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Vibrotactile localization on the abdomen: Effects of place and space

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In this study, we explore the conditions for accurate localization of vibrotactile stimuli presented to the abdomen. Tactile orientation systems intended to provide mobility information for people who are blind depend on accurate identification of location of stimuli on the skin, as do systems designed to indicate target positions in space or the status of remotely operated devices to pilots or engineers. The spatial acuity of the skin has been examined for simple touch, but not for the types of vibrating signals used in such devices. The ability to localize vibratory stimuli was examined at sites around the abdomen and found to be a function of separation among loci and, most significantly, of place on the trunk. Neither the structures underlying the skin nor the types of tactor tested appeared to affect localization. Evidence was found for anatomically defined anchor points that provide localization referents that enhance performance even with wide target spacing.

The touch of a mosquito on the skin or a tap on the shoulder are stimuli that, in the absence of disease, disorders of body schema, or tactile illusion, are processed quickly, and their location on the body identified with extraordinary accuracy. The remarkable manner in which we can identify where on the body's surface natural stimuli touch us suggests a perceptual mapping of proximal space that could, with advanced technology, provide for a precise sensor of more distal stimuli (Van Erp, 2001). There have been a number of attempts to describe the factors that influence this ability. Often, such examinations have focused on the variation in several types of tactile sensitivity over the body's surface. For much of the past 175 years, since the work of Weber (1826/1978), studies have generally concluded that the closer the location of the test site to the trunk of the body, the less precise is the capability being tested. Vierordt (1870) described this relationship in his *law of mobility*, claiming that the more "mobile" the body site, the greater its sensitivity either to the location of a touch or to the separation between touched locations. Examples of studies supporting these notions include demonstrations of how the ability to localize taps (Weinstein, 1968) or to detect gaps in a stimulus pressed into the skin (Gibson & Craig, 2002) varies from finger to forearm. Physiologists have been able to demonstrate that the variations in sensitivity across these sites appear to be closely related to the density of innervation of the underlying cutaneous receptors, as well as to the size of the associated region of the somatosensory cortex devoted to the representation of these sites (e.g., Kaas, Nelson, Sur, Lin, & Merzenich, 1979). The well-known sensory homunculus is a graphic description of this variation in sensitivity over the body's surface (Cholewiak & Collins, 1991; Penfield & Rasmussen, 1950).

However, the types of tactile stimuli that have been used in these studies have been generally limited to brief pressure pulses, or *touches*. For example, Stevens's studies of spatial acuity (Stevens & Cruz, 1996; Stevens, Foulke, & Patterson, 1996) and Weinstein's (1968) studies of pressure sensitivity, two-point thresholds, and error of localization over many body sites were conducted with individual or paired probes that merely touched the skin. However, in

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order to be able to produce rapidly changing patterns of stimulation on the skin for cutaneous communication systems, vibrating stimuli have almost universally been adopted. One reason for the utility of vibration is that stationary touch stimuli tend to adapt rapidly (e.g., Nafe & Wagoner, 1941), so they have to be repeated in order to produce a sensation that will remain in conscious awareness. Repeated pressure or touch impulses can thus create a vibratory stimulus. Wilska (1954) found that the detection sensitivity of the skin to 200-Hz vibratory stimuli was greatest at the fingers (and the lips and genital areas), dropping at sites closer to the abdomen, a pattern similar to the variation in sensitivity to pressure or to the spatial aspects of multiple touches described earlier. The Optacon (Telesensory Systems, Inc.) and the Tactaid (Audiological Engineering Corp.) are two devices designed to present printed text or speech signals to persons who are blind or deaf, respectively, using multichannel vibrotactile displays. Similarly, Dobbins and Samways (2002), Priplata, Niemi, Harry, Lipsitz, and Collins (2003), Rupert (2000), H. Z. Tan, Lu, and Pentland (1997), Van Erp (2000), and Wall, Weinberg, Schmidt, and Krebs (2001) have demonstrated the potential utility of vibratory arrays, applied to or worn on the abdomen (or even the feet), intended to present information to individuals regarding their posture, position, or location in three-dimensional space and to enhance spatial awareness.

For some applications, including identifying where an event occurred in three-dimensional space, these new technologies could require accurate localization of stimuli on body sites such as the arm or the abdomen. Despite the increased interest in applying vibrotactile stimuli to these areas, little is known about their spatial resolution for such events or how many unique vibratory sites can be accurately localized on their surfaces. The measures of two-point spatial resolution described by Weinstein (1968) are inappropriate, for several reasons, for addressing these questions, even though they are often referred to in instrument design. First of all, as was mentioned above, his data were collected with touch stimuli. It is likely that if these points were vibrated, the pattern of sensitivity over the body's surface would change dramatically. With vibratory signals, tissue movement can extend for centimeters (Franke, von Gierke, Oestreicher, & von Wittern, 1951), and movement can occur deep in the epidermis and dermis where, after all, many of the receptors for vibration exist (e.g., Bolanowski, Gescheider, & Verrillo, 1994; Greenspan & Bolanowski, 1996). It is possible that these characteristics would serve to blur the locus of a punctate vibratory sensation by recruiting distant receptors (e.g., Johnson, Phillips, & Freeman, 1985; Pubols, 1987). As was described earlier, Wilska (1954) did measure vibrotactile detection sensitivity to punctate 200-Hz vibrations over a number of discrete sites representing major areas of the body and found that it varied greatly from region to region. We are, however, unaware of any systematic studies of spatial resolution over the body's surface for vibrotactile stimuli. The second reason why using Weinstein's (1968) data to estimate vibrotactile acuity could raise problems is that it is likely that response biases exist in the traditional methodology used in those studies (e.g., Craig & Johnson, 2000; Johnson, Van Boven, & Hsiao, 1993; Tawney, 1895). These biases appear to operate in the direction of measuring greater spatial sensitivity than actually exists. For example, these authors argue that discrimination between one and two points (one of Weinstein's methods) can often be made accurately solely on the basis of intensitive, rather than spatial, distinctions, leading to the appearance of high acuity, underestimating the actual spatial resolution of the skin. More recently, alternative methodologies that circumvent these biases have been used to explore the acuity for touch stimuli (e.g., Gibson & Craig, 2002; Stevens & Cruz, 1996; Van Boven & Johnson, 1994a), but not on the abdomen. Finally, Weinstein's task demands were so unlike those that might be required in a communication system that further studies of the type described here were warranted.

In our previous work, we evaluated localization for vibrotactile stimuli at a number of sites on the arm and confirmed the notion from the literature that, like touch, such stimuli are located best when they are presented near anatomical points of reference (Cholewiak & Collins, 2003). Such anchor or reference points were described by Weber (1826/1978) and others (see Boring, 1942) as being related to the joints of the body. Although there has not been a systematic exploration of this relationship, our work with bursts of vibration showed that, indeed, they were localized best near the wrist, elbow, and shoulder of the arm, regardless of the actual physical separation among tactor sites. Furthermore, we found that the vibrotactile detection sensitivity of the forearm for 100- and 250-Hz stimulation over this extent was unrelated to location, despite claims in the literature (e.g., Békésy, 1960, p. 566).

In the present study, we were interested primarily in extending these findings in order to identify the limits of vibrotactile localization at sites around the circumference of the abdomen near the level of the waist (specifically, a belt 2.5 cm above the navel or higher). The rationale for proposing this site over others, such as the fingers or arms, that have been tested and used for communication systems was that the potential clients for such orientation or mobility displays (visually disabled persons, aircraft pilots, or underwater divers) require mobile limbs and free hands for their normal control activities, so the fingers, hands, and arms are poor candidate sites. Furthermore, the location of the body in three-dimensional space is often referenced to the orientation and location of the relatively stable trunk of the body, rather than to the mobile limbs (e.g., Karnath, Schenkel, & Fischer, 1991), where perceived pattern orientation is a function of the physical position of the limb in space. In this study, we sought to identify how many sites can be accurately localized around the body. Because one common method of referencing space around the body uses the 12 hours of the clock, we started with that number, in an attempt to take best advantage of the area of skin available on a belt. By testing absolute localization (a task that would be useful to indicate the presence and location of a comrade, an object, or an intruder into one's space) and performing an analysis of information transmission, we expected to be able to determine the optimal number of sites that could be used in a tactile communication system. If fewer than 12 sites could be identified reliably, the prediction from the information analysis would be verified by testing arrays with reduced numbers of tactors. However, the characteristics of the body underlying the skin vary greatly as one moves around the abdomen from the area of the navel, over the gut, and around to the muscles of the lower back to the spine. Consequently, we felt it important first to measure vibrotactile thresholds for the detection of several frequencies of vibration at a number of sites over this region, in order to determine whether existing local features might influence detection sensitivity and the subsequent tests of localization.

Preliminary Studies of Vibrotactile Threshold Around the Abdomen

Method

Four individuals (3 females and 1 male) were tested who were either students or employees of Princeton University, covering an age range of 22–28 years. The treatment of these subjects, as well as of the individuals in all of the experiments to be described, was reviewed and approved by the Princeton University Institutional Review Panel, in accordance with the ethical standards of the APA. Detection threshold was tested on six sites, located equidistant around the abdomen, at a level 25 mm above the navel. The loci included the spine, the navel, and two additional loci on both sides of the abdomen. Detection thresholds were measured at each locus with a two-alternative forced-choice adaptive tracking procedure. The subjects were presented with two 500-msec presentation intervals, 1 sec apart, indicated both on a visual display and with acoustic cues. During one of the intervals, a burst of vibration was presented, and the observer was required to respond on a two-button keyboard to indicate which interval contained the stimulus. If the quiet interval was responded to, the intensity on the next trial was increased by 1 dB. If the active interval was correctly identified 3 trials in a row, the intensity on the following trial was reduced by 1 dB (1-up 3-down rule). Convergence on the psychometric function following this method occurred at approximately 79% correct (Levitt, 1971). Each session consisted of six blocks of trials (one at each frequency) on each body site. Each observer was tested twice on each of the six locations and was required to track the changing intensity of the signal until 12 reversals or a maximum of 90 trials were completed. All the observers met the 12-reversal criterion within the 90-trial limit.

The observers wore headphones to attenuate potentially distracting ambient sounds. They were asked to lie on a supportive but firm surface, rotating the body so that the specific site to be tested for that session was uppermost and exposed for testing. The temperature of the skin at the test site was measured and maintained within the range of 31º–35ºC. One site was tested in each of six sessions, with the order of sites counterbalanced over observers. The stimuli were presented with a counterweighted Bruel & Kjaer 4810 minishaker with an integral 40-mm-diameter surround. The contactor was 7 mm in diameter, protruding 0.5 mm through a 9-mm hole in the surround, and the signal/noise ratio between the surround and the moving element of the shaker was greater than 40 dB in free air. The contactor itself was a PCB Electronics accelerometer that allowed for measurement of threshold displacement while the system was under load on each test site. The system rested on the body with approximately 50 g of force. The stimuli consisted of 500-msec bursts of sinusoidal vibration that were gated and shaped with an electronic switch so as to have 25-msec Gaussian rise–fall times, intended to minimize transients that might spuriously activate high-frequency–sensitive cutaneous receptors. The sinusoidal stimuli were presented at 25, 50, 80, 160, 250, and 320 Hz. Threshold at each frequency was calculated as the average stimulus intensity over the last seven reversals. Threshold acceleration was measured in situ with the contactor/accelerometer vibrating at the stimulus intensity set to the average level measured from the tracking data and the displacement amplitude calculated from the acceleration.

