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A Haptic Back Display for Attentional and Directional Cueing

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ABSTRACT

We have been developing a haptic back display using a 3-by-3 tactor array. This paper reports two studies that investigated the use of such a display for delivering attention- and direction-related information to its user. The first study measured the effectiveness of haptic cues in redirecting an observer's visual spatial attention. The observer was first tapped on the back, and then asked to detect a change between two similar visual scenes. We found that reaction time decreased by an average of 41% (1630 ms) when the location of the tactor coincided with the quadrant of the visual scene where a change occurred. We also found that reaction time increased by an average of 19% (781 ms) when the locations of the tapping and visual change did not coincide. Such a haptic attentional cueing system can be beneficial to a user who must attend to information in small areas within a large and complex visual display (e.g., an aircraft cockpit). In the second study, sequenced pulses were employed to impart directional information. We found that naïve and minimally-trained observers were able to discern the directions of a set of horizontal, vertical and diagonal directional lines with an overall accuracy of 81%. Means of improving the overall accuracy were suggested and tested. These directional lines can be applied to a haptic navigation guidance or situation awareness system.

I. INTRODUCTION

The growing trend in interface research is towards multimodal human-computer interfaces. This is motivated by the facts that humans naturally employ multimodal information channels for communication, and that multimodal interfaces have been demonstrated to be effective [1]. Cognitive research has shown that multimodal communication results in an increased amount of transmitted information [2]. Therefore, multimodal interfaces facilitate more natural and efficient human-computer interactions.

One challenge in multimodal interface research is the lack of multimodal interface systems. Robust systems for applications such as speech recognition or gesture interpretation require long-term research and development efforts from a multidisciplinary team of investigators. True multimodal interactions can not take place until problems in each of these application domains are solved. Compared with visual and auditory interfaces, the field of haptic interface research is a less developed, but fast-growing and promising area. For the past several years, we have been developing tactor-based haptic interfaces in the context of multimodal human-machine interfaces. Our studies have examined the effectiveness of a back display as a haptic navigation guidance system [3,4], as a wearable haptic interface [5], for integrating visual and tactile information about moving objects [6], and for redirecting a user's spatial attention in a visual task [7].

We have chosen the back of a person to be interfaced with a haptic display, because this part of the body is rarely engaged by other human-machine interfaces, is easily accessible, and can be stimulated by tethering a piece of clothing (a vest) or furniture (a chair) rather than the user. In general, users enjoy the massage-like vibrations produced by tactors. The relatively poor spatial resolution of the back is well compensated for by its large stimulation area. According to [8], the two-point thresholds on the finger and on the back are 2 mm and 40 mm, respectively. The width of the back, however, is more than 20 times the width of a finger for most individuals.

The idea of presenting tactile information to a person's back is not entirely new. Earlier attempts, such as the Tactile Vision Substitution System (TVSS), have demonstrated limited success at conveying digitized pictorial information through a 20-by-20 tactor array covering an area of 22.8×22.8 cm^2 [9,10]. Unlike these earlier systems, however, our back display is characterized by its simplicity both in its hardware configuration (a 3-by-3 tactor array) and in the nature of the information that it conveys. Many recent studies have explored the use of simple tactors to attract attention and to present the state of machinery to its operator [11-18]. For example, using a matrix of pneumatic stimulators on the torso, the Tactile Situation Awareness System (TSAS) informs a pilot the direction of helicopter drift with the tactor location and the magnitude of drift with the rate of pulses [15].

We envision our back display to impart intuitive and non-verbal information to its user, and to form multimodal user interfaces with other existing visual and/or auditory interfaces. Towards these objectives, we have recently completed two studies on the use of our back display for attentional and directional cueing. In the first study, we examine whether haptic cues (taps on the back) can affect visual spatial attention when an observer is asked to detect a change between two scenes. We have chosen a visual task that is known to require visual spatial attention in order for a viewer to perceive (even large) changes in a scene. This phenomenon, termed "change blindness," occurs in both laboratory [19] and real-world [20] conditions. The proposed explanation for "change blindness" is that we do not form a complete detailed visual representation of our surroundings. Such a representation occurs only for the small part of the visual field that we are attending. It has been shown that reaction time to detect a difference between two similar visual scenes depends on the degree to which the changing element is of interest (i.e., captures the viewer's attention). If attention is indeed the key factor affecting reaction time, then any means of manipulating an observer's attention should affect the reaction time associated with the detection of scene changes. Our experiment is therefore designed to investigate whether such effects can be elicited by drawing an observer's attention to a spatial location via haptic stimulation.

In the second study, we explore the use of a phenomenon called "sensory saltation" in conveying directional information to the back. We expect such a display to be useful in a number of scenarios where visual or auditory information is absent or obscure, and where directional signals are needed for performing a certain task. One example is to outfit a blind traveler with a tactile vest (with embedded vibrotactile array on the back) that is integrated with a global positioning system (GPS) and a wearable computer. Compared with other blind navigation aids based on sonification,[1] a tactile system has the advantage of allowing the blind user to focus the auditory system on monitoring environmental sounds for situation awareness. Another application is to outfit a driver's seat with a tactor array and use it as a navigation guidance system. Current navigation systems require a driver to look at a dashboard display for navigational instructions. Research on phenomena such as "change blindness" reveals how dangerous it is for a driver to take the eyes off the road, even for as brief as 80 ms [19]. By keeping the driver's eyes on the road, a haptic directional display that instructs a driver to go left or right at the next intersection can greatly improve the safety associated with the use of a navigation system.

Details of the haptic back display are presented in Section II. The experiments on haptic attentional and directional cueing are summarized in Sections III and IV, respectively. Finally, Section V discusses our findings and potential applications of the haptic back display.

