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A PSYCHOPHYSICAL STUDY OF SENSORY SALTATION WITH AN OPEN RESPONSE PARADIGM

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ABSTRACT
As we develop new haptic interfaces, it is desirable to present haptic information in an intuitive and effective manner. The sensory saltation phenomenon is a haptic spatiotemporal illusion that, with the appropriate spatial and timing parameters, evoke a powerful perception of directional lines. Efforts are underway to develop a general-purpose haptic display based on sensory saltation that can find application in many areas including a haptic driving navigation guidance system. The current study is designed to test the hypothesis that saltatory signals can be readily perceived by human observers without training. Using a 3-by-3 tactor array, horizontal, vertical and diagonal saltatory lines are generated. An open response paradigm is used to permit subjects to describe saltatory signals with their own imagination. Results show that the saltatory signals used in this study share unique and consistent interpretations among the group of observers tested. Future work include a follow up study of the same saltatory signals using a standard absolute identification paradigm.

1. INTRODUCTION
For the past few years, we have been studying the sensory saltation phenomenon in an effort to develop a general-purpose haptic interface that can find a wide range of applications. There are several reasons why we choose to study this phenomenon. Firstly, sensory saltation provides a mechanism for displaying directional information that is highly intuitive. Compared with sensory aids for the deaf (for example, Vocoder [13], Tickle-Talker [2, 3], Tactaid II and Tactile VII [14]) and for the blind (for example, the Optacon [11], the TVSS — Tactile to Vision Substitution System [1, 18]) that require a user to learn unfamiliar tactile stimulation patterns, our saltatory display can be readily interpreted by naive 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. [12]) that require motor assemblies and force ground in order to deliver appreciable force variations, our saltatory 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 [4]. This flexibility led to the development of saltatory displays built into the back of an office chair [16] and the back of a vest for wearable applications [5]. Finally, the saltatory sensation is characteristically vivid. Informal demonstration to first-time observers has met with enthusiastic response and interest. We have so far implemented several versions of saltatory displays for applications including blind navigation, driving navigation guidance system, and situation awareness display.[1]

The rest of this section discusses the sensory saltation phenomenon, our vision for a general-purpose haptic display based on this phenomenon, and the motivation for the current study.

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 (Fig. 1), three mechanical tactors are placed with equal distance on the forearm. Three brief pulses are 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 is under the impression that the pulses seem to be distributed with more or less uniform spacing from the site of the first to that of the third tactor (Fig. 2). The sensation is characteristically discrete as if a tiny rabbit was hopping up the arm from wrist to elbow, hence the

1. See http://www.ecn.purdue.edu/HIRL/projects_vest.html for more information.

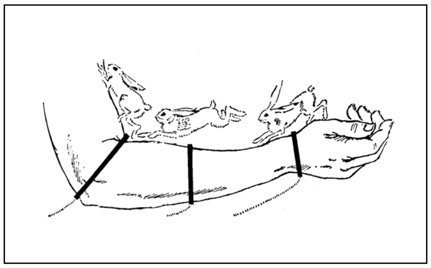

Figure 1. A Norwegian newspaper cartoonist's illustration of "sensory saltation" [6].