Results

Detection thresholds are shown in Figure 1 for all six sites over the six tested frequencies. Note that threshold appears to vary little as a function of body site over the six stimulus frequencies. Because, to our knowledge, the receptor populations in this area of hairy skin had not been examined in the literature, we were unsure of what to expect regarding the overall shapes of the functions. However, the pattern of results is not unlike those described by Bolanowski et al. (1994) on the hairy skin of the forearm, suggesting that a similar range of receptor types underlies vibrotactile sensitivity on the abdomen. Figure 2 illustrates the spatial distribution of sensitivity. These data and those from the experiments to follow are plotted in a manner isometric to a section through the abdomen, so the distribution of data points around the circumference of the graph represents the distribution of stimulus sites around the abdomen. As is shown in Figure 2, the results illustrate the variation in sensitivity over the sites tested, with points having greater detection sensitivity plotted closer to the center of the circle. There is a suggestion that the spine and the navel were the least sensitive loci for the lowest frequencies, and the back seemed a bit less sensitive to the higher frequencies. None of these differences, however, was statistically significant. These results are particularly surprising if one considers the wide variation in tissue types found below the surface. Tendon, gut, muscle, and bone are all represented under the tested sites, yet thresholds are remarkably consistent over these. The results suggest that we are likely appealing to sensitivity of the skin alone and that the underlying structures have a negligible effect on detection thresholds. Nevertheless, because some variation in sensitivity does exist over these sites, the procedure for the series of experiments to be described next, in which vibrotactile localization over this region of the abdomen will be explored, took this into account. Intensity was varied over trials (and sites) so as to ensure that sensation magnitude would not serve as a cue to localization. All of the following experiments were conducted at the Naval Aerospace Medical Research Laboratories (NAMRL) in Pensacola, FL. All the subjects in this experiment and in those to follow completed consent forms approved by the Institutional Review Board of the Naval Aerospace Medical Research Laboratory as directed by the Bureau of Medicine (BUMED) of the Navy.

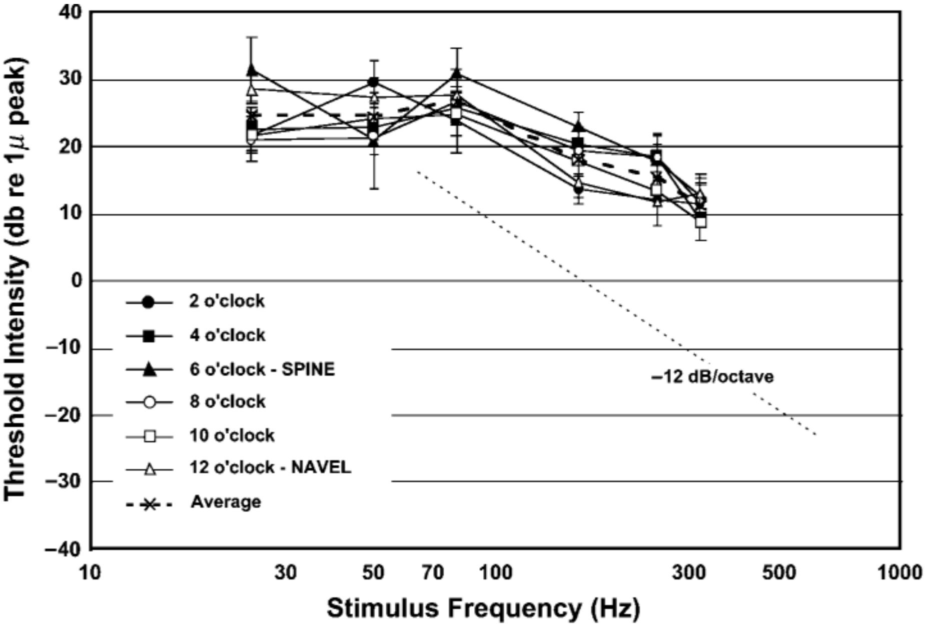

Figure 1. Vibrotactile detection thresholds, in decibels, relative to 1 μ of peak displacement as a function of stimulus frequency, measured at six sites around the abdomen at a level 25 mm above the navel. For reference, a line representing a slope of −12 dB/octave is also shown, representing the slope of high-frequency vibrotactile sensitivity functions on glabrous skin. The mean is also shown with standard errors about the data points.

EXPERIMENT 1
Vibrotactile Localization at 12 Sites Around the Abdomen

The question of resolution for vibrotactile stimuli on the abdomen not only is an issue when basic questions regarding spatial acuity are addressed, but also applies directly to systems being developed around the world for spatial orientation and awareness in situations in which the information from typical sources, such as vision or the vestibular senses, is obscured or misleading. A common application being tested with arrays of tactile stimulators involves an attempt to represent the location of an object in the environment as a stimulus on the surface of the body, with the user in the center of the field. A military aircraft pilot could use such a display to indicate the direction of approach of an enemy plane, whereas a pedestrian who is blind could use a simpler version tied to optical or GPS sensors to aid in navigation. Because the hour markers on a clock face are often used to indicate direction, it was hoped that the system would be able to display 12 readily localized sites. The first question, therefore, was to determine the optimal manner in which to present 12 equidistant loci on a belt circling the abdomen so that observers would be able to best localize each of them.

General Procedures

We considered a number of methods that would allow the subject to indicate the location of the body that was stimulated. Pointing would invariably involve different frames of reference as one or the other side of the body was stimulated, and much of the back would be inaccessible. Finally, because our intention was eventually to test a three-dimensional tactile array involving as many as five rows (belts) of 12 tactors on the abdomen, responding on a flat-panel screen would have required undesirable visuomotor transformations, particularly as the additional belts at various levels on the abdomen were added. Consequently, an isomorphic three-dimensional keyboard was created as the response device: a cylindrical keyboard that was easily manipulated by our subjects and read by the computer, allowing accurate measurement of response time, and that represented the three-dimensional surface of the abdomen. This device is shown in Figure 3. The keyboard was oriented so that the key farthest away was designated as *12 o'clock* and represented the location at the navel, whereas the key closest to them was called *6 o'clock* and represented the location at the spine. Similarly, the rightmost key was labeled *3 o'clock* and the leftmost *9 o'clock*, with the remaining keys arrayed among these. The keys at these four positions also had tactile cues (bumps on the surface) to aid orientation of the hands and fingers. Finally, anatomical cues (ears and a nose) were added to the keyboard to help prevent mapping errors. The resulting configuration allowed the observers to operate the keyboard from an "over the shoulder" perspective, allowing them to isomorphically map their bodies onto it. In all cases, the observers were encouraged to respond as quickly and accurately as possible. Although response times were monitored during these experiments, the usual controls for measuring reaction time, such as requiring a fixed starting position, were not imposed on the subjects. Initial testing with 10 naive individuals (9 males and 1 female) demonstrated that the observers were very accurate in responding to visual prompts (the numbers 1–12) with this device: Performance ranged from 96.4% to 99.6% correct, with no discernable pattern of variation around the keyboard.

In the first tactile localization experiment, we used a wearable array constructed of an elastic Velcro belt worn around the waist, on which

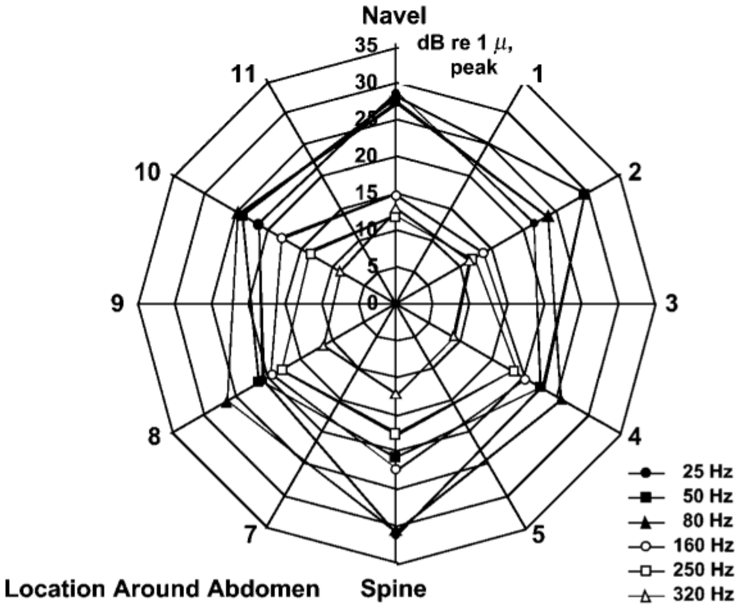

Figure 2. Vibrotactile detection thresholds, in decibels, relative to 1 μ of peak displacement for six stimulus frequencies, measured at six sites around the abdomen at a level 25 mm above the navel. The data were plotted on polar coordinates to illustrate the spatial distribution, with the numbers representing 12 locations circling the abdomen. Site 12 is located at the navel, whereas Site 6 is located at the spine. These data are identical to those in Figure 1, except for the graphic representation.

either one of two types of vibrators was mounted: pneumatic tactors (P2) that pulsed at 40 pps and electromechanical devices (C2) that had a resonant frequency at about 250 Hz. The nonmetallic pneumatic tactors were manufactured by Steadfast Technologies (Des Moines, IA). They were c. 8 mm deep and 20 mm in diameter and consisted of an air chamber closed by an elastic membrane that was placed against the skin. Pulsed air alternatively filled and exhausted the chamber, producing the mechanical stimulus by expansion and

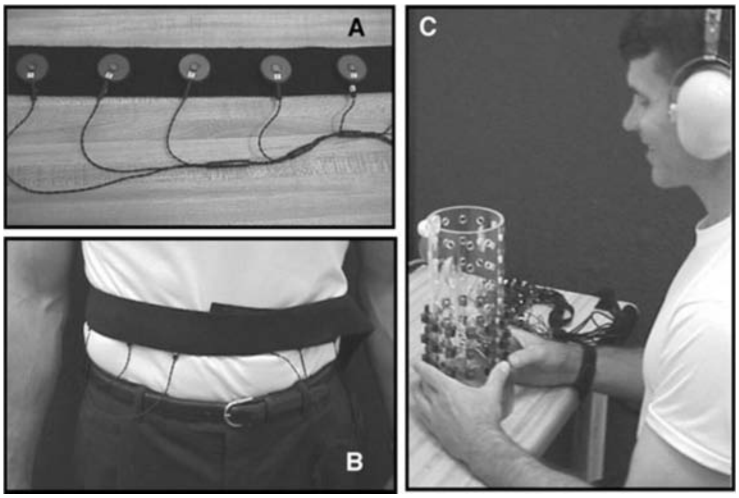

Figure 3. (A) Five electromechanical tactors are shown on the Velcro belt used in Experiments 1–4. (B) Tactor spacing was calculated to place them at sites equidistant around the circumference of the observer. (C) A cylindrical keyboard, isomorphic with the belt of tactors, was used as the response device. Twelve columns of keys were mounted around the circumference of the cylinder. (Three rows of keys are shown, although the upper two rows were covered during testing.)

contraction of the membrane. The pulse rate and stimulus amplitude were constrained by a complex combination of the characteristics of the pneumatic tubing, the strength of the air pump, the size of the tactor's air chamber, the elasticity of the contactor's membrane, and its interaction with the stiffness of the skin, among other factors. Consequently, a definition of the stimulus waveform was not readily accomplished.