II. THE HAPTIC BACK DISPLAY

The hardware of our haptic back display consists of the tactors and the associated driver circuit. Shown in Fig. 1 is our latest prototype implemented in an office chair.[2] The tactors form a 3-by-3 array with an equal inter-tactor spacing of 8 cm. Each tactor is fastened to a piece of supporting fabric by elastic bands. The supporting fabric is then draped over the back rest of an office chair. Each tactor is modified from a 40-mm diameter flat magnetic speaker (FDK Corp., Tokyo, Japan) with modifications to lower its resonant frequency and to increase the gain at the resonant frequency (David Franklin, President of Audiological Engineering Corp., personal communication, 1996). Audio power amplifiers based on LM383 (National Semiconductor Corp.) are used to drive the modified speakers at around 250-300 Hz, a frequency range over which people are most sensitive to vibrations. The pulse duration and interpulse interval are controlled by a PIC16C84 (Microchip Inc., Arizona) microcontroller. The intensity of the tactors are adjusted to be around 27 dB SL,[3] as measured by an accelerometer (ACH-01-03, by Measurement Specialties Inc., Fairfield, NJ). The intensity measurements are taken with the subject's back pressing against the tactors (i.e., loaded condition).

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[1] See, for example, http://ourworld.compuserve.com/homepages/Peter_Meijer/winvoice.htm.

[2] See http://www.ece.purdue.edu/HIRL/projects_vest.html for a description of our earlier prototypes.

[3] SL stands for sensation level. It denotes the signal strength in dB relative to the human absolute detection threshold at the same driving frequency.

Figure 1. The haptic back display. Shown here is a 3-by-3 tactor array. Each tactor is fastened, by two crisscross elastic bands, to a piece of supporting fabric that is draped over the back rest of an office chair.

Figure 2 shows our custom-made amplifier and controller circuitry. The main components are the microcontroller and the 9-channel amplifier bank. The circuitry receives, from either a keypad or the parallel port of a PC, an input encoding the stimulation pattern to be generated. The programmable microcontroller then generates the appropriate enable signals that determine when and for how long each tactor is to be activated. These signals are in turn used to gate the outputs of the amplifier bank that supplies the amplified oscillating signals to the tactor array. This circuitry allows us to precisely control the relative on-off patterns of the nine tactors in real time.

III. EXPERIMENT 1: HAPTIC ATTENTIONAL CUEING

A. Objectives

The goal of this study was to measure whether and to what extent haptic cueing can affect an observer's visual spatial attention. Towards that end, reaction times for detecting a visual change at a controlled location of a scene were recorded and compared for conditions where haptic cueing was (1) absent, (2) present and valid, and (3) present and invalid.

B. Methods

1) Stimuli

The visual stimuli used in these experiments were based primarily on the flicker paradigm used for the study of "change blindness" [21]. The visual scenes consisted of rectangular elements of equal sizes, but in either horizontal or vertical orientations (Fig. 3). Two scenes, differing only in the orientation of one of the elements, were presented in an alternating order with a blank scene inserted in between (to mask motional cues). The duration of either of the two patterned scenes was called the "on time". The same "on time" was used for both scenes for a given experimental condition. The duration of the blank scene was called the "off time."

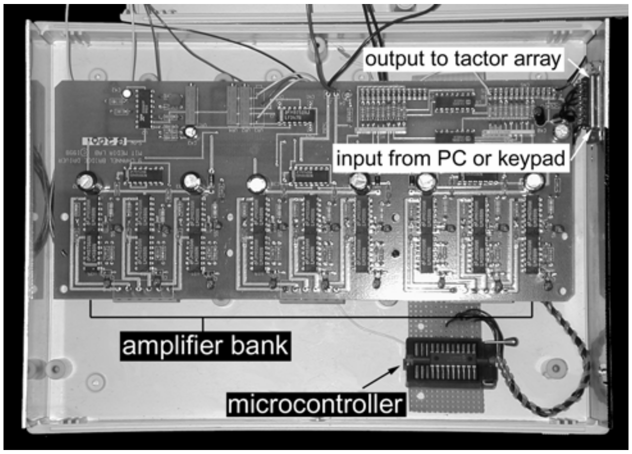

Figure 2. The electronic circuits that control and supply amplified oscillating signals to the tactor array in our haptic back display.

For haptic attentional cueing, only the four corner tactors (i.e., tactors #1, 3, 7, and 9 in Fig. 1) were used. The intensity of the vibration was between 26.1-27.9 dB SL for the four tactors. A Pre-cueing paradigm was used. At the beginning of each trial, one of the four corner tactors was turned on for 60 ms with a 290-Hz sinusoidal pulse. After a 140-ms pause during which the subject received neither haptic nor visual stimulation, the scene sequence as illustrated in Fig. 3 began.

2) Subjects

Ten (10) college students, 5 females and 5 males, participated in these experiments as paid research participants. The average age of the subjects was 21 years old. All subjects had normal or corrected vision. They reported no known abnormalities with haptic perception on their back.

3) Procedures

Before the experiments began, subjects were told that they needed to locate a rectangular element on the computer screen that was changing its orientation, and that their job was to *locate* and *identify* this element as quickly as possible.

To ensure that the subjects could clearly locate the vibrations presented by the tactor array on their back, an absolute identification experiment was conducted with the tactor array before each new session. During these pretests, subjects were asked to click on one of the four quadrants on the monitor (represented by four large rectangles) in response to a vibration on their back (e.g., click on the upper-right quadrant of the monitor if a vibration near the right shoulder was perceived). Each subject had to complete one perfect run (i.e., 100% correct) of 60 trials before starting the visual change-detection task. This test was repeated each time the subject left and returned to the chair.

During the visual change-detection task, the subjects were instructed to click the left mouse button as soon as the changing element was found (without moving the cursor over that element). The screen then froze and the color of all elements changed from white to pink. The subjects were then required to make a second mouse click with the cursor centered on the element that they perceived to have changed its orientation. The timing of the first mouse click was recorded as the reaction time. The x-y positions of the second click were analyzed later to determine whether the correct element was detected.