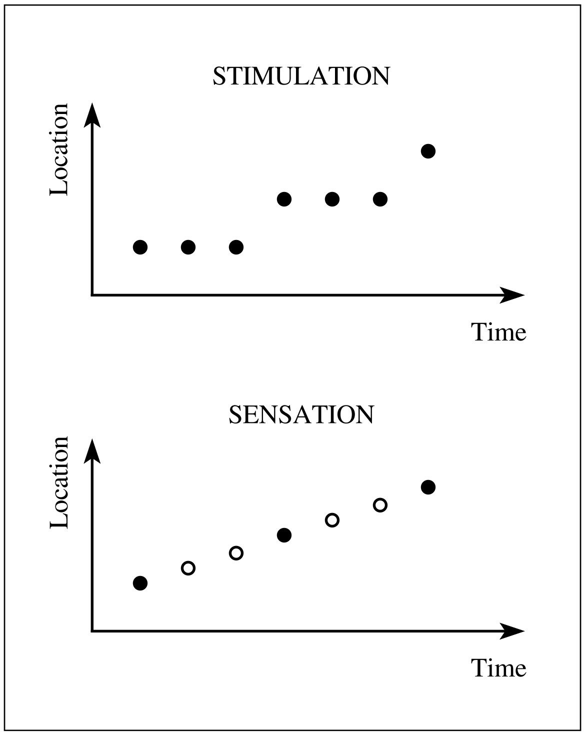

Figure 2. An illustration of sensation vs. stimulation pattern for "sensory saltation". Open circles indicate perceived pulses at phantom locations [16].

nickname "cutaneous rabbit".

Since its initial discovery, the "rabbit" has been examined in many ways by researchers at Princeton University. It is known that for the back, the tactors need to be placed at distances no greater than 10 cm in order to solicit the "rabbit" [6]. The interstimulus duration can vary from about 20 to 300 msec, with 50 msec being near optimal [8]. The optimal number of pulses to be sent to each tactor is between 3 and 6 [9]. Intensity and duration of the pulses are of secondary importance [8, 9]. 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 [6]. The fact that saltatory illusion occurs in vision, audition as well as other forms of tactual stimulation (thermal and electrocutaneous) suggests that the mechanism is of a central, rather than peripheral nature. Reviews of earlier work can be found in [6, 7].

Recently, a comprehensive study of the perceived qualities of lines generated by saltation was completed [4]. 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 are very similar for the veridical and saltatory modes. In the veridical mode, seven linearly spaced tactors are successively activated to generate a dotted line with perceived stimulation sites corresponding exactly to the locations of the tactors. In the saltatory mode, only three of the seven tactors (the 1^{st}, 4^{th} and 7^{th}) are activated to create a sensation of dotted line with phantom sensations at sites corresponding to the 2^{nd}, 3^{rd}, 5^{th} and 6^{th} 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 in this case). Secondly, perceived line qualities are very similar for the finger, forearm and back, and vary in similar manners with timing parameters. This is despite the fact that the two-point thresholds on the finger and on the back differ greatly (fingertip: 2 mm, back: 40 mm) [17]. It seems that the large size of the back compensates well for its low spatial sensitivity. Because that the back is usually not engaged by any other human-computer interfaces, and because a display built into a chair has the advantage of not tethering the user, our study focuses on the back as the stimulation site.

A General-Purpose Haptic Display for Directional Information

We envision a back display based on sensory saltation 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 blind navigation. A tactile vest with embedded vibrotactile array can be integrated with a global positioning system (GPS) and a wearable computer to provide macro navigation signals to a blind traveler. Compared with other blind navigation aids based on sonification (for example, vOICe[1]), a tactile system has the advantage of allowing the blind user to use the auditory sensory system for monitoring environmental sounds and for situation awareness. Another application is a navigation guidance system embedded in a driver's seat. Current navigation systems require a driver to look at a heads-up display for navigational directions. Research has shown that observers of visual scenes never form a complete, detailed representation of their surroundings. Attention is required to perceive (even large) changes in a scene. This phenomenon, termed "change blindness", reveals how dangerous it is for a driver to take the eyes off the road, even for as brief as 80 milliseconds [15]. 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 by keeping the driver's eyes on the road during driving.

Motivation for the Current Study

The experimental study reported here addresses the issue of the intuitiveness of a saltatory back display. In order for such a display to be widely available and useful, minimum training should be required of the user. Informal testing shows that naive subjects can easily discern the direction of saltatory signals presented to their back. This suggests that a directional display based on the sensory saltation phenomenon may require no training at all. In the present study, we test this

1. http://ourworld.compuserve.com/homepages/Peter_Meijer/winvoice.htm

Figure 3. Experimental apparatus. Shown here is an office chair fitted with the 3-by-3 tactor array. Each tactor, enclosed in a white case, is fastened to a piece of fabric with two crisscross elastic bands.

hypothesis by using an open response paradigm where a subject can freely assign any meaning to directional saltatory signals. Data so obtained are then analyzed to reveal the most natural interpretation of a saltatory signal, and the consistency of interpretation among a group of people.