The second half of this experiment and all of the remaining experiments were conducted with commercially available electromagnetic tactors that had been shown to provide stimuli of strength sufficient for even insensitive body sites. These tactors, Model C2, manufactured by Engineering Acoustics, Inc. (Winter Park, FL), are of sufficient mass (17 g) to ensure proper driving of the skin with perpendicular movement of the contactor, yet are small enough (30-mm diameter, 8 mm deep) to provide for the array densities we intended to study. The diameter of the moving element is 7 mm, centered in a 9-mm hole in the top surface of the tactor so as to provide a stationary surround with a 1-mm gap (see Gescheider, Capraro, Frisina, Hamer, & Verrillo, 1978). The tip of the contactor protrudes 0.5 mm above the surface of the surround to ensure firm contact with the skin (e.g., Verrillo, 1966, Figure 4). These can faithfully reproduce a large range of vibrotactile stimulus frequencies and were driven with 250-Hz sinusoidal waveforms in these experiments. The tactor design has an open back exposing the moving element, allowing us to monitor displacement amplitude and waveform of the stimulus while the tactor is loaded by the skin, using a rear-mounted miniature accelerometer (PCB Piezotronics, Buffalo, NY). The frequency responses of the tactors were measured so that the set could be matched as closely as possible. The stimuli were generated by an IEEE-488 computer-controlled Wavetek function generator that allowed us to vary intensity and frequency, as desired, on a trial-by-trial basis. Stimulus amplitude was controlled over a 60-dB range, using the IEEE-488 interface. The interface could activate any number of tactors for any duration, with independent control of stimulus locus, frequency, and intensity. Because of the variation in vibrotactile sensitivity around the body revealed in the preliminary studies of detection threshold described above, the possibility existed that the observers could identify loci solely on the basis of intensive cues. In order to minimize the influence of sensation magnitude on the localization judgments, stimulus intensity for the C2 electromechanical tactors was randomly varied on a trial-by-trial basis in 1-dB steps over a 7-dB range (baseline, ±3 dB), dissociating perceived intensity from stimulus locus. The stimulus signal was finally passed to an audio amplifier and then gated through a bank of relay switches to select and drive the vibrator sites for stimulation. This combination of tactors and drivers was able to generate carefully controlled and monitored stimuli.

At the beginning of the first of their four sessions of participation, each individual read and signed an informed consent and completed a personal information/medical questionnaire. This form was intended to document any conditions that might affect performance, such as unusual tactile sensitivity on the abdomen (e.g., a history of herpes zoster), as well as to obtain information on other individual characteristics, such as handedness. The subjects also took a paper-and-pencil test of visual spatial ability, the Mental Rotations Test (MRT; Vandenberg & Kuse, 1978). The MRT was used here because this measure has been shown to be related to body size (U. Tan, Okuyan, Bayraktar, & Akgun, 2003) and either the MRT or tests like it are used in flight officer selection batteries at NAMRL and elsewhere (e.g., Skinner & Ree, 1987). Following these preliminaries, they were then fitted with the tactile array to be used for that session. There were two locations for the tactor belt; one was around the waist, over the hips, at a level 25 mm above the navel, whereas the second was about 10 cm higher, over the lower margin of the rib cage. The rationale for using these two levels was to provide a further test to determine whether the characteristics of underlying tissue would affect localization of the vibrotactile stimuli on the skin's surface. The circumference of the waist was measured at these two levels on each subject, as well as the major axes (side to side and front to back), to account for the elliptical shape of the torso at each level. The measurements were transferred for reference to a plain white, 100% cotton medium-weight T-shirt that was provided to each person to wear throughout the experiment. Note that most of our subjects did not have a ratio of these axes equal to 1 (rather, in Experiment 1, for example, the ratios averaged about 1.35 and 1.32 for the high and the low levels, respectively). The tactors were attached to an elastic Velcro belt at locations equidistant around the body, as calculated from the circumferential measures, and were placed on the observer, who was wearing the shirt. Consequently, the tactors were not placed at equal angular separations with respect to the geometrical center of the body (as in the first experiment in Van Erp, 2000). In this respect, the circular presentation of the data in the figures does not accurately represent the geometry of the situation. The force applied by each of the tactors was approximately 50 g, as measured with a calibrated pressure transducer (developed by Thomas Allen, the biomedical engineer at NAMRL) that had the same dimensions as the C2 tactors.

The electromechanical tactor belt, the test arrangement, and an observer responding on the keyboard are illustrated in Figure 3. During testing, all the observers wore headphones to attenuate potentially distracting ambient sounds and to mask any acoustic cues that might be related to the activation of specific tactors that could provide nontactile cues to location. In both the C2 electromechanical system and the P2 pneumatic test series, baseline intensity for the set of tactors was set to a comfortable level estimated to be approximately 14 dB SL. Although vibrotactile intensity was varied about the baseline on a trial-by-trial basis with the C2 system, owing to equipment limitations, the P2 stimulus intensity was fixed for the session. On a given trial, the subjects received a single 200-msec burst of vibration on one of the 12 tactors in the belt. A constrained random order determined the tactor site, so that each was presented an equal number of times in the five 60-trial blocks in each of the four test sessions. Each of the 12 stimulus locations was thus presented 25 times in a session. The subjects were required to press the button on the cylindrical keyboard corresponding to the perceived location of the stimulus on the body. Feedback was provided on each trial in the form of an acoustic cue (a high-pitched tone for a correct response) and visually with the number of the correct tactor presented on a fluorescent desktop display. The four combinations of tactor types and belt locations on the abdomen were counterbalanced among the participants over sessions in order to control for the potential effects of experience. Twelve young (average age of 23 years) military individuals recruited from the local NAMRL training commands were tested. The 1 female and 11 males who served in this specific experiment were all naive with respect to psychophysical testing.

Results and Discussion

The results of this experiment are shown in Figure 4. A repeated measures analysis of variance indicated that there were no main effects of electromechanical versus pneumatic tactor types [$F(1,11) = 0.472, p = .51$] or upper versus lower belt location on the abdomen [$F(1,11) = 0.0, p = 1.0$], in which case the means were identical. Remarkable differences, however, existed in localization accuracy over the 12 stimulus sites [$F(11,121) = 15.822, p < .01$]. Note, in particular, that performance was a function of proximity to the spine and navel (6 o'clock and 12 o'clock, respectively), where the ability to identify the locus of stimulation was virtually perfect, and sites adjacent to these were localized better than those at

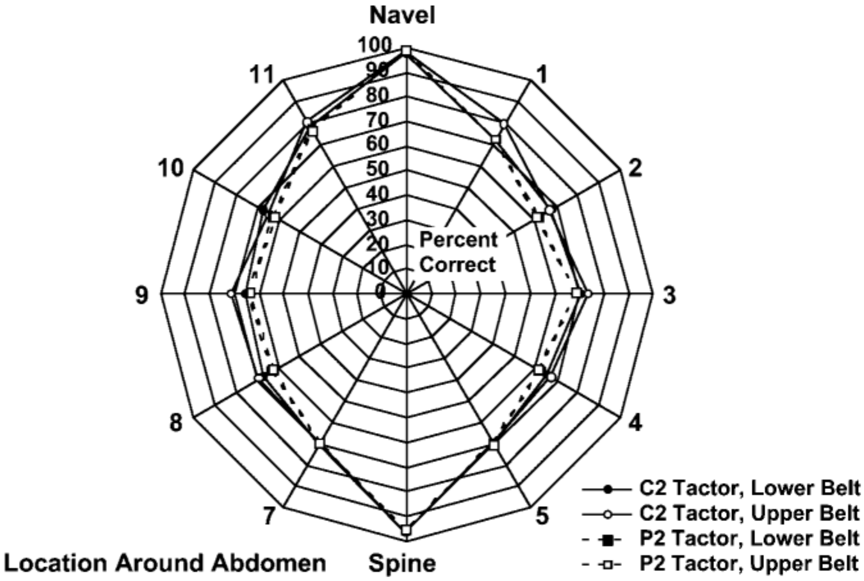

Figure 4. Localization performance (in percent correct, shown on the radius of the graph) for bursts of vibrotactile stimuli presented to 12 sites around the abdomen (represented by the 12 radii around the graph). Data from four conditions are shown, representing combinations of two tactor types (C2 electromechanical tactors and P2 pneumatic tactors) and two belt levels (lower and upper).

the sides. Although they used different response measures than we did, Van Erp and Werkhoven (1999) indicated that a form of spatial acuity for an array of 11 vibrotactile stimuli across the upper or the lower back had thresholds that were lower in the middle of the array than at the sides. Similarly, Van Erp (2000) found that pointing errors were smallest for vibrotactile stimuli presented at the navel, increasing to the sides. It appears from both their studies and ours that the spine (6 o'clock) and the navel (12 o'clock) can serve as anatomical reference points. In our case, if a stimulus was presented to the front or the back of the body, the observers apparently were quite sure whether or not it occurred at either of these particular sites, as reflected in the high levels of localization accuracy at these loci. Consequently, they could readily exclude these sites as possible alternatives when stimuli occurred at nearby loci (5 or 7 o'clock or 11 or 1 o'clock, respectively). Support for this notion comes from an analysis of the errors that were made at each of the 12 sites. The confusion matrix that describes the responses to each stimulus indicates interesting response biases that are similar from front to back, as well as from side to side on the abdomen. Specifically, the majority of erroneous responses to a Site 1 stimulus were "2," and those to a Site 2 stimulus were "3." This pattern of errors was identical, in direction, to stimuli at Sites 11

Table 1
Stimulus/Response Localization Confusion Matrix from Experiment 1, Condition C2L, $N = 12$

Stimulus Site	Response (O'Clock, in Percentages)											
(O'Clock)	"1"	"2"	"3"	"4"	"5"	"6"	"7"	"8"	"9"	"10"	"11"	"12"
1	70.67	29.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	7.33	64.00	22.33	6.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.67	11.33	**71.33**	15.00	1.33	0.00	0.00	0.33	0.00	0.00	0.00	0.00
4	0.00	2.00	20.67	66.00	11.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.33	25.00	73.33	1.00	0.00	0.33	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	**98.00**	2.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	1.33	73.67	24.00	1.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	10.67	61.67	27.33	0.33	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	2.00	17.33	**67.00**	12.67	1.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	1.33	8.67	17.33	63.33	9.33	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.00	0.33	25.67	73.00	0.33
12	2.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	**96.33**

Note—Correct responses are in the cells on the diagonal axis of the array; the cardinal points around the circumference of the abdomen are shown by boldface entries in the array.

and 10, respectively, as well as 5- and 4-o'clock and 7- and 8-o'clock stimuli. At the remaining sites (3, 6, 9, and 12 o'clock), errors were symmetrically distributed to either side of the target. These data are shown in Table 1. Our interpretation, repeated from above, is that it is unlikely that stimuli close to anchor points will be mistaken for those points, even when errors are made.