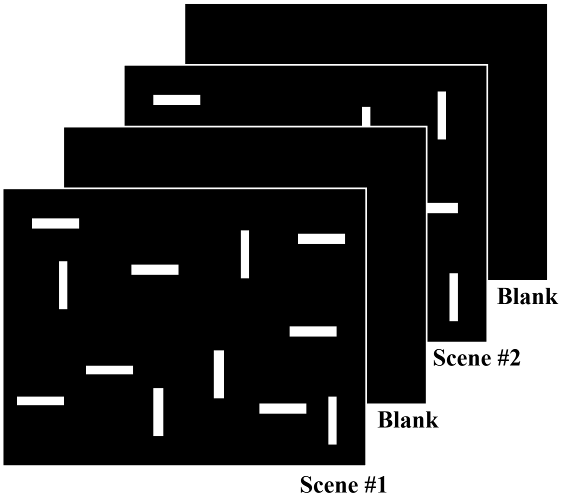

Figure 3. The two visual scenes used in Exp. 1 (modified from Fig. 2 in [21]).

The independent variables employed were the state of the tactors (OFF or ON), on time (80, 480, and 800 ms), and off time (fixed at 120 ms). For the tactor ON conditions, an additional independent variable was the validity of the haptic cues (kept at 50%). A haptic cue was termed *valid* if the location of the vibrating tactor coincided with the quadrant where the changing element occurred; a haptic cue was termed *invalid* otherwise. Three 60-trial runs were conducted for each experimental condition and each subject. The order of the eighteen runs (2 tactor state × 3 on time × 3 runs) were randomized. The trials with valid and invalid haptic cues were mixed in the same run with equal probabilities of being selected on each trial. The total number of rectangular elements was fixed at 12 (or equivalently, 3 elements per quadrant). The x-y positions of the elements were chosen randomly within each quadrant with the constraint that the elements never overlapped. Our subjects were aware of the fact that the location of the haptic cue may or may not be valid on a given trial. They were left to decide on their own whether and how they would utilize the information provided by the haptic cues.

Throughout the experiments, subjects were instructed to sit upright with their back pressed against the tactor array. They were instructed not to move their body relative to the chair, or to move the chair relative to the monitor. Headphones were used to block any audible noise from the tactor array. Subjects were informed of the experimental condition before each run. They typically finished all the experiments over a 2-3 day period.

4) Data Analysis

The dependent variables were mean reaction times and their standard errors. For each of the six experimental conditions tested (2 tactor state × 3 on time), data from all subjects were pooled. Data from the tactor OFF condition served as a baseline measure for reaction time. Data from the tactor ON condition were separated into two subgroups: those with valid haptic cues and those with invalid cues. Mean reaction times for the two subgroups of trials were computed separately. All error trials (where the subject selected the wrong rectangle element during the second mouse click) were discarded. The average number of error trials varied among the subjects tested, with a range of 0-9 per experimental run of 60 trials. Averaged across the subjects, there were fewer than 4 error trials per 60-trial run.

C. Results

Reaction times averaged over all ten subjects are shown in Fig. 4. It can be seen that mean reaction time increased with on-time, for the invalid-cue (circles), no-cue (triangles) and valid-cue (diamonds) conditions [F(2,76)]=72.98, p<0.001]. Cueing conditions had a significant effect on reaction time for an on-time of 80 ms [F(2,81)=31.48, p<0.001], 480 ms [F(2,81)=46.39, p<0.001], and 800 ms [F(2,81)=65.46, p<0.001]. Overall, compared with baseline measures (i.e., reaction times with no haptic cues, shown as triangles), reaction time decreased by 1630 ms (40.6%) with valid haptic cues, and increased by 781 ms (18.9%) with invalid haptic cues. All standard errors were relatively small as compared to the means. We conclude, therefore, that reaction times decreased with valid haptic cues, and increased with invalid haptic cues.

The extent to which haptic cues affected reaction times varied from subject to subject, and the baseline measures were also highly dependent on the individual [F(9,76)=8.31, p<0.001]. However, our general conclusion holds for each of the ten subjects tested, despite large inter-subject differences.

Standard deviations of reaction times from pooled data are shown in Fig. 5. We can observe a general trend that the standard deviations for the valid-cue condition (diamonds) are lower than those for the other two conditions (circles and triangles) across the three on-time values tested. We therefore conclude that valid haptic cueing reduces the inter-subject variability in the response times for the visual change-detection task employed in this study.

IV. EXPERIMENT 2: HAPTIC DIRECTIONAL CUEING

A. Overview

In addition to tapping on a person's back to affect spatial attention, we also experimented with other forms of vibrotactile stimulation that are effective in conveying non-verbal information. Specifically, we chose to study the use of the "sensory saltation" phenomenon to impart directional information for the following reasons. Firstly, sensory saltation provides a mechanism for displaying directional information that is highly intuitive. Compared with sensory aids for the deaf (for example, Vocoder [22], Tickle-Talker [23,24], Tactaid II and VII [25]) and for the blind (for example, the Optacon [26], the TVSS [9,27]) that require a user to learn unfamiliar tactile stimulation patterns, our haptic back display can generate saltatory signals that can be readily interpreted by naïve observers. Secondly, the sensory saltation illusion can be evoked with relatively simple hardware configurations. Compared with force-feedback devices (for example, the Impulse Engine™ by Immersion Corp., San Jose, Calif.; the PHANToM™ by SensAble Technologies, Cambridge, Mass. [28]) that require motor assemblies and force ground in order to deliver appreciable force variations, our haptic back display consists of a simple 3-by-3 vibrotactile array. Thirdly, the sensory saltation phenomenon can be elicited at many body sites including the fingertip and the back [29]. This flexibility led to the development of saltatory displays built into the back of an office chair [30] and the back of a vest for wearable applications [3]. Finally, the saltatory sensation is characteristically vivid. Informal demonstration to first-time observers has met with enthusiastic response and interest.

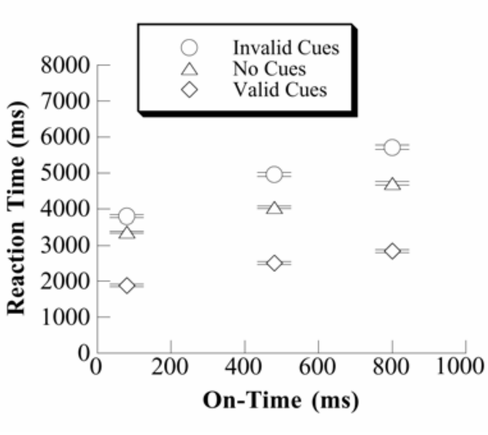

Figure 4. Mean reaction times and standard errors from Exp. 1, averaged over all ten subjects.

