment to the user, load placed on the tactor surface, orientation of the tactor, and individual differences in tactors, precludes the use of static calibration data. Among these factors, the most significant is the location and method of attachment of the tactor to the subject. For example, if a tactor's attachment loosens during use, the frequency and amplitude of vibration of that tactor for a given input voltage may well change. We have decided that a dynamic control approach, which constantly monitors the vibration frequency (and/or amplitude) and adjusts the voltage to maintain a constant value, will be necessary for studies where precise characterization of these parameters is required.

We would also like to be able to measure precisely the delay between a start signal to the tactor and the perception of vibration. We can then investigate using vibrotactile "priming" as an enhancement to visual prompting. Building on the work of others (Erp, 2000a; Erp, 2000b), what are the practical limits of deploying vibrotactile devices for priming a user to attend to information that is out of the field of view? The experimental setup we used in the current work only required the user to perform the visual search task on a standard display screen, where no head movement was necessary. An interesting area to explore would be the use of vibrotactile cues for extending the attentional workspace of the user beyond this small visual workspace.

Some research has shown that providing visual location and place cues can improve memory retention (Tan *et al.*, 2001). In future studies, we will explore how vibrotactile cues can be utilized in a similar manner. We are interested in discovering whether stimulating a specific part of the body during the learning process results in better retention if the same part is stimulated during retrieval. Furthermore, we will continue to perform assessments about the limitations on the use of vibrotactile cues (*e.g.*, encoding resolution and human spatial discrimination at various parts of the body).

Finally, with regard to our current scenario, it should be noted that the visual cuing was integrated with the search space, while the vibrotactile cues were separated in space. Follow-on studies could look at varying the location of the search space, as well as the location of the visual and vibrotactile cues, in order to better tease out the relationships of these.

We see many possible applications areas for vibrotactile cues. For virtual reality applications, arrays of vibrotactile devices could be placed on parts of the body (for instance, on the forearms), and users could be fed collision information as their arms intersect virtual objects. This "virtual bumping" into the environment might aid users in maneuvering. Physical props could be outfitted with tactors to provide feedback for when the prop contacts virtual objects. For instance, a physical stylus could be outfitted to give the user a better sense of contact.

As touched upon above, this technology has been used to allow pilots to better judge the down-vector, and could also be used for scuba divers to orient themselves with respect to the up-vector. The automobile industry could embed tactors in the driver's seat or steering wheel as a warning system for alerting or notifying drivers of certain situations. For example, a monitoring system could be used to measure how close a car is to the line markers on the road, and alert the driver when the car nears the line. Coupled with a GPS system, a route-following application could be developed to alert drivers when it is time to make a turn. If the tactors are spaced at different locations in the driver's seat, spatial information can be used as well.

In firefighting scenarios, a firefighter with a GPS transponder could be guided through a smoke-filled building in order to search for victims (*e.g.*, find the bedrooms). This could be done autonomously, or using a human guide. Because these environments are often very loud, verbal communication is not always an option, so vibrotactile cues could provide the same information using a nonverbal channel.

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