Performance at the navel/spine reference points contrasts dramatically with the poorer performance at the remaining sites. In particular, it was expected that the left- and rightmost sites (9 and 3 o'clock, respectively) would be better localized owing to the "natural" references provided by the proximity to the arms. In addition, note the bilateral symmetry in the pattern of performance from the left to the right and from front to back. The latter finding in particular, that there is no difference between the front and the back of the body, combined with the findings from the analysis of belt height, above, argues that underlying tissue type plays a minor role in vibrotactile spatial localization. Specifically, when the lower belt was used, Loci 1, 2, 10, and 11 fell over the tissue of the belly, whereas they were over the ribs when in the upper belt position. Their counterparts on the back typically were located over muscular tissue. Nevertheless, the symmetry in performance over these sites belied the anatomical differences. Finally, we performed analyses of static information transfer, calculated from the stimulus/response confusion matrixes (Senders, 1958.) In this context, the amount of *information* is directly related to the range of possible alternatives available to the observer. However, because the observer might not be able to appreciate all of the possible alternatives, the information *transmitted* (sometimes called *uncertainty reduction*) can be less than that originally present in the stimulus array. Miller (1956) noted that *information transmitted* describes the correlation between the amount of information in the stimuli and the amount in the observer's responses. The amount of information is measured in terms of *bits*, calculated as the logarithm (to the base 2) of the number of alternatives. In Experiment 1, with 12 alternatives, there were potentially 3.58 bits of information available in the stimulus array. The analysis resulted in an average over the four conditions of 2.66 bits of information transferred out of the possible 3.58 bits. This value corresponds to just over six tokens (6.33), suggesting that an array that is half as dense might result in nearly perfect localization performance, which would be the goal of a tactile display system intended to be used for accurate targeting of dangerous objects in the environment, such as approaching enemy vehicles. Typically such absolute judgments of nonvisual unidimensional stimuli asymptote near a level of some 2.5 bits (about six likely alternatives), defining the *channel capacity* of the observer for absolute judgments of the stimulus dimension being tested (Miller, 1956). Even when multidimensional displays are tested, this rate is rarely exceeded (e.g., Rabinowitz, Houtsma, Durlach, & Delhorne, 1987; Sherrick, 1985; H. Z. Tan, Durlach, Reed, & Rabinowitz, 1999).

The relationships between the anthropometric measures taken on each of the subjects and their overall localization performance were also examined in order to evaluate the potential relationship between tactor separation and accuracy, realizing that our sample included only 12 subjects, so the analyses will necessarily be tentative. Recall that the tactors were placed at loci equidistant around the abdomen, so the smaller the circumference of the trunk, the closer the tactor spacing. In fact, the range of circumferences over our observer population was only 77–98 cm (representing tactor separations of 6.4–8.2 cm), with a mean of 86 cm. Over this small range, correlation coefficients between the measures of girth and localization accuracy for the four belt conditions averaged .183, well below the level necessary for statistical significance. There are a number of factors that can contribute to girth, so distance alone may not be sufficient to account for differences, although this factor will be explored in more detail below. Similarly, the relationships between localization performance and MRT test performance and handedness averaged .121 and .408, respectively, neither being at statistically significant levels. Again, the small number of individuals in the sample limit the interpretation of these nonsignificant results.

The localization data in this experiment were collected for each combination of height and tactor type in only a single session consisting of 300 trials from the 12 observers. Perceptual learning, however, can take considerably longer. For example, it has been known for many years that tactile acuity for pairs of touches can show substantial improvement with continued training (Boring, 1942, p. 480). Although it has been reported that performance in a visual hyperacuity task can improve significantly over tens of trials (Sathian, 1998), in audition the course of perceptual learning can be lengthy, as Watson (1980) has described, with Morse code training taking 30 or more weeks of practice before reaching asymptote. Is it possible that some training might improve the ability to identify 12 vibrotactile sites around the abdomen? A follow-up experiment evaluated this possibility, using the same stimulus arrangement as that used in the first part of this experiment. Twelve additional observers were chosen to serve in this experiment, including 9 males and 3 females. Some of the members of this group were recruited from the laboratory staff because of the intensive nature of the testing schedule. These subjects were tested with the belt of 12 electromechanical tactors located at the lower abdominal position, as described above. The subjects served in 10 successive daily testing/training sessions (excluding a weekend) that were identical to those in Experiment 1, including trial-by-trial feedback. As is shown in Figure 5, when overall performance was plotted as a function of session, localization performance did improve [$F(9,11) = 21.250$, $p < .01$], but apparently at the rate of less than 2% per ses-

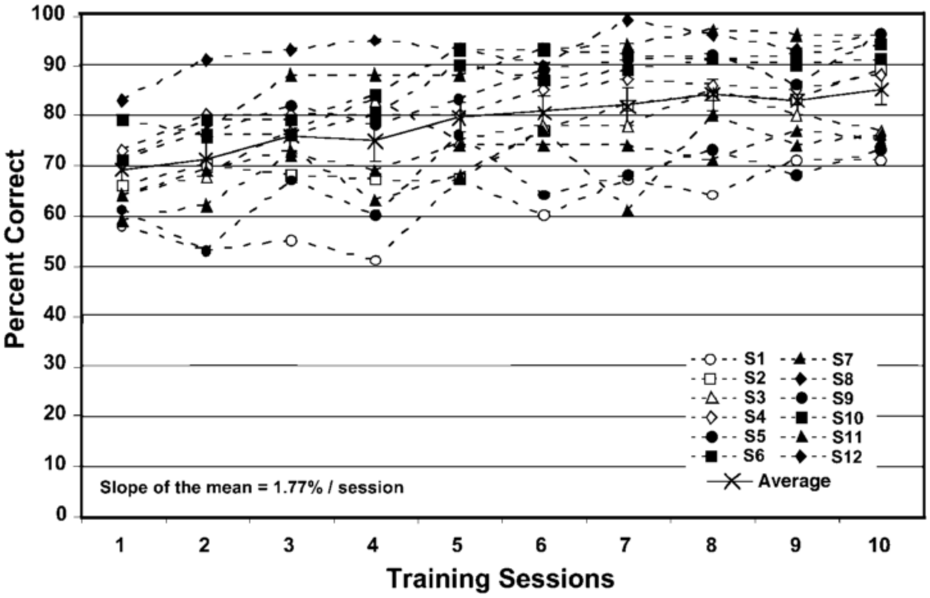

Figure 5. Overall localization performance for the C2 tactor belt in the lower position (C2L) shown in Figure 4, as a function of number of training sessions for 12 subjects. The solid line connects the mean performance for each session. The standard deviations about those points are also shown.

sion of 300 trials. There were no significant differences in the rate of improvement among the 12 sites. Although many of Watson's examples indicated that asymptote was reached within 300 trials for auditory perceptual learning tasks, a number of our observers were still improving by the end of this series of 3,000 trials. The averages shown in Figure 5, however, should be regarded with the caveat that often accompanies attempts to summarize perceptual learning over a group of individuals: Owing to the fact that some persons achieved asymptote and other did not and those who achieved asymptote reached it at different points in the training series, the average alone does not represent the variety of possible response patterns. Furthermore, the average acquisition rate of less than 2% is likely an underestimate, particularly later in training, when some of the individuals were no longer improving. There is no clear explanation of the sources of these considerable differences in rates of acquisition or in the final performance levels among the members of this sample.

In summary, these data argue that localization of vibrotactile stimuli presented to sites in an array of 12 tactors around the waist is immune to large variations in stimulus waveform, tactor type, height of array on the waist, and, apparently, type of tissue underlying the site of stimulation, whereas there is some small improvement with experience. The one factor documented here that does influence localization is the place on the body that was stimulated, but proximity of the tactors to one another is likely the ultimate limiting factor in localization accuracy.

EXPERIMENT 2

Vibrotactile Localization at Eight or Six Sites Around the Abdomen

What would happen, then, if we were to increase the physical separation among the tactors? In the next experiment, we examined the effects of increasing separation. By reducing the number of active loci to only eight or even six, average separation on the trunk of the body will increase greatly. To see how these distances might relate to the classically reported measures, we compared Weinstein's (1968) touch threshold data against our vibrotactile measures. For simple touch, Weinstein's point localization thresholds from the belly and back predict that sites would have to be separated by at least 10 mm to be accurately located, whereas his two-point discrimination data argue that touched sites would have to be separated by at least 39 mm in order to be able to be resolved. On the other hand, in Experiment 1 when 12 tactors were separated by 64–82 mm, depending on the person, localization of vibrotactile stimuli averaged c. 74%, a considerably greater distance.[1] Consequently, although alternative methodologies could certainly affect these values, the assumption can be reached that vibrotactile signals produced stimuli that were much more difficult to localize than the simple taps tested by Weinstein and his predecessors.

From the analysis of information transfer in the data from Experiment 1, recall that the results implied that only 6 tokens could be accurately appreciated out of the 12 available in the vibrotactile array. By testing eight- and six-tactor arrays, we would be able to determine whether, indeed, six is the limiting number of sites on the abdomen. In this experiment, the tactors were also evenly distributed around the circumference of the waist in the same manner that they were arrayed in Experiment 1. Because we did not find an effect of either tactor type (and stimulus frequency) or height of the tactor belt on the abdomen, we only used C2 electromechanical tactors at the lower belt location (the level just above the navel) in this experiment. An interesting opportunity presented itself with this arrangement, however. Because of the increase in tactor separation, it was now possible to position the tactor belt so that two of the members of the set fell on the navel and spine anchor points, described above, *or* the belt could be rotated slightly so that these two anatomical sites were spanned by the tactors. This manipulation provided the opportunity to examine the strength of the abdominal reference points described above, positing that once observers are able to define the anchors, they know where nearby sensations are *not* located.