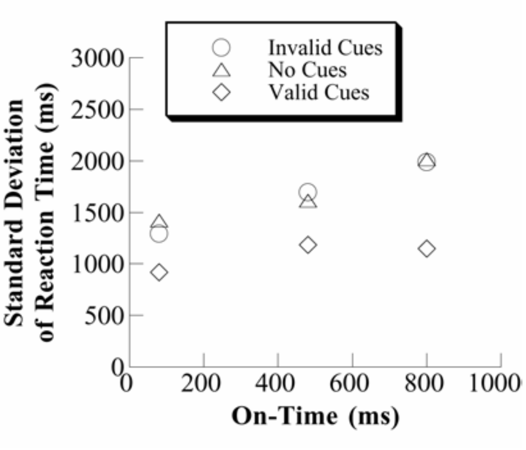

Figure 5. Standard deviations of reaction times from Exp. 1, with data pooled over all subjects.

1) Sensory Saltation

The "sensory saltation" phenomenon was discovered in the 1970s in the Princeton Cutaneous Communication Laboratory (the word *saltation* is Latin for *jumping*). In an initial setup that led to its discovery, three mechanical tactors were placed with equal distance on the forearm. Three brief pulses were delivered to the first tactor closest to the wrist, followed by three more at the middle tactor, followed by more pulses at the tactor farthest from the wrist. Instead of feeling the successive taps localized at the three tactor sites, an observer was under the impression that the pulses seemed to be distributed with more or less uniform spacing from the site of the first to that of the third tactor (Fig. 6). The sensation is characteristically discrete as if a tiny rabbit was hopping up the arm from wrist to elbow, hence the nickname "cutaneous rabbit".

Since its initial discovery, the "rabbit" has been examined in many ways by researchers at Princeton University. It was known that for the back, the tactors needed to be placed at distances no greater than 10 cm in order to create the "rabbit" [31]. The interstimulus duration could vary from about 20 to 300 ms, with 50 ms being near optimal [32]. The optimal number of pulses to be sent to each tactor was between 3 and 6 [33]. Intensity and duration of the pulses were of secondary importance [32,33]. In terms of its mechanism, the hypothesis that the phenomenon was due to standing waves produced by mechanical stimulation of the skin proved to be false [31]. The fact that saltatory illusion occurred in vision, audition as well as other forms of tactual stimulation (thermal and electrocutaneous) suggested that the mechanism was of a central, rather than peripheral nature. Reviews of earlier work can be found in [31,34].

Recently, a comprehensive study of the perceived qualities of lines generated by saltation was completed [29]. This study examined two stimulation modes (veridical and saltatory), three body sites (fingertip, forearm, back), four perceived qualities (length, smoothness, spatial distribution, and straightness of the line), and a wide range of pulse-burst duration and inter-burst interval. Two important conclusions can be drawn from this study. Firstly, judgments on perceived line qualities were very similar for the veridical and saltatory modes. In the veridical mode, seven linearly spaced tactors were successively activated to generate a dotted line with perceived stimulation sites corresponding exactly to the locations of the tactors. In the

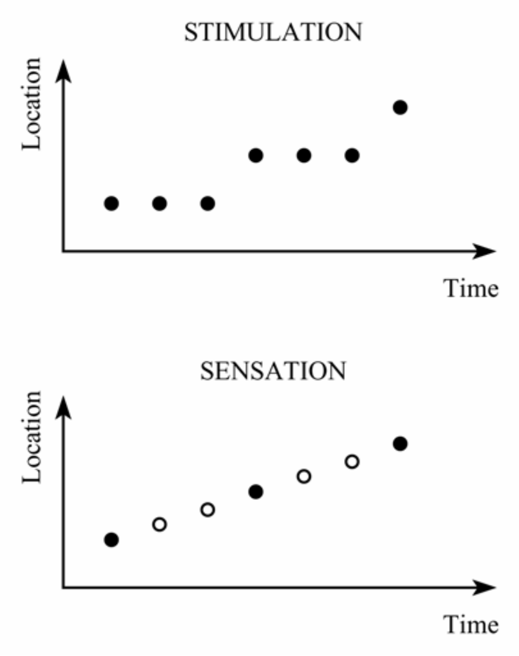

Figure 6. An illustration of sensation vs. stimulation pattern for "sensory saltation". Open circles indicate perceived pulses at phantom locations.

saltatory mode, only three of the seven tactors (the 1st, 4th and 7th) were activated to create a sensation of dotted line with phantom sensations at sites corresponding to the 2nd, 3rd, 5th and 6th tactors. Since subjects could hardly distinguish the two stimulation modes, the saltatory mode is preferred due to its simpler hardware configuration (3 vs. 7 tactors). Secondly, perceived line qualities were very similar for the finger, forearm and back, and varied in similar manners with timing parameters. Therefore, we expect no major disadvantages in using the back.

2) Objectives

The experiments reported here were designed to investigate the *intuitiveness* and the *distinctiveness* of saltatory directional signals. To test the hypothesis that directional saltatory signals are intuitive and share consistent interpretations among first-time observers, we used an open response paradigm where a subject could freely assign any meaning to directional saltatory signals (Exp. 2a). To test the hypothesis that these saltatory signals are easily distinguishable from one another, we tested another group of minimally trained subjects with an absolute identification paradigm (Exp. 2b).

B. Methods

1) Stimuli

Two stimulus sets were designed. Stimulus set A contained eight saltatory signals in the directions of *east*, *west*, *south*, *north*, *southeast*, *southwest*, *northeast*, and *northwest* (Table 1). These directions were defined in a coordinate system centered at subject's torso and viewed from subject's back. Each saltatory signal was generated by successively sending three high frequency pulses to three tactors. For example, successive activation of tactors #8, #5 and #2 produced a saltatory line heading *north* (see the timing diagram in Fig. 7).