2. METHODS

Apparatus

Our "rabbit" display consists of a 3-by-3 vibrotactile array with an equal inter-tactor spacing of 8 cm. The tactor array is sewn between two supporting layers of fabric, so they can be draped over the back of an office chair (Fig. 3). Care is taken so that the middle column of the tactor array is lined up with a subject's spine area.[1] Each tactor is made from a 40-mm diameter flat magnetic speaker (FDK Corp., Tokyo, Japan) with modifications to lower its resonant frequency and to increase the gain [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 the fixed frequency of 290 Hz. Pulse duration and interpulse interval are controlled by a PIC16C84 (Microchip Inc., Arizona) microcontroller. The tactors are adjusted to operate at 27 dB SL (sensation level), as measured by an accelerometer. The intensity measurements are taken with subject's back pressing against the tactor (loaded condition).

Stimulus

Each saltatory signal is generated by successively sending three high frequency pulses to three tactors. For example, as shown in Fig. 4, a direction of *north* is generated by successively activating tactors #8

1. Geldard & Sherrick reported that saltation might not cross the midline of the back unless a tactor is placed along the midline of the body to "bridges the neurological gap" [10].

Figure 4. Illustration of saltatory signal patterns and their corresponding perception.

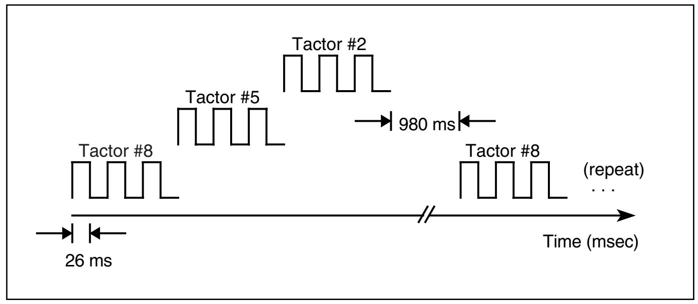

Figure 5. Timing diagram for a saltatory signal heading *north*. See Fig. 4 for an illustration of tactor locations in the 3-by-3 tactor array.

(three times), #5 (three times) and #2 (three times). A timing diagram for this signal is shown in Fig. 5. The pulse duration and interpulse interval are fixed at 26 msec. The pattern repeats itself after about 1 sec until the subject presses a key.

Directional saltatory signals are examined in this study. Specifically, we tested how well subjects can perceive the eight directions of *east*, *west*, *south*, *north*, *southeast*, *southwest*, *northeast*, and *northwest*. These directions are defined in a coordinate system centered at subject's torso and viewed from subject's back. For example, as shown in Fig. 4, successive activation of tactors #6, #5 and #4 produces a saltatory line heading *west*. Also tested in this study is whether a saltatory direction, say *north*, is best presented by activating the center column or all three columns of the 3-by-3 tactor array. Referring again to Fig. 4, an alternative way to generate a *NORTH* direction would be to simultaneously send three pulses to tactors #7, #8 and #9, followed by simultaneous pulses sent to tactors #4, #5 and #6, followed by simultaneous pulses sent to tactors #1, #2 and #3. In this paper, we use capital letters such as *NORTH* to indicate the directions of "thick" saltatory lines. Two stimulus sets, one with the eight directions generated with a single row or column of the 3-by-3 tactor array (set A) and the other with eight "thick" directional signals (set B) are used in this study (see Table 1 for a complete listing of the sixteen saltatory signals).

Subject

Sixteen individuals (S1–S16, seven males and nine females), all Purdue undergraduate and graduate students, served as paid subjects. The subjects were asked if they had any back problems, and none indicated so. All subjects were tested with both stimulus sets A and B, except for one subject (S3) who was only tested with stimulus set A.