Twelve new subjects (10 males and 2 females) were drawn from the same population of military students as that described above. They served in four test sessions in which they were required to identify the locations of tactors on belts consisting of either six or eight sites, either with two of those locations either at the navel and spine or with loci spanning the navel and the spine. The figures in which the data are presented will graphically represent the difference between these conditions on a polar, or "radar," plot, in the same manner as the earlier data were plotted. The order in which these four conditions were presented was counterbalanced across subjects and sessions. The general procedures from Experiment 1 were followed, with the exceptions that new cylindrical keyboards were constructed with reduced numbers of keys to be appropriate for this experiment and the number of trials in each session was adjusted to provide for presentation of an equal number of tokens within the five blocks of trials.

Results and Discussion

The results for the 6 or 8 tactor navel-and-spine conditions are shown in Figure 6, compared against those obtained with the 12-tactor condition in Experiment 1. By reducing the number of tactors, performance was found to be dramatically improved. The overall accuracy of localization, calculated from the data shown in the figure, was 74%, 92%, and 97% for 12, 8, and 6 tactors, respectively. Again, the superior localization at the navel and spine sites in the figure is obvious for all conditions, whereas the general improvement in localization performance with increasing separation occurs primarily because of the dramatic improvement of performance at the sites over the hips. When overall performance was compared between the 12- and the 8-tactor conditions at the four common sites, there was a significant main effect of condition [$F(1,22) = 5.586, p < .03$]. Similarly, when the data from the 6-tactor condition were compared against those for the same sites in Experiment 1, a significant difference was also found [$F(1,22) = 42.739, p < .01$]. There was a significant interaction between num-

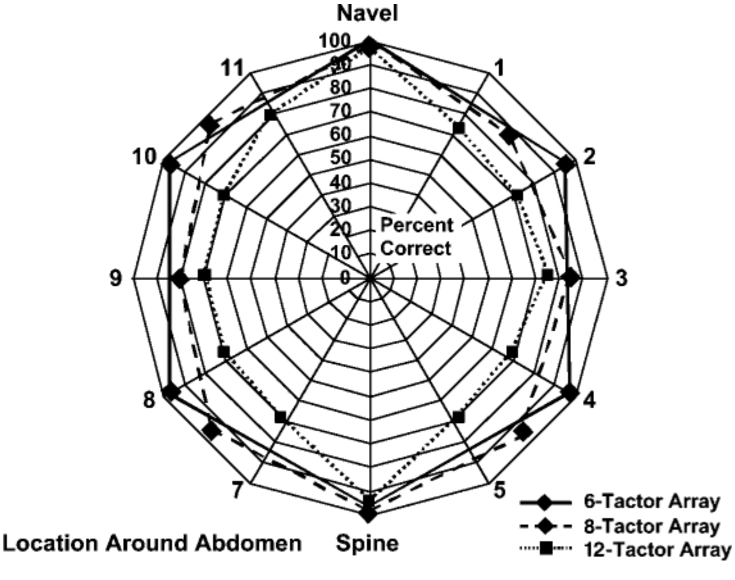

Figure 6. Localization performance (in percent correct, shown on the radius of the graph) for bursts of vibrotactile stimuli presented to sites around the abdomen (represented by the radii). Performance is shown for belts having three different numbers of electromechanical tactors: 6 (solid lines), 8 (dashed lines), and 12 (dotted lines). All the belts were positioned so that two tactors fell on the navel and the spine. Twelve-tactor data are reproduced from Figure 4. Standard errors (not shown) averaged 3%–5%.

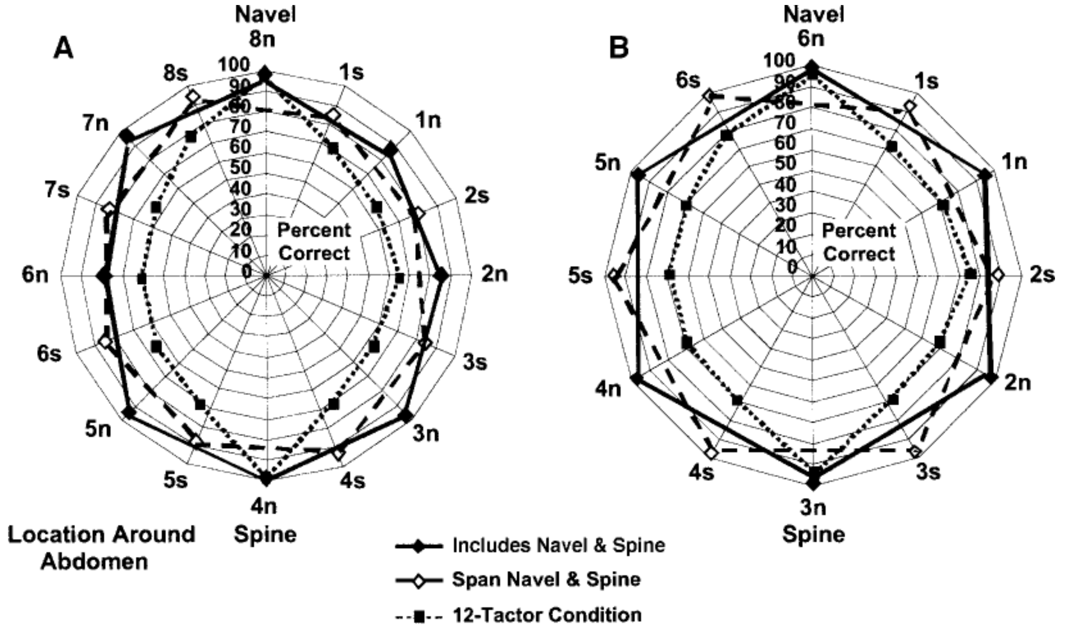

Figure 7. Localization performance (in percent correct, along the radius of the graphs) is shown for bursts of vibrotactile stimuli presented to sites around the abdomen (represented by the radii). Either 8 (A) or 6 (B) electromechanical tactors were mounted in the belt. The solid lines in each graph connect the performances for tactors when two tactors were placed on the spine and the navel (n); dashed lines connect the points for sites when the navel and the spine were spanned (s). The data represented by the dotted lines are from the 12-tactor C2L condition in Figure 4.

ber and tactor sites, resulting primarily from the improvement in performance at the nonreference sites [$F(1,5) = 13.965, p < .01$], likely because of the increased separation between adjacent tactors.

What happens if the spine and navel anchor points are not used in the tested array? In these conditions, the arrays were rotated slightly so that tactors fell on either side of these sites, spanning them. In both of these cases, performance was inferior to that in the nonrotated conditions. As is shown in Figure 7A, when the eight sites to be localized were positioned so as to stimulate the reference sites (Condition 8n), correct localization reached 92%, whereas performance dropped to 87% when the reference sites were spanned (Condition 8s). In this case, the effect of belt rotation did not reach significance [$F(1,11) = 4.778, p = .051$], although the main effect of tactor location was still highly significant [$F(7,77) = 7.535, p < .01$], primarily because of the superiority of the sites closest to the body midline. Even when only six sites were tested, as in Figure 7B, the two conditions differed in the same direction, although only slightly because of the strong ceiling effect: 97% correct localization was observed when the sites included the spine and navel, 95% when these sites were spanned. In the case of the 6s versus the 6n conditions, however, neither belt rotation [$F(1,11) = 2.416, p = .15$] nor tactor location on the abdomen [$F(5,55) = 3.123, p = .06$] was found to be statistically significant, indicating that the differential influence of the anchor points has been overcome by the overall improvement in performance at all of the six sites.

Finally, an analysis of static information transfer indicated that even in the optimal condition, in which the anchor points were included, only 2.46 bits of information were transmitted, representing 5.50 tokens—fewer than predicted by the 12-tactor data. These data are shown in Table 2 and, graphically, in Figure 8. In the case of eight tested loci with anchor points, there was a large difference between the two belt rotations with regard to the information that was transmitted: When the anchor points were not included but, rather, were spanned, 2.49 bits, or 5.68 tokens, were transmitted. These numbers rose to 2.65 bits, or 6.33 tokens, when the anchor points were included. Notably, this is exactly the level that was predicted in Experiment 1 from the analysis of 12 tactors. Consequently, although reducing the number of sites did not result in a meaningful improvement in the amount of transmitted information, overall accuracy for these fewer items did improve.

These data argue well that increasing the separation between vibrotactile sites improves the ability to localize brief bursts of vibration and that the anchor points observed in Experiment 1 continue to influence overall performance even with a more diffuse array. There is an alternative explanation for this improved performance, however. In addition to increasing the separation, the

Table 2
Summary Statistics for All Conditions

Measure	6-Stim N&S	6-Span N&S	7-Across Front	7-Around Back	7-Right Side	7-Left Side	8-Stim N&S	8-Span N&S	12-P2U Tactors	12-P2L Tactors	12-C2U Tactors	12-C2L Tactors	12-Kbd Test
Number of tactors	6	6	7	7	7	7	8	8	12	12	12	12	12
Percent correct	97.58	95.00	85.16	82.94	77.52	77.12	91.50	86.63	73.81	74.14	73.53	73.19	98.53
Bits of information	2.46	2.37	2.22	2.18	2.10	2.04	2.65	2.49	2.69	2.71	2.70	2.71	3.50
Number of tokens	5.50	5.23	4.69	4.57	4.32	4.15	6.33	5.68	6.51	6.58	6.54	6.62	11.31
Response time (sec)	0.739	0.773	0.742	0.779	1.163	1.190	0.815	0.958	1.019	1.036	0.870	0.912	1.042
Bits per second	3.328	3.074	2.996	2.793	1.806	1.714	3.250	2.600	2.636	2.613	3.100	2.973	3.357
Information loss	0.127	0.210	0.584	0.632	0.707	0.767	0.350	2.185	2.471	2.517	2.109	2.227	3.369
Token loss	0.499	0.774	2.312	2.430	2.680	2.850	1.670	2.320	5.486	5.423	5.463	5.380	0.691
Proportional token loss	8.32	12.89	33.03	34.71	38.29	40.71	20.88	29.00	45.72	45.19	45.52	44.83	5.76
						Standard Deviations							
Percent correct	1.56	6.21	3.76	7.04	7.36	6.52	4.60	7.91	9.22	6.97	8.92	8.24	1.04
Bits of information	0.08	0.21	0.13	0.22	0.21	0.18	0.16	0.24	0.23	0.20	0.20	0.22	0.06
Number of tokens	0.29	0.73	0.42	0.74	0.68	0.48	0.69	0.88	1.02	0.96	0.91	1.09	0.44
Reaction time (sec)	0.142	0.122	0.248	0.192	0.285	0.232	0.126	0.240	0.182	0.271	0.297	0.274	0.237

Note—P2U, pneumatic tactor, upper belt; P2L, pneumatic tactor, lower belt; C2L, electromechanical tactor lower; C2U, electromechanical tactor upper; N&S, navel & spine.

number of loci that the observer was required to attend to was also reduced. It is possible that the cognitive load resulting from having to focus on 12 potential stimulus sites made it more difficult to localize these with any degree of accuracy. In the next experiment, we reduced the number of active sites to 7 but retained the same formula for calculating physical separation as that in the 12-tactor belt.