Table 1. Stimulus set A. The notation for signal A1 means that three pulses are sent to tactor #4, followed by three more to #5, followed by another three to #6 (see the enclosed tactor-array photo for tactor numbering). Lowercase letters are used to indicate the directions of these "thin" saltatory lines, as seen from the back of the chair.

	Saltatory Signal Pattern	Saltatory Direction
A1	444555666	east (e)
A2	666555444	west (w)
A3	222555888	south (s)
A4	888555222	north (n)
A5	111555999	southeast (se)
A6	333555777	southwest (sw)
A7	777555333	northeast (ne)
A8	999555111	northwest (nw)

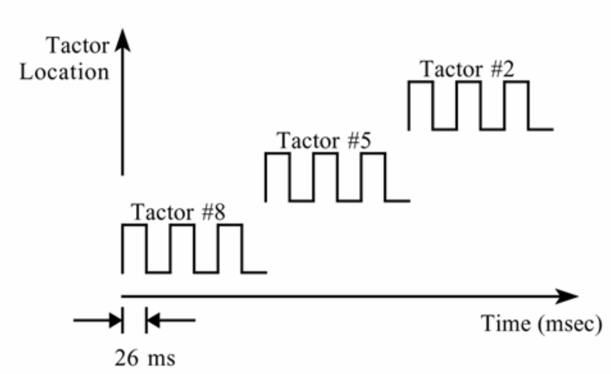

Figure 7. Timing diagram for a saltatory signal heading *north*. The pulse and inter-pulse duration was kept at 26 ms.

Instead of activating one tactor at a time (stimulus set A), three tactors could be simultaneously activated to generate a "thick" saltatory line (stimulus set B, see Table 2). For example, a *NORTH* direction could be generated by simultaneously sending three pulses to tactors #7, #8 and #9, followed by three simultaneous pulses to tactors #4, #5 and #6, followed by another three simultaneous pulses to tactors #1, #2 and #3. To differentiate the signals in stimulus sets A and B, we use lowercase letters for single-tactor saltatory patterns ("thin" lines) and uppercase letters for multi-tactor patterns ("thick" lines).

2) Subjects

Sixteen individuals (seven males and nine females, S1-S16), all Purdue undergraduate and graduate students, served as paid subjects in Exp. 2a. Another group of 10 subjects (5 males and 5 females, S17-S26) participated in Exp. 2b. None of the subjects reported any sensory problems with their back.

Table 2. Stimulus set B. The notation for signal B1 (EAST) means that three pulses are sent simultaneously to tactors #1, #4 and #7, followed by three more simultaneously delivered to tactors #2, #5 and #8, followed by another three sent simultaneously to tactors #3, #6 and #9 (see the enclosed tactor-array photo for tactor numbering). Uppercase letters are used to indicate the directions of these "thick" saltatory lines.

	Saltatory Signal Pattern	**Saltatory Direction**
B1	111222333 444555666 777888999	EAST (E)
B2	333222111 666555444 999888777	WEST (W)
B3	111444777 222555888 333666999	SOUTH (S)
B4	777444111 888555222 999666333	NORTH (N)
B5	222333666 111555999 444777888	SOUTHEAST (SE)
B6	222111444 333555777 666999888	SOUTHWEST (SW)
B7	444111222 777555333 888999666	NORTHEAST (NE)
B8	666333222 999555111 888777444	NORTHWEST (NW)

3) Procedures

Care was taken so that the middle column of the tactor array was lined up with a subject's spine area. (Saltation might not cross the midline of the back unless a tactor is placed along the midline of the body to "bridge the neurological gap" [35]). All subjects were informed that they would feel a series of vibrational patterns on their back. They were told that the sensation would be very similar to that from a massage chair, and that their task was to describe these sensations.

During Exp. 2a where an open response paradigm was used, the subjects (S1-S16) were given a response sheet with trial numbers and a small rectangular area beneath each number (see Fig. 8 for an example). The subjects were instructed to render an illustration on the response sheet to describe the sensations associated with the signals presented on their back. This paradigm allowed the most natural interpretation of the saltatory signals to be revealed. At no time was the subject informed of the nature of the saltatory directions tested with the two stimulus sets. The subjects were not aware that there were only eight possible directions, or that all stimulus patterns consisted of straight lines. Each subject was first presented with the eight patterns in stimulus set A over four runs, followed by four runs with stimulus set B (with the exception that S3 was only tested with stimulus set A). Each run consisted of forty trials with each of the eight patterns presented exactly five times (i.e., randomization without replacement). One of the subjects (S9) was also tested with stimulus sets A and B combined for a total of 160 trials (10 presentations per stimulus alternative).

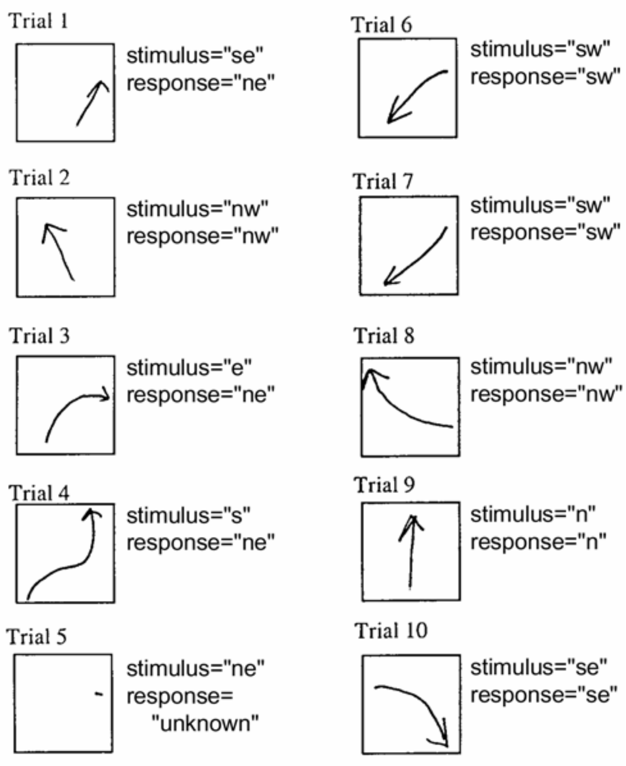

Figure 8. Sample response sheet for stimulus set A (Exp. 2a, Subject S9). Shown are the notations used by S9 (drawings inside the rectangular boxes), and the corresponding stimulus and response labels.