TABLE 1. Stimulus sets A and B. The notation for signal "A1" means that three pulses are sent to tactor #4, followed by three pulses to #5, followed by another three pulses to #6. The notation for signal B1 means that tactors #1, #4 and #7 are simultaneously activated, so are tactors #2, #5 and #8, as well as tactors #3, #6 and #9. Signals in stimulus set B are therefore "thick" saltatory lines, and their directions are labeled with capital letters.

	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)
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)

Procedure

Each subject was first asked to sign an informed consent form that stated:

> *"You will be asked to feel a series of vibrational patterns on your back. The sensation will be very similar to what you'd feel in a massage chair. You will be asked to describe the sensation associated with these vibrational signals."*

The subject was then presented the eight patterns in stimulus set A over four runs (session A), followed by four runs with stimulus set B (session B). Each run consisted of forty trials with each of the eight patterns presented exactly five times (randomization without replacement). Pink noise was presented binaurally through headphones to mask any audible noise from the tactor array.

At the beginning of each run, the subject was shown the following instructions on the computer screen:

1. *Write your INITIALS on the User Response Sheets.*
2. *You will feel directional vibrations on your back during the experiment when you press your back against the chair.*
3. *Wear the headphones during the experiment.*
4. *For each trial, record your observation (drawings, writings, etc.) in the corresponding box on the User Response Sheets.*

The subject was given a response sheet with trial numbers and a small rectangular area beneath each number (see Fig. 6 for an example). The subject was instructed to render an illustration on the response sheet to describe the sensations associated with the signals presented on the back. By using an open response paradigm such as this, the most natural interpretation of the saltatory signals could be revealed.

At no time was the subject informed of the nature of the eight saltatory directions tested with the two stimulus sets. The subjects were not aware that there were only eight possible stimulus alternatives, and that all stimulus patterns consisted of straight lines. At the end of each experimental session, each subject was debriefed. The experimenter took notes on the meanings of the notations used by each subject. This enabled the experimenter to later categorize the subject's responses into those listed in Table 1 under "Saltatory Direction". Most subjects resorted to arrows to indicate the direction of saltatory lines within the initial few trials.

Data Analysis

The following general procedure was used to categorize the subject's responses as belonging to one of the labels listed in Table 1 under the heading "Saltatory Direction". 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 travelling 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 (for example, trial #5 in Fig. 6).

For each subject, responses from all four runs of session A and session B are pooled separately. The number of times each signal is identified correctly is computed. The percent correct scores for each signal are then averaged over all sixteen subjects for set A, and over fifteen subjects for set B (because subject S3 was not tested with stimulus set B).

3. RESULTS

An example of typical response notations used by one subject is shown in Fig. 6. This is the very first ten trials performed by subject S9 with stimulus set A. It is evident that this subject quickly adopted to a line notation with arrow heads indicating its direction. The stimulus sequence corresponding to these ten trials, along with experimenter's

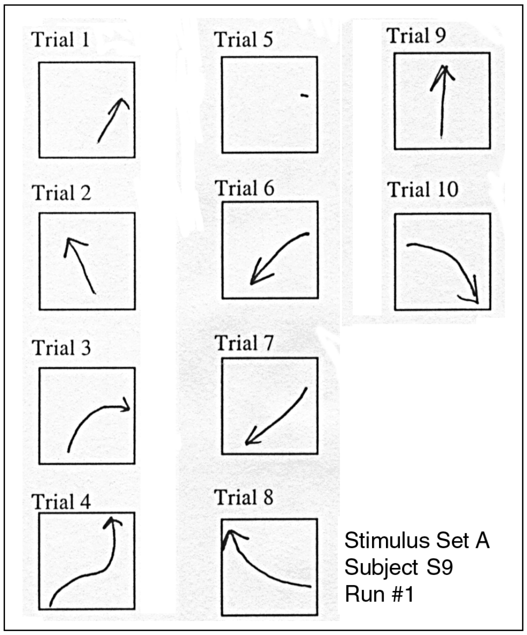

Figure 6. Sample response notations for stimulus set A.