EXPERIMENT 3
Vibrotactile Localization at Seven Sites in a Semicircle Around the Abdomen

Several numbers of sites could have been tested in order to reduce number but retain the same separation as that in Experiment 1, but seven were chosen in order to allow the possibility of reconciling several issues. First of all, this number falls between those already tested with the 360° circular arrays. Second, testing a small dense array with seven tactors covering half of the body's circumference allows us to examine the influence of both of the previously defined anchor points. Finally, the use of this spatially limited array allows us to test the effect of endpoints on localization judgments. In the two experiments described so far, all of the arrays were circular, so every site had the same number of available response alternatives. In the case of a semicircular array of seven tactors spaced 30° apart, only 180°, or half of the circumference of the trunk, would be covered, meaning that the endpoints in the array could influence judgments. For example, the middle tactor (4) in a seven-tactor array could be responded to with responses 4, or 3, or 5 (or even 2 or 6). On the other hand, the number of response alternatives for Site 1 or 7 are fewer because they fall at the ends of the array. Consequently, the likelihood that performance will improve at the endpoints is greater, owing simply to the increased probability of a correct response. However, depending on the orientation of the array, the endpoint effect, if it exists, could be hidden by placing these loci at normally well-appreciated sites. Therefore, several placements of the array around the waist were explored.

The general procedures from Experiment 1 were used, with the following exceptions. First, again, a modified keyboard was constructed that had only seven keys arrayed at 30° increments around a semicircle of the array. Second, after the circumference of the waist was measured, only seven tactors were mounted on the belt covering half of the distance measured with equidistant spacing over that distance. Finally, the number of presentations was adjusted so that each of the five blocks consisted of 70 trials, or 10 randomly distributed repetitions of each locus. Two separate groups of 12 subjects were recruited from the same population as that described earlier. One group of 9 males and 3 females was tested over a pair of test regions that covered the front and the back of the body. In these cases, the array across the front was oriented so that Tactor 1 was at the left side, Tactor 4

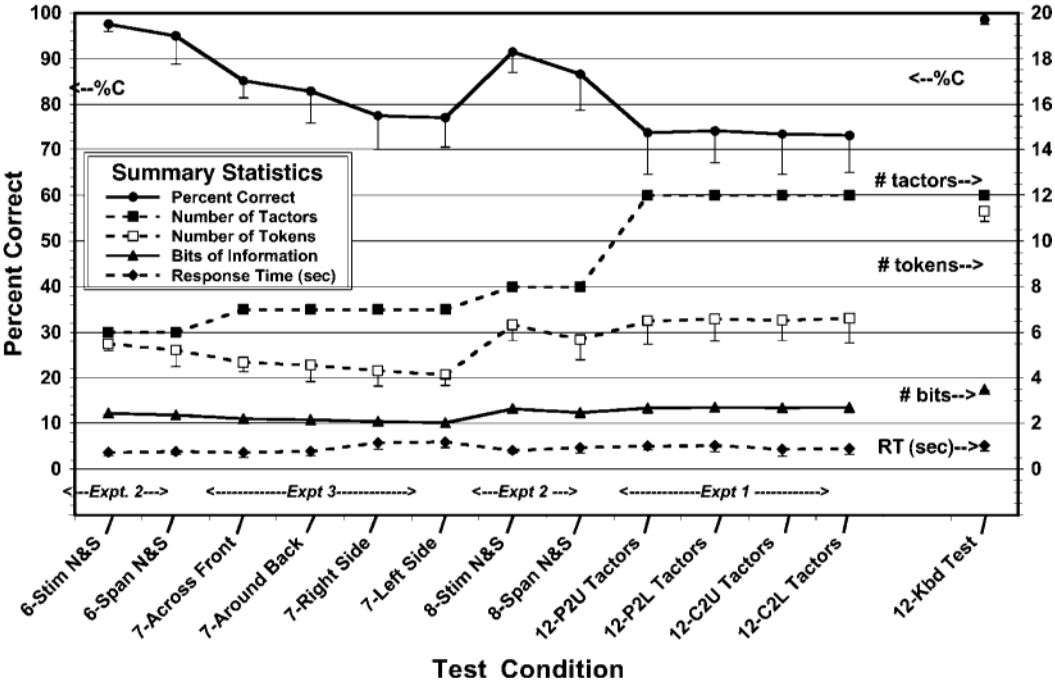

Figure 8. Summary statistics for the data from the three experiments. Note that the data in the upper curve (labeled "Percent Correct") are referred to the left ordinate, whereas the remaining functions are referred to the right ordinate. Standard deviations are shown about the data points.

at the navel, and Tactor 7 at the right. When the back was tested, the array was rotated clockwise, so that Site 1 was now at the right side of the body, 4 at the spine, and 7 at the left. The second group (of 12 males) was tested with two orientations as well: one over on the right side of the body, ranging from the navel to the spine, and the other over the left, extending from the spine around to the navel.

Results and Discussion

When the seven sites were arrayed either on the right or the left side of the body, starting at the navel and ending at the spine, the data in Figure 9A were obtained. The results from the two sides of the body, divided by the sagittal plane, were identical to one another [$F(1,10) = 0.060$, $p = .81$], although the effect of tactor location over the surface of the body was highly significant [$F(6,60) = 44.45$, $p < .01$]. Furthermore, there were no statistically significant differences in performance at any of the locations when the 7-tactor data from the left or right side of the body were compared against the same sites from the 12-tactor belt tested in Experiment 1 [left side, $F(1,6) = 0.093$, $p = .76$; right side, $F(1,6) = 0.019$, $p = .89$]. Finally, if the patterns of errors for these two conditions are analyzed, the same distribution is found as was described in the discussion of Experiment 1 and displayed in Table 1: Stimuli near the anchor points were rarely confused with those anchors, and errors were typically made to sites farther away. So, for these belt orientations, reducing the number of tactors alone does not improve the poor performance at sites other than the anchor/endpoints, and localization is a function of the same processes as those operating when 12 sites were to be identified. So far, separation, not number, appears to be the controlling factor in vibrotactile spatial localization.

If the semicircle was arrayed around the front or the back of the body, however, a somewhat different pattern of results emerges. In this case, the optimal sites for localization performance were still found to be the two previously defined reference sites, the spine and the navel, but performance for the remaining sites improved as well. These data are shown in Figure 9B. First of all, as with the right–left array orientations, the overall results from these two array positions, on either side of the coronal plane of the body, were identical [$F(1,10) = 1.569$, $p = .24$], and the main effect of tactor location was found to be highly significant [$F(6,60) = 8.642$, $p < .01$]. In this case, however, a highly significant interaction was also found [$F(6,60) = 6.579$, $p < .01$], owing primarily to the differences in performance between the two conditions at Sites 1 and 5, and at Site 3, as can be seen in the figure. In this case, performance at virtually all of the sites (except 6 o'clock and 12 o'clock) in the 7-tactor array was significantly improved over that for the 12-tactor array, unlike that for the left–right orientation of these belts. When the performance at the seven

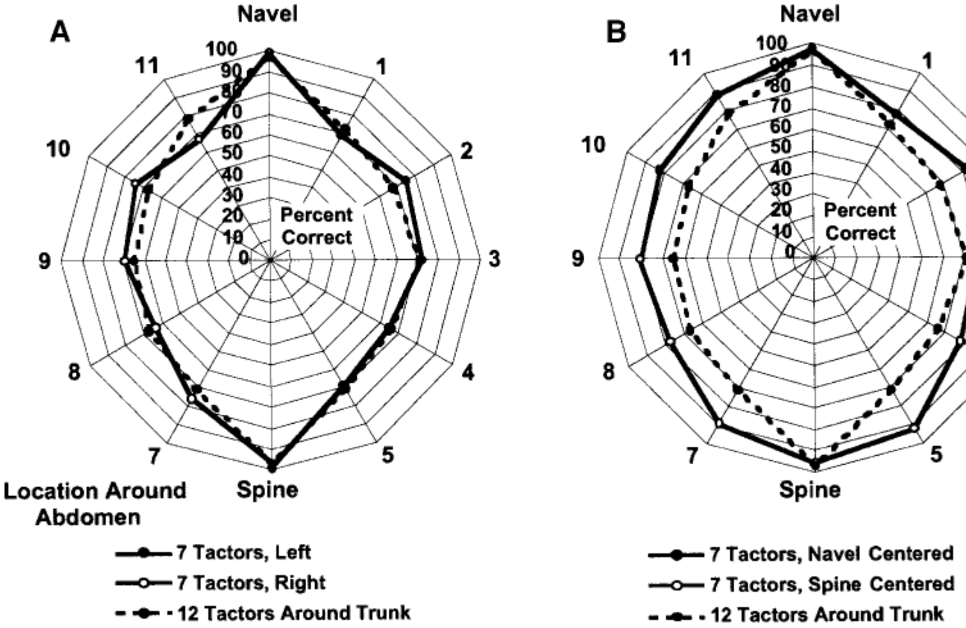

Figure 9. Localization performance (in percent correct, along the radii) is shown for bursts of vibrotactile stimuli presented to seven sites in a semicircle around the abdomen (represented by the radii). The array of tactors was fitted around half of the abdomen, either to the left (panel A, open circles) or to the right (panel B, filled circles), or around the back (panel B, open circles) or across the front (panel B, filled circles). Data from the standard 12-tactor condition (C2L) from Experiment 1 are also shown for comparison.

sites across either the front or the back of the body from the 12-tactor condition in Experiment 1 are compared against the results from testing the same sites with the 7-tactor arrays in this experiment, a highly significant improvement in performance is revealed [front, $F(1,21) = 13.852$, $p < .01$; back, $F(1,21) = 9.872$, $p < .01$]. Our interpretation of these findings is that the 7-tactor arrays worn across the front or back of the body now have unique endpoints, in addition to stimulating the spine and navel reference points, and these provide additional landmarks against which localization at all sites can be referred. Although these terminal tactors were positioned at poorly localized body sites, performance improved considerably, when compared against the condition in which the same sites were embedded in the array of 12 tactors surrounding the body. As was mentioned earlier, we contend that this performance enhancement occurred because there were fewer alternative responses at the endpoints, so it was more likely that these sites would be correctly identified. This advantage was obscured when the 7-tactor belts were worn in the left–right orientation, by nearly perfect localization at the spine and navel loci. When the 7-tactor arrays are worn around the sides of the abdomen, the array endpoints are co-located with these anatomical anchor points, so a ceiling effect prevents performance improvement in this case. So vibrotactile localization now appears to be a function of reference to special body locations, the proximity of nearby sites, and the unique characteristics associated with array endpoints.