The second group of subjects (S17–S26) were tested with an absolute identification paradigm. On each trial, one of the stimulus alternatives was presented with equal *a priori* probability. Subject responded by selecting one of eight directional arrows on the computer monitor. Trial-by-trial correct-answer feedback was provided. Each run consisted of 100 trials. Each subject was tested with (1) stimulus set A alone (four runs total), (2) stimulus set B alone (four runs total), and (3) stimulus sets A and B combined (five runs total). Unlike the first group who received no training with the stimuli, the second group of subjects were required to feel all the directional signals in a stimulus set before data collection began. Training was repeated after a subject left and came back to the chair.

Throughout all the experiments, the tactor array in our back display was covered with a black cloth so the subjects were unaware of the size of the 3-by-3 tactor array. The subjects were asked to press their back on the tactor array all the time. They wore earphones to block any audible noise from the tactor array.

4) Data Analysis

Percent-correct scores were calculated from data pooled over the multiple runs within the same experimental condition. This was straight forward for Exp. 2b since we employed an absolute identification paradigm with forced-choice responses. For Exp. 2a, the hand-drawn pictures from the subjects were manually scored by one experimenter. This was based on extensive debriefing that revealed the meanings of the various notations used by the subjects to indicate their perception. The following general procedure was followed. The tail of an arrow was taken to indicate the starting point and the head the ending point of the perceived direction.

Decisions were made regarding the direction of the perceived signal based on the length and the slope of an imaginary line drawn between both points. For example, if the line connecting a starting point on the left to an ending point on the right had a negligible slope, it was interpreted as a signal traveling in the *east* direction. The subjects' clarification of their responses during debriefing was also taken into consideration. In cases where a notation did not seem to correspond to any of the eight directions, the response was labeled as "unknown" and skipped in data analysis.

C. Results

1) Results from Exp. 2a (Open Response Experiments)

An example of typical response notations used by one subject is shown in Fig. 8, along with the directions of the stimuli presented and the experimenter's interpretations of the responses. This was the very first ten trials performed by subject S9 with stimulus set A. It is evident that this subject quickly adapted to a line notation with arrow heads indicating the perceived direction. After the initial five trials where only the second trial was considered to be "correct," the subject was able to correctly discern the directions of the saltatory lines from trials 6 through 10.

The average percent-correct scores are shown as bar graphs (with standard errors) for stimulus sets A and B in Fig. 9. For stimulus set A, average percent-correct scores varied from 79% (*w*) to 91% (*n*). The performance differences with the eight "thin" lines were not statistically significant [F(7,232), p=0.8531]. Compared with a chance performance of 12.5% (one out of eight signals per stimulus set), the data clearly demonstrate subjects' ability to correctly interpret the direction of saltatory signals when a single row or column of our 3-by-3 tactor array was used. For stimulus set B, average percent-correct scores varied from 49% (*NW*) to 89% (*N*). Again, the results were well above the chance performance level of 12.5%. Notice that for set B, performance with the four horizontal/vertical saltatory signals (*E*, *W*, *S*, *N*) were clearly better than that with the four diagonal signals (*SE*, *SW*, *NE*, *NW*) [F(7,232)=9.42, p<0.0001]. This may have to do with the way the "thick" diagonal lines were generated. As shown in Table 2, a diagonal saltatory line, say *SE* (signal B5), was generated by simultaneously activating tactors #2, #1, #4, followed by simultaneous activation of #3, #5, #7, followed by simultaneous activation of #6, #9, #8. The "width" of this diagonal line was therefore not kept constant. It was perceived as emerging from one point (tactor #1), spreading out, then terminating at another point (tactor #9). The change in "width" clearly interfered with subjects' ability to concentrate on the direction of this saltatory line.

A comparison of percent-correct scores with the four horizontal/vertical saltatory signals in sets A and B indicated essentially no difference in performance levels whether "thin" or "thick" saltatory lines were used [F(7,232)=0.45, p=0.8665]. Percent-correct scores averaged over the four signals of *e*, *w*, *s* and *n* in set A was 85%, so was the average over the signals of *E*, *W*, *S* and *N* in set B. It can therefore be concluded that horizontal/vertical saltatory directions can be equally well perceived whether a single row/column or multiple rows/columns are used to generate the signals. On the contrary, performance levels with the diagonal signals in sets A and B were statistically different [F(7,232)=11.37, p<0.0001], with subjects performing much better with the "thin" diagonal lines.

To find out whether subjects could reliably detect the difference between saltatory signals generated by single or multiple tactors, one subject (S9) was tested with a stimulus set containing all sixteen salutatory signals in stimulus sets A and B. This subject could easily differentiate

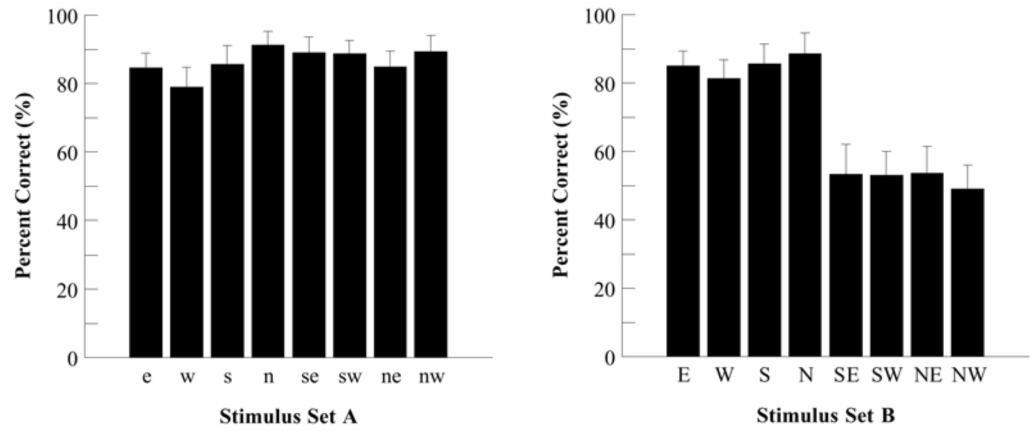

Figure 9. Average percent-correct scores for stimulus set A or B from Exp. 2a using an open response paradigm.

between stimuli from the two stimulus sets. The percent-correct scores in Fig. 10 indicate near perfect performance for all the horizontal/vertical lines as well as the "thin" diagonal lines. However, the performance with the "thick" diagonal lines were near chance.