interpretation of the response notations, are shown on the left side of Table 2. Fig. 7 shows the first ten trials performed by the same subject with stimulus set B. Notice the wavy lines starting at trial #4. During debriefing, subject S9 explained that the wavy lines (singles in trials 4 and 5, and multiples for subsequent trials) were her way of indicating the wave-like sensation associated with the stimuli in stimulus set B. The corresponding stimulus and responses sequences are shown on the right side of Table 2. In general, subjects experienced the sensory saltation phenomenon (except for subject S16). Inquiries made during debriefing revealed that most subjects judged the number of tapping locations felt per saltatory signal to be between 4 to 8 for stimulus set A. The fact that more than 3 locations were perceived indicates that these subjects experienced the sensory saltation illusion.[1]

The average percent-correct scores for stimulus sets A and B are shown as bar graphs (with ±1 standard deviation) in Figs. 8 and 9. For stimulus set A, average percent-correct scores vary from 79% (*w*) to 91% (*n*). 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 is used. For stimulus set B, average percent-correct scores vary from 51% (*NW*) to 87% (*S* or *N*). Again, the results are 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*) are clearly better than that with the four diagonal signals (*SE*, *SW*, *NE*, *NW*). This may have to do with the way the "thick" diagonal lines are generated. As shown in Table 1, a diagonal saltatory line, say *SE* (signal B5), is generated by simultaneously activating tactors #2, #1, #4, followed by simultaneous activation of #3, #5, #7, followed by simultaneous activation of #6, #9, #8 (see Fig. 4 for tactor locations). The "width" of this diagonal line is therefore not kept constant. It is perceived as emerging from one point (tactor #1), spreading out, then terminating at another point (tactor #9). The change in "width" has clearly interfered with subjects' ability to concentrate on the direction of this saltatory line. For both stimulus sets A and B, there are considerable intersubject differences in performance, as indicated by the relatively large standard deviations in Figs. 8 and 9.

TABLE 2. Stimulus and response sequences for Figs. 6 and 7, respectively. See Table 1 for a complete listing of the stimulus used in stimulus sets A and B.

Trial #	Stimulus (Fig. 6)	Response (Fig. 6)	Stimulus (Fig. 7)	Response (Fig. 7)
1	A5	ne	B6	SW
2	A8	nw	B7	NE
3	A1	ne	B8	NE
4	A3	ne	B7	NE
5	A7	unknown	B6	SW
6	A6	sw	B3	S
7	A6	sw	B7	N
8	A8	nw	B4	N
9	A4	n	B5	SE
10	A5	se	B5	SE

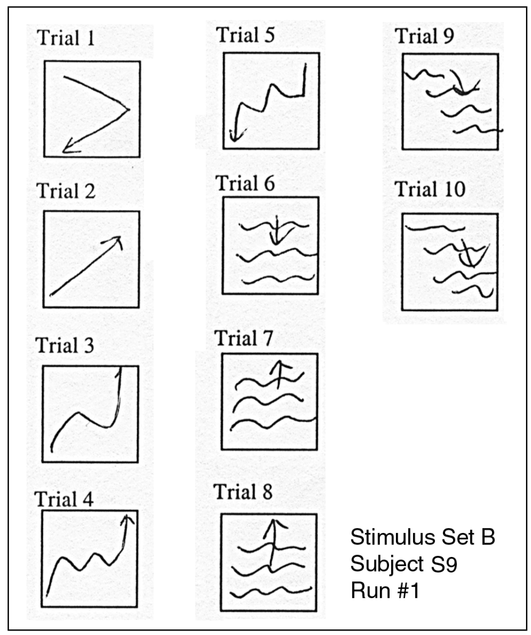

Figure 7. Sample response notations for stimulus set B.