These results show that the spine and the navel can provide for natural anchor points and that the array endpoints can result in functional anchor points. The possibility exists of introducing artificial anchor points that might enhance performance at the poorly localized sites in the 12-tactor array. Cholewiak and Collins (2003) have shown that incorporating qualitative differences into an array of otherwise undifferentiated tactile stimuli can provide for additional referents that have the potential of improving overall localization. Such additional, well-localized sites in an array have the possibility of enhancing performance at adjacent sites, perhaps through the "halo" effect alluded to in the discussion of Experiment 1. Obviously, there will be a limit to the number of such "tagged" stimuli that could be added to the display, because of the perceptual limitations of the observers. Although potentially useful tactual stimulus dimensions, such as vibratory frequency or intensity, might have large ranges covering many just-noticeable differences, a practical limitation of about three usable levels is typically observed when they are presented in communication systems (e.g., Sherrick, 1985), so as body-worn arrays become more and more elaborate, it is unlikely that processing limitations could be expanded too greatly by simply adding many additional reference points. Future work along these lines will explore these specific mechanisms in order to achieve our original intent, which was to present 12 sites around the abdomen in a manner that would optimize information transfer.

GENERAL DISCUSSION AND CONCLUSIONS

In the more than 175 years since Weber (1826/1978) discussed the conditions that influenced the accuracy with which touched locations on the body could be identified, studies of localization for vibratory stimuli have been rare. The majority of work that has been done with touch, however, has indicated that localization appeared to be better when the stimulus touched the skin close to joints, such as the wrist or elbow. These special places became known as *Anhaltspunkte*, or anchor points (Boring, 1942), and were regarded as *local signs* that could provide reference points against which the observer could measure the position of less well localized tactile stimuli. Later, Lewy (1895) and Parrish (1897), cited by Boring (1942), noted that we are most accurate when localizing stimuli close to such points of reference and that responses to stimuli between Anhaltspunkte are biased toward the closest joint, or *point of mobility*. In companion publications, Cholewiak and Collins (2002, 2003) were able to show that, regardless of stimulus frequency, the accuracy with which bursts of vibration could be localized on a number of sites along the forearm was a direct function of its proximity to either the wrist or the elbow and that, indeed, response proclivities did exist in the directions predicted by our predecessors. The data collected in the present study also show a nonuniform pattern of performance over the 12 sites around the belt of tactors at the waist. The wrist and the elbow are certainly points of mobility, but what distinctive features characterize the spine and the navel? Although not mobile, they do share a neurological quirk. Falling on the midline of the body, these sites have bilateral cortical representation and dermatomal overlap, so stimulation at these loci is likely appreciated by both sides of the brain. In addition, however, the abdomen is an important body site with regards to *ego location*. That is, because other parts of the body can rotate relative to the trunk, they do not provide the stable frame of reference that the abdomen provides in the spatial awareness of our orientation relative to the environment. As Van Erp (2000) describes in his review of research on the kinesthetic ego center, “the trunk midline constitutes the physical anchor for calculation of the internal egocentric coordinate frame for representing body position with respect to external objects” (p. 8). Karnath et al. (1991) and Beschin, Cubelli, Della Salla, and Spinazzola (1997) also have argued, on the basis of studies of neglect, that the trunk midline divides our perceptual space and is more important as a determinant in body scheme than head or eye position. In fact, data support the notion that the perceived position of the trunk provides for a set of stable coordinates that are resistant to perturbations from changing eye positions or even in microgravity and appears to be resistant to changes from environmental conditions (Gurfinkel, Lestienne, Levik, & Popov, 1993). So the apparent superiority in localization performance at the navel location may have ecological validity in that the navel dependably “points in the direction we are aimed,” although the extension of this argument to explain the superior performance at the site on the spine fails to have similar empirical or theoretical support. Both neurological redundancy and the ecological significance of the body midline may ultimately be the reasons for the superiority in localization at these two sites, the abdominal anchor points, and for the demonstrated asymmetrical pattern of responses around the body when 12 sites are to be localized.

Increasing the separation among the tactors should have improved the ability to identify the actual sites of stimulation if mislocalization was the result of interference or blurring across the set, owing to the proximity of the stimuli to one another. As the separation between adjacent tactors was increased from an average of about 72 mm (with 12 tactors) to 107 mm (with 8 tactors) to over 140 mm (with 6 tactors), a comparable improvement in performance was found, with optimal performance in all cases occurring when the spine and the navel anchor points were 2 of the active sites in the array (see Table 2 and Figure 8). An analysis of the static information transmitted indicates that the number of bits (and therefore, tokens) transmitted increased when the number of tactors in the array was increased from 6 to 8 to 12 tactors, although the number of tokens asymptote close to Miller’s (1956) “magical number seven”: 6 sites transmitted 5.5 tokens, or 2.46 bits, whereas 8 sites transmitted 6.3 tokens (2.65 bits), and 12 sites transmitted 6.6 tokens (2.71 bits). The results indicate that 8 stimuli are just as informative as 12.

Some variation in vibrotactile detection threshold was found over the sites to be tested, but there was not an obvious association between the localization data from Experiment 1 and the preliminary measures of threshold over the circumference of the abdomen. Cholewiak and Collins (2003) also found no relationship between vibratory detection sensitivity and localization over seven sites arrayed along the length of the forearm. One might question whether there should be a relationship at all. As was described earlier, in the present series of experiments, the observers were discouraged from using perceived intensity as a cue to localization by varying the suprathreshold intensity of the stimulus on a trial-by-trial basis. Furthermore, the literature that describes the recovery of function from nerve injuries following orofacial surgery suggests only a secondary relationship between the two. The course of recovery of facial pattern perception (as tested by sensitivity to tactile grid orientation) is found to take considerably longer than that for punctate vibratory sensitivity (e.g., Van Boven & Johnson, 1994b; Van Boven, Johnson, & Tilghman, 1991). In fact, these data indicate that, after surgery, the restoration of preoperative levels of tactile pattern perception follows the same time course as that required for patients’ subjective reports that “normal sensation” has returned. Obviously, touch and vibratory sensitivity are required for these types of judgments, but the effect of variations in sensitivity seems to be minimal. The most obvious way in which such variations would be manifest would be by affecting the perceived intensity of the stimulus, and this does not seem to influence judgments of location or orientation (e.g., Gibson & Craig, 2002; Johnson & Phillips, 1981; Van Boven & Johnson, 1994b).

Recall that observers were encouraged to respond as quickly and accurately as possible. The primary reason for this direction was that tactile memory, particularly for location, appears to be very labile (Geldard, 1975; Watkins & Watkins, 1974). There were, however, a number of interesting observations that were related to the primary variables and the measures of response time. The analysis of overall response time, shown in Table 2 and Figure 8, indicated that conditions in which the navel and the spine were included as stimulus sites, regardless of number of tactors, had shorter response times than did conditions in which these sites were spanned and that times generally increased with number of tactors. Finally, response times for the electromechanical tactors, in Experiment 1, were somewhat shorter than those for the pneumatic tactors. This effect could have been the result of secondary mechanical delays within the pneumatic driver hardware, including opening of the valves in the pneumatic manifold and the transmission and growth of pressure along the length of tubing and within the tactors themselves.

It is important to note the only other study of which we are aware that has employed circumferential abdominal stimulation for spatial orientation (although Bice, 1969, stimulated sites around the trunk in his study of apparent motion). Van Erp (2000) also employed a linear array of vibrotactile stimuli at the level just above the navel to examine directional acuity. In his several experiments, observers manipulated a dial that moved a light beam across the surface of a tabletop surrounding the person to indicate the presumed distal source of a vibratory stimulus on the abdominal array. Given that two points were so defined for each tactor (the location of the proximal tactile stimulus and that of the distal light beam), a line could be drawn through the observer's body to indicate the presumed centroid of the abdomen—the *ego center*—that served as the focus of these measurements. In fact, the set of lines converged at two such foci, about 3 cm to either side of the midline, that did not seem to be related to response biases or several other potential sources of artifact that were explored. As was found here, errors were found to be smallest for stimuli at the midline, although mislocalization biases were found in a direction opposite to what we observed. Our data reveal just the opposite directional bias: When they were incorrect, observers responded much more often with loci in the direction away from the midline than toward it. As was discussed above, we believe that perceptual strategies involving response certainty at the anchor points strongly influence performance at nearby sites, improving the probability of correct performance at those loci as well.

The following conclusions regarding vibrotactile localization on the abdomen may be drawn from these data.

The effect of place, or where on the body the stimulus occurred, was revealed in Experiment 1. Specifically, the accuracy with which 12 sites could be localized appeared to depend on the proximity of the stimulus loci to either the spine or the navel. Even when the number was reduced to 8 or even 6 sites, the influence of these anchor points persisted, despite the overall improvement in performance. When the tactor belt was arranged so that these unique sites were not stimulated, performance fell slightly. Furthermore, an analysis of response probabilities revealed that the influence of these two sites extended to adjacent loci, because the spine and navel were rarely included in erroneous responses to nearby loci. In effect, the spine and navel acted like array endpoints, limiting the alternative responses at nearby sites. If a stimulus occurred at these anchor points, the observer almost always knew that the anchor was stimulated; when a stimulus occurred at a nearby site, the observer was quite certain that it did *not* occur at the anchor.

The effect of separation, revealed by a comparison between the results of Experiments 1 and 2, indicates that when vibrotactile sites are placed close together, average performance falls. Although the amount of information that was transmitted in these conditions increased slightly with number of tactors over the range of 6–12 (see Table 2), the ratio of the number of items presented that were in fact appreciated dropped with increasing number. This does not necessarily mean that the smallest number is the optimal choice. Depending on the particular application, even 12 tactors might prove useful if the application could tolerate the lower absolute accuracy for the individual lateral sites. Knowing the location of an intruder within an angular region of some 60° (an error of ±1 tactor out of 12) could provide sufficient accuracy to redirect attention to that region of space for visual fixation in many circumstances.

Indeed, if the reduction of the number of tactors and, therefore, the reduction of the cognitive load alone could account for the improvement of localization performance, percentage correct for the seven-tactor conditions should be somewhere in between that for the six- and the eight-tactor conditions. In fact, localization performance for seven tactors was always worse than that for eight tactors, indicating that it was the physical separation between the tactors that determined localization accuracy.

The effect of number, controlling for separation, was mixed. If the results from Experiment 1 and the left/right orientation for the 7 tactors in Experiment 3 are compared, performance at the common sites was identical, so a smaller number of tactors alone did not improve localization. However, in the same condition, when the endpoints of the 7-tactor array were not at the abdomen's anchor points, a very different picture emerged. Not only was overall performance for the 7-tactor front/back orientation better than that for the 7-tactor left/right orientation, it was also significantly improved for the majority of the same sites when they were embedded in the array of 12. The primary reason for the improved performance with the front/back orientations of the 7-tactor arrays is that the endpoints of the arrays are available as reference points *and* the navel or the spine is also available to the observer as a localization anchor. An additional reason for the salience of the endpoints may result from the fewer response alternatives at these two sites, leading to a greater probability of a correct response in the face of uncertainty.