2) Results from Exp. 2b (Absolute Identification Experiments)

Recall that the main difference between Exps. 2a and 2b was whether a subject used open (Exp. 2a) or forced-choice (Exp. 2b) responses. The average percent-correct scores for stimulus sets A or B from Exp. 2b are shown in Fig. 11. For stimulus set A, average percent-correct scores varied from 85% (*e*) to 95% (*n*). There was no statistically significant difference among the scores for these "thin" lines [F(7,144)=0.70, p=0.6681]. For stimulus set B, average percent-correct scores varied from 72% (*W*) to 87% (*NE*). Unlike the results for set B in Exp. 2a, there was no significant difference in performance with the "thick" lines tested in Exp. 2b [F(7,144)=1.28, p=0.2642]. The effect of stimulus set, however, was significant [F(15,144)=3.26, p=0.0001]. Subjects performed better with the "thin" lines than with the "thick" ones in Exp. 2b. As was the case with data from Exp. 2a, the average percent-correct scores from Exp. 2b were well above the chance level of 12.5%.

It was expected that with an absolute-identification paradigm, subjects would perform better at identifying the directions of saltatory lines due to the initial training and the limited response choices. It turned out that there was no significant difference between the percent-correct scores for stimulus set A under open response or absolute-identification paradigms [F(1,199)=2.21, p=0.1388] (see the left panels in Figs. 9 and 11). A direct comparison of the percent-correct scores for the four horizontal/vertical directions in stimulus set B from Exps. 2a and 2b did show significant difference [F(1,95)=7.66, p=0.0068], with better performance levels in Exp. 2a. Finally, it is quite clear (from the right panels in Figs. 9 and 11) that performance with the "thick" diagonal lines improved drastically with the absolute-identification paradigm. These results suggest that the "thin" saltatory lines are highly intuitive, and performance with the "thick" diagonal lines benefited from some training and the restricted response set used in Exp. 2b. We were somewhat baffled by the decrease in performance levels with the "thick" horizontal/vertical lines in Exp. 2b. This issue is addressed in the next section (Sec. IV.C.3).

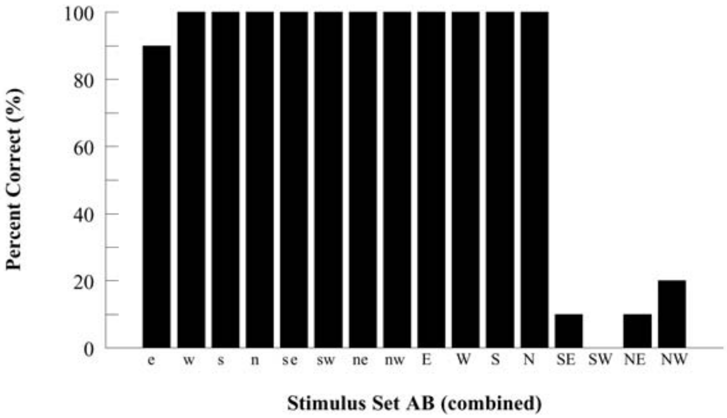

Figure 10. Percent-correct scores for Subject S9 with stimulus sets A and B combined, from Exp. 2a using an open response paradigm.

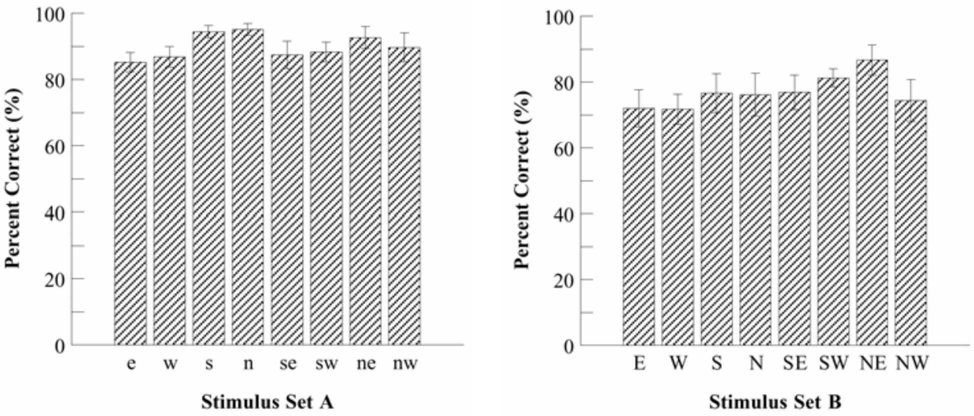

Figure 11. Average percent-correct scores for stimulus set A or B (Exp. 2b, absolute identification paradigm).

The average percent-correct scores for stimulus sets A and B combined are shown in Fig. 12. The performance varied from 73% (*S*) to 93% (*n*), with an overall average of 83%. Compared with the corresponding data from Exp. 2a where subject S9 performed much worse with the "thick" diagonal lines (Fig. 10), the percent-scores for all sixteen "thin" and "thick" saltatory lines from Exp. 2b were not significantly different [F(15,144)=1.46, p=0.1288]. Apparently, the subjects were able to overcome the difficulties associated with the non-uniform thickness of the "thick" diagonal lines with minimal training and a forced response set.