A comparison of percent-correct scores with the four horizontal/vertical saltatory signals in sets A and B indicates essentially no difference in performance levels whether "thin" or "thick" saltatory lines are used. Percent-correct scores averaged over the four signals of *e*, *w*, *s* and *n* in set A is 85%, as compared to 86% over the signals of *E*, *W*, *S* and *N* in set B. It is therefore concluded that horizontal/vertical

1. Cholewiak & Collins reported that their subjects could not discern the differences in sensation with a veridical and a saltatory line [4]. Since the timing parameters used in our current study fall into the same ranges of those used by Cholewiak & Collins [4], we only qualitatively verified that our subjects experienced the sensory saltation phenomenon.

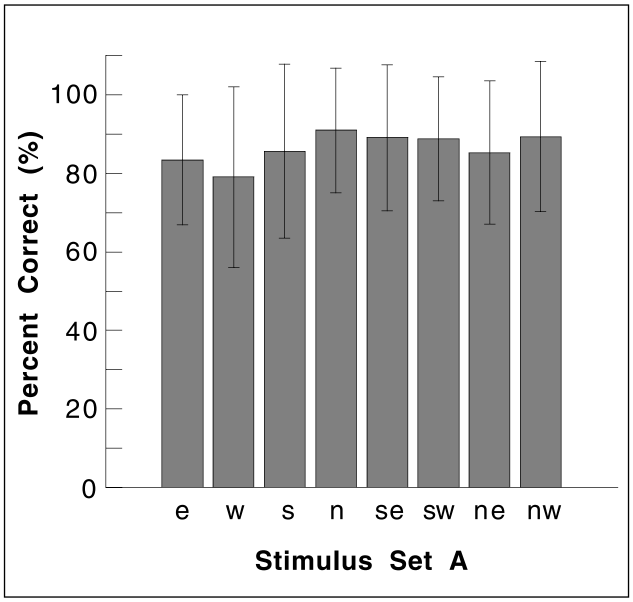

Figure 8. Percent-correct scores for stimulus set A, averaged over sixteen subjects.

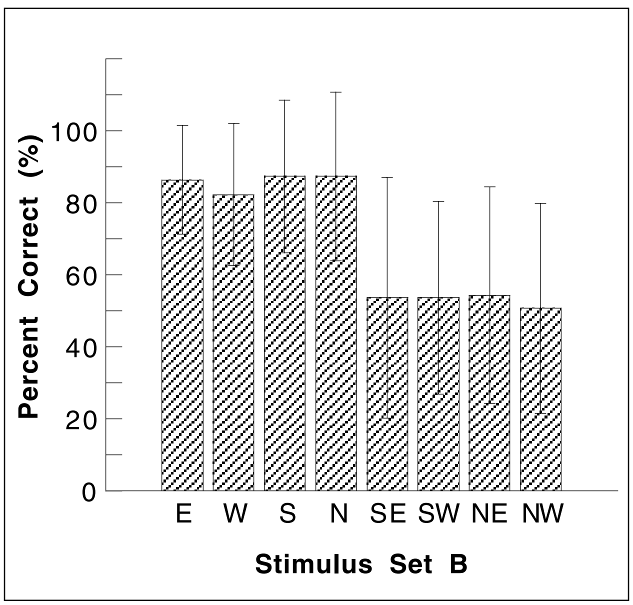

Figure 9. Percent-correct scores for stimulus set B, averaged over fifteen subjects.

saltatory directions can be equally well perceived whether a single row/column or multiple rows/columns are used to generate the signals.