REFERENCES

Békésy, G. von (1960). *Experiments in hearing*. New York: McGraw-Hill.

Beschin, N., Cubelli, R., Della Salla, S., & Spinazzola, L. (1997). Left of what? The role of egocentric coordinates in neglect. *Journal of Neurology, Neurosurgery, & Psychiatry*, **63**, 483-489.

Bice, R. C. (1969). Apparent movement in vibrotactile displays. *Perceptual & Motor Skills*, **29**, 575-578.

Bolanowski, S. J., Gescheider, G. A., & Verrillo, R. T. (1994). Hairy skin: Psychophysical channels and their physiological substrates. *Somatosensory & Motor Research*, **11**, 279-290.

Boring, E. G. (1942). *Sensation and perception in the history of experimental psychology*. New York: Appleton-Century.

Cholewiak, R. W., & Collins, A. A. (1991). Sensory and physiological bases of touch. In M. A. Heller & W. Schiff (Eds.), *The psychology of touch* (pp. 23-60). Hillsdale, NJ: Erlbaum.

Cholewiak, R. W., & Collins, A. A. (2002). Vibrotactile pattern localization: Influences of body site and aging. *Abstracts of the Psychonomic Society*, **7**, 18.

Cholewiak, R. W., & Collins, A. A. (2003). Vibrotactile localization on the arm: Effects of places, space, and age. *Perception & Psychophysics*, **65**, 1058-1077.

Craig, J. C., & Johnson, K. O. (2000). The two-point threshold: Not a measure of tactile spatial resolution. *Current Directions in Psychological Science*, **99**, 29-32.

Dobbins, T., & Samways, S. (2002, November). *The use of tactile navigation cues in high-speed craft operations*. Paper presented at the International Conference on High Speed Craft: Technology and Operations, London.

Franke, E. K., von Gierke, H. E., Oestreicher, H. L., & von Wittern, W. W. (1951). *The propagation of surface waves over the human body* (USAF Tech. Rep. 6464). Dayton, OH: United States Air Force, Aeromedical Laboratory.

Geldard, F. A. (1975). *Sensory saltation: Metastability in the perceptual world*. Hillsdale, NJ: Erlbaum.

Gescheider, G. A., Capraro, A. J., Frisina, R. D., Hamer, R. D., & Verrillo, R. T. (1978). The effects of a surround on vibrotactile thresholds. *Sensory Processes*, **2**, 99-115.

Gibson, G. O., & Craig, J. C. (2002). Gap-detection as a measure of tactile spatial sensitivity. *Abstracts of the Psychonomic Society*, **7**, 51.

Greenspan, J. D., & Bolanowski, S. J. (1996). The psychophysics of tactile perception and its peripheral physiological basis. In L. Kruger (Ed.), *Pain and touch* (2nd ed., pp. 25-104). San Diego: Academic Press.

Gurfinkel, V. S., Lestienne, F., Levik, Y. S., & Popov, K. E. (1993). Egocentric references and human spatial orientation in microgravity: I. Perception of complex tactile stimuli. *Experimental Brain Research*, **95**, 339-342.

Johnson, K. O., & Phillips, J. R. (1981). Tactile spatial resolution: I. Two-point discrimination, gap detection, grating resolution, and letter recognition. *Journal of Neurophysiology*, **46**, 1177-1191.

Johnson, K. O., Phillips, J. R., & Freeman, A. W. (1985). Mechanisms underlying the spatiotemporal response properties of cutaneous mechanoreceptive afferents. In M. Rowe & W. D. Ellis (Eds.), *Development, organization, and processing in somatosensory pathways* (pp. 111-122). New York: Liss.

Johnson, K. O., Van Boven, R. W., & Hsiao, S. S. (1993). The perception of two points is not the spatial resolution threshold. In J. Boivie, P. Hansson, & U. Lindblom (Eds.), *Touch, temperature, and pain in health and disease: Mechanisms and assessments* (pp. 389-403). Seattle: IASP Press.

Kaas, J. H., Nelson, R. J., Sur, M., Lin, C. S., & Merzenich, M. M. (1979). Multiple representations of the body within the primary somatosensory cortex of primates. *Science*, **204**, 521-523.

Karnath, H. O., Schenkel, P., & Fischer, B. (1991). Trunk orientation as the determining factor of the "contralateral" deficit in the neglect syndrome and as the physical anchor of the internal representation of body orientation in space. *Brain*, **114**, 1997-2014.

Levitt, H. (1971). Transformed up–down methods in psychoacoustics. *Journal of the Acoustical Society of America*, **49**, 467-477.

Lewy, W. (1895). Experimentelle Untersuchungen über das Gedächtnis. *Zeitschrift für Psychologie*, **8**, 231-292.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limitations on our capacity for processing information. *Psychological Review*, **63**, 81-97.

Nafe, J. P., & Wagoner, K. S. (1941). The nature of pressure adaptation. *Journal of General Psychology*, **25**, 323-351.

Parrish, C. S. (1897). Localization of cutaneous impressions by arm movement without pressure upon the skin. *American Journal of Psychology*, **8**, 250-267.

Penfield, W., & Rasmussen, T. (1950). *The cerebral cortex of man: A clinical study of localization of function*. New York: Macmillan.

Priplata, A. A., Niemi, J. B., Harry, J. D., Lipsitz, L. A., & Collins, J. J. (2003). Vibrating insoles and balance control in elderly people. *Lancet*, **362**, 1123-1124.

Pubols, B. H., Jr. (1987). Effect of mechanical stimulus spread across glabrous skin of raccoon and squirrel monkey hand on tactile primary afferent fiber discharge. *Somatosensory Research*, **4**, 273-308.

Rabinowitz, W. M., Houtsma, A. J. M., Durlach, N. I., & Delhorne, L. A. (1987). Multidimensional tactile displays: Identification of vibratory intensity, frequency, and contactor area. *Journal of the Acoustical Society of America*, **82**, 1243-1252.

Rupert, A. H. (2000). Tactile situation awareness system: Proprioceptive prostheses for sensory deficiencies. *Aviation Space & Environmental Medicine*, **71**(Suppl.), A92-A99.

Sathian, K. (1998). Perceptual learning. *Current Science*, **75**, 451-458.

Senders, V. L. (1958). *Measurement and statistics*. New York: Oxford University Press.

Sherrick, C. E. (1985). A scale for rate of tactual vibration. *Journal of the Acoustical Society of America*, **78**, 78-83.

Skinner, J., & Ree, M. J. (1987). *Air Force Officer Qualifying Test (AFOQT): Item and factor analysis of Form O* (Tech. Rep. AFHRL-TR-86-68). Brooks Air Force Base, TX: Air Force Human Resources Laboratory, Manpower and Personnel Division.

Stevens, J. C., & Cruz, L. A. (1996). Spatial acuity of touch: Ubiquitous decline with aging revealed by repeated threshold testing. *Somatosensory & Motor Research*, **13**, 1-10.

Stevens, J. C., Foulke, E., & Patterson, M. Q. (1996). Tactile acuity, aging, and Braille reading in long-term blindness. *Journal of Experimental Psychology: Applied*, **2**, 91-106.

Tan, H. Z., Durlach, N. I., Reed, C. M., & Rabinowitz, W. M. (1999). Information transmission with a multifinger tactual display. *Perception & Psychophysics*, **61**, 993-1008.

Tan, H. Z., Lu, I., & Pentland, A. (1997, October). The chair as a novel haptic user interface. In *Proceedings of the Workshop on Perceptual User Interfaces* (pp. 56-57). Redmond, WA: Microsoft Research.

Tan, U., Okuyan, M., Bayraktar, T., & Akgun, A. (2003). Covariation of sex differences in mental rotation with body size. *Perceptual & Motor Skills*, **96**, 137-144.

Tawney, G. (1895). The perception of two points not the space-threshold. *Psychological Review*, **2**, 585-593.

Van Boven, R. W., & Johnson, K. O. (1994a). The limit of tactile spatial resolution in humans: Grating orientation discrimination at the lip, tongue, and finger. *Neurology*, **44**, 2361-2366.

Van Boven, R. W., & Johnson, K. O. (1994b). A psychophysical study of the mechanisms of sensory recovery following nerve injury in humans. *Brain*, **117**, 149-167.

Van Boven, R. W., Johnson, K. O., & Tilghman, D. M. (1991). A new clinical test for quantifying somatosensory impairment. *Journal of Oral and Maxillofacial Surgery*, **49**, 141.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual & Motor Skills*, **47**, 599-604.

Van Erp, J. B. F. (2000). *Direction estimation with vibro-tactile stimuli presented to the torso: A search for the tactile ego-centre* (TNO-report TM-00-B012). Soesterberg, The Netherlands: TNO Human Factors.

Van Erp, J. B. F. (2001). Tactile displays in virtual environments. In S. Brewster & R. Murray-Smith (Eds.), *Haptic human–computer interaction: Lecture notes in computer science* (Vol. 2058, pp. 165-173). Berlin: Springer-Verlag.

Van Erp, J. B. F., & Werkhoven, P. J. (1999). *Direction estimation with vibro-tactile stimuli presented to the torso: A search for the tactile ego-centre* (TNO-report TM-99-B007). Soesterberg, The Netherlands: TNO Human Factors.

Verrillo, R. T. (1966). Effect of spatial parameters on the vibrotactile threshold. *Journal of Experimental Psychology*, **71**, 570-575.

Vierordt, K. (1870). Die Abhängigkeit der Ausbildung des Raumsinnes der Haut von der Beweglichkeit der Körpertheile. *Zeitschrift für Biologie*, **6**, 53-72.

Wall, C., III, Weinberg, M. S., Schmidt, P. B., & Krebs, D. E. (2001). Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt. *IEEE Transactions on Biomedical Engineering*, **48**, 1153-1161.

Watkins, M. J., & Watkins, O. C. (1974). A tactile suffix effect. *Memory & Cognition*, **2**, 176-180.

Watson, C. S. (1980). Time course of auditory perceptual learning. *Annals of Otology, Rhinology, & Laryngology*, **89**(Suppl. 5, Pt. 2), 96-102.

Weber, E. H. (1978). *The sense of touch* (*De Tactu*, H. E. Ross, Trans., and *Der Tastsinn*, D. J. Murray, Trans.). New York: Academic Press. (Original works published 1826)

Weinstein, S. (1968). Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In D. R. Kenshalo (Ed.), *The skin senses* (pp. 195-222). Springfield, IL: Thomas.

Wilska, A. (1954). On the vibrational sensitivity in different regions of the body surface. *Acta Physiologica Scandinavica*, **31**, 284-289.

NOTE

1. One of our readers pointed out an alternative interpretation to us. He noted that, since our information analysis predicts that six tactors surrounding the abdomen (separated by c. 128–164 mm) should yield near-perfect performance (a value of d' of about 4), localization threshold (defined as $d' = 1$) would be one fourth of those values, or about 32–41 mm. This range almost perfectly brackets Weinstein's (1968) threshold estimates.

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