3) Improvements to Exp. 2b

One of the authors noticed that some of the lowest performance levels in Exp. 2b were obtained by subjects with a relatively large back area as compared to the overall contact area of our haptic back display. Informal testing showed that it was easier for these subjects to identify the directions of the saltatory lines with a wider spacing of the tactors. Therefore, additional data were collected from two such subjects (S19 and S21) with the inter-tactor spacing increased from 8 cm to 9 cm. These two subjects repeated the absolute-identification experiments with stimulus set A alone, set B alone, and with sets A and B combined. The results show that both subjects benefited from the larger spacing of the tactor array (Table 3). Specifically, the average

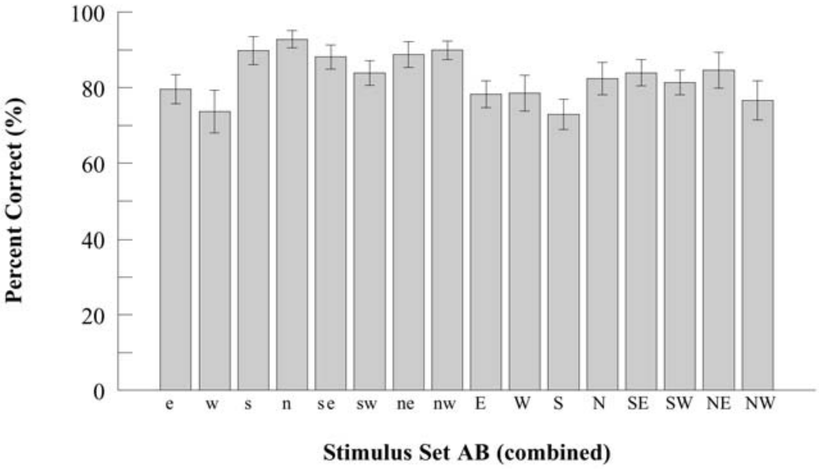

Figure 12. Average percent-correct scores for stimulus sets A and B combined from Exp. 2b using an absolute identification paradigm.

percent-correct scores for the "thick" horizontal/vertical lines in stimulus set B increased from 61% to 86% for S19, and from 82% to 94% for S21. The results with the 9 cm spacing were therefore similar to or better than 85%, the average of the percent-correct scores for the *E*, *W*, *S*, and *N* directions obtained from Exp. 2a (see Fig. 9, right panel).

V. GENERAL DISCUSSION

We have developed a haptic back display based on a 3-by-3 tactor array for displaying attentional and two-dimensional directional information to a human user. We have conducted two psychophysical experiments to test the effectiveness of our display. In the first study, we examined the extent to which haptic spatial cues can speed up or slow down an observer's reaction time to detect a change in a visual scene. Our data suggest that (1) valid haptic cues decrease the reaction time for the detection of a visual change, and (2) invalid haptic cues increase the reaction time (to a lesser degree) for the same task. This general conclusion holds for data from individual subjects as well as for those pooled from all subjects. This conclusion also holds despite the inter-subject differences in their "natural" reaction time (i.e., some subjects tend to react faster than others when no haptic cues are present). Similar results have been reported for visual spatial cueing of a visual change-detection task [36]. The present findings are also consistent with recent evidence that tactile cues can speed reaction times in a up-down visual discrimination task [37], although in these previous experiments response facilitation only occurred when the cue and target were in the same spatial location (e.g., on or near the left hand). Finally, we have some evidence suggesting that valid haptic cues decrease the inter-subject variability in their reaction time.

In the second study, we investigated the intuitiveness and discriminability of a set of directional lines "drawn" on the subjects' back using the sensory saltation phenomenon. Using an open response paradigm, a group of sixteen subjects were asked to depict the sensations associated with two stimulus sets that differed in the number of tactors that were simultaneously activated. Our results suggest that each saltatory signal has a unique and consistent interpretation among the observers tested. Furthermore, simultaneous activation of multiple

Table 3. Comparison of percent-correct scores with an 8 cm and 9cm inter-tactor spacing using an absolute-identification paradigm for subjects S19 and S21.

	8 cm Spacing			9 cm Spacing		
	Set A	Set B	Set A+B	Set A	Set B	Set A+B
S19	88%	63%	72%	95%	82%	89%
S21	92%	85%	92%	99.8%	93%	93%

tactors do not seem to enhance performance. These results have been obtained with subjects who had never experienced sensory saltation before, and who were unaware of the range of saltatory signals used in each stimulus set. One difficulty with the open response paradigm has to do with the way the graphical response notations were scored. Although the experimenter took careful notes during debriefing of the subjects, the procedure was nonetheless subjective.

This problem was alleviated in a follow-up study where the same two stimulus sets were tested on a different group of ten subjects using the standard absolute identification paradigm. With such a forced-choice paradigm, subjects were informed of the (limited) number of acceptable responses, and were briefly trained to associate each response with a stimulus. Our results from the absolute identification experiment suggest that as far as the "thin" saltatory lines (stimulus set A) are concerned, identification accuracies remain the same whether the subjects have received no training (open response paradigm) or some training (absolute identification experiment). This result further attests to the intuitiveness of the saltatory lines for imparting directional information. The main performance difference between the two groups of subjects is found with the "thick" diagonal signals. In other words, identification performance with the *SE*/*SW*/*NE*/*NW* directions was much worse than that with the *E*/*W*/*S*/*N* directions when the open response paradigm was employed, but became similar to that with the *E*/*W*/*S*/*N* directions when the absolute-identification paradigm was employed. These results indicate that the diagonal saltatory lines can be effectively used with minimal user training. In summary, we have collected evidence that a small set of directional signals can be easily and consistently interpreted by the general population.

Our results have implications for designers of multimodal interfaces. In an automobile, for example, a haptic display built into the driver's seat can be useful in alerting the driver of impending collision on one side of the car. A haptic navigation guidance system can inform the driver which direction to turn at the next intersection with saltatory lines. Such a system allows the drivers to keep their eyes on the road, thereby improving the safety associated with the use of a navigation guidance system. In a large and complex visual display for air traffic control, a haptic display used in conjunction with a non-invasive eye-tracking system can remind the operator to look at a neglected area of the visual display, or to pay attention to an area with busy traffic. For astronauts, pilots or divers who routinely experience environments with distorted spatial orientation, a haptic back display can be used to indicate which way is "up" or "down." In general, a haptic attentional/directional cueing system such as our back display can serve as an effective addition or alternative to visually- or auditorily-based human-machine interfaces.

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