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 saltatory signals in sets A and B. Two runs of eighty trials each were conducted, again with an open response paradigm. Fig. 10 shows the response notations used by this subject for the very first ten trials. The corresponding stimulus and response sequences are shown in Table 3. It can be seen that this subject had no difficulty differentiating between stimuli from stimulus set A and B. The percent-correct scores for each

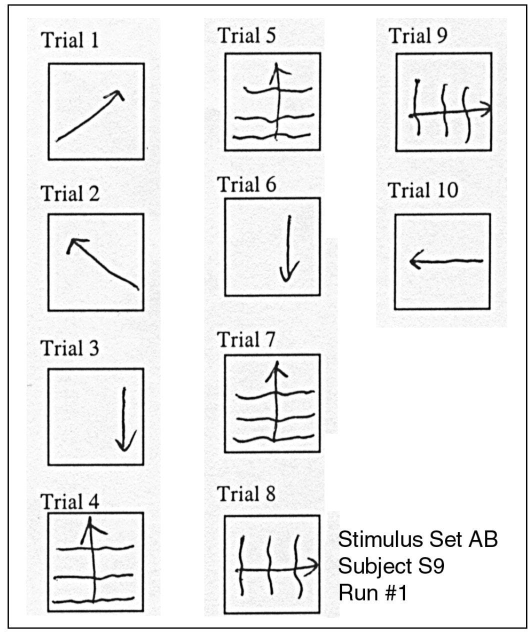

Figure 10. Sample response notations for stimulus sets A and B combined.

TABLE 3. Stimulus and response sequences for Fig. 10, for subject S9. See Table 1 for a complete listing of the sixteen stimuli in stimulus sets A and B.

Trial #	Stimulus	Response
1	B2	W
2	A3	s
3	B6	W
4	A1	unknown
5	B1	E
6	A3	s
7	A2	w
8	A4	n
9	B2	W
10	B4	N

of the sixteen saltatory signals are shown in Fig. 11. This subject performed nearly perfectly on the first twelve of the sixteen saltatory signals. Her performance with the four "thick" diagonal signals, however, was much worse than when stimulus set B was used alone.

4. DISCUSSION

We have developed a 3-by-3 tactor array for displaying two-dimensional directional lines based on the sensory saltation phenomenon. Using an open response paradigm, a group of sixteen subjects have been asked to depict the sensations associated with two stimulus sets that differed in the number of tactors that are simultaneously activated. Our results suggest that each saltatory signal has a unique and consistent interpretation among the observers tested. Furthermore, simultaneous activation of multiple tactors do not seem to

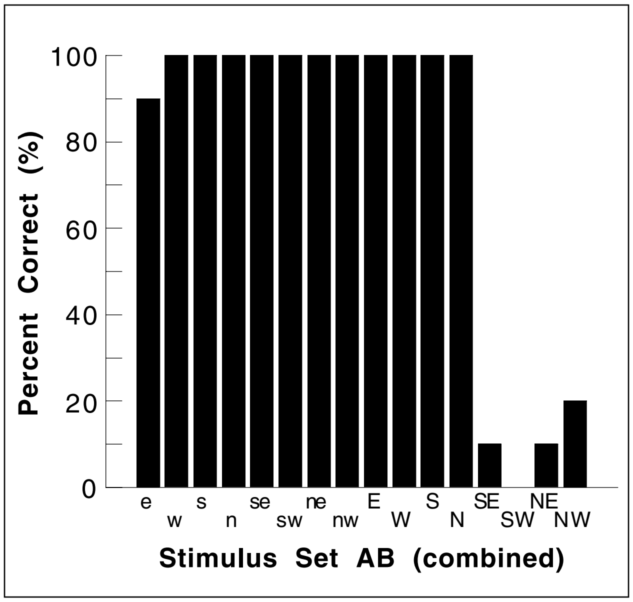

Figure 11. Percent-correct scores for stimulus sets A and B combined (subject S9).

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 current study 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 will cease to be a problem for a planned follow-study where the same two stimulus sets will be tested on a different group of subjects using the standard absolute identification paradigm. With such a forced-choice paradigm, subjects will be informed of the (limited) number of acceptable responses, and be briefly trained to associate each response with a stimulus. It is expected that higher performance levels (in terms of percent-correct scores) can be obtained with the absolute identification paradigm. If this turns out to be true, then we will have collected evidence for a small set of directional signals that can be easily and consistently interpreted by the general population. Such results will greatly facilitate the design of stimulation patterns for a general-purpose haptic directional display.

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