Tactile Displays: Guidance for Their Design and Application

Article *in* Human Factors The Journal of the Human Factors and Ergonomics Society · March 2008

DOI: 10.1518/001872008X250638 · Source: PubMed

Nadine B. Sarter
University of Michigan

Tactile Displays: Guidance for Their Design and Application

Lynette A. Jones, Massachusetts Institute of Technology, Cambridge, Massachusetts, and **Nadine B. Sarter,** University of Michigan, Ann Arbor, Michigan

Objective: This article provides an overview of tactile displays. Its goal is to assist human factors practitioners in deciding when and how to employ the sense of touch for the purpose of information representation. The article also identifies important research needs in this area. **Background:** First attempts to utilize the sense of touch as a medium for communication date back to the late 1950s. For the next 35 years progress in this area was relatively slow, but recent years have seen a surge in the interest and development of tactile displays and the integration of tactile signals in multimodal interfaces. A thorough understanding of the properties of this sensory channel and its interaction with other modalities is needed to ensure the effective and robust use of tactile displays. **Methods:** First, an overview of vibrotactile perception is provided. Next, the design of tactile displays is discussed with respect to available technologies. The potential benefit of including tactile cues in multimodal interfaces is discussed. Finally, research needs in the area of tactile information presentation are highlighted. **Results:** This review provides human factors researchers and interface designers with the requisite knowledge for creating effective tactile interfaces. It describes both potential benefits and limitations of this approach to information presentation. **Conclusion:** The sense of touch represents a promising means of supporting communication and coordination in human-human and human-machine systems. **Application:** Tactile interfaces can support numerous functions, including spatial orientation and guidance, attention management, and sensory substitution, in a wide range of domains.

INTRODUCTION

The sense of touch was first proposed and systematically developed as a means for communication by Geldard (1957, 1960). He highlighted the various affordances of touch: (a) the ability of the skin to make temporal and spatial discriminations that rival those achieved by our eyes and ears; (b) the effectiveness of cutaneous sensations for capturing attention; (c) the large area for potential stimulation of the skin (approximately 1.8–2.0 m^2 in area in the average adult; Montagu, 1971), and (d) the underutilization of this channel for presenting information.

Geldard (1957) designed the first tactile language, Vibratese. It consisted of 45 basic elements that varied along three dimensions: amplitude, duration, and location. Vibratese was initially tested on three individuals who were able to learn the language in only 12 hr and reached a plateau at a receiving rate of 38 words per minute.

Although Vibratese has since vanished, research and development in the area of tactile information presentation has continued and, in recent years, experienced a surge that is driven by both need and opportunity: the need to present increasing amounts of complex data to users in work domains that face problems with visual and auditory data overload and the need to support immersion and embeddedness in virtual environments. The opportunity to utilize the sense of touch for these purposes emerged as a result of tactile display technologies becoming more sophisticated, less intrusive, and thus more effective and acceptable to users.

The sense of touch is not only a promising but also a unique communication channel. In contrast to vision and hearing, the two senses traditionally employed in the design of user interfaces, it also represents a proximal sense – that is, it senses objects that are in contact with the body – and it is bidirectional in that it supports both perception and

Address correspondence to Lynette Jones, Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., Room 3-137, Cambridge, MA 02139; ljones@mit.edu. ***HUMAN FACTORS,*** Vol. 50, No. 1, February 2008, pp. 90–111. DOI 10.1518/001872008X250638.

acting on the environment (Jones & Lederman, 2006). In addition, the proximal nature of touch allows for the creation of private displays. This is an important affordance when information is confidential or privileged (e.g., in military contexts) and in environments that suffer from auditory clutter. In the latter situation, some information may be relevant for one or only a few people (e.g., alarms and notifications in an operating room).

The focus of this review is on tactile displays that provide vibrotactile or static tactile inputs to the user to assist in the performance of a task. In the context of display technologies, interfaces that present both the tactile and kinesthetic cues associated with active movements are called haptic displays and typically present the forces associated with contact to users. The forces are actively produced by the device and are of sufficient magnitude that they can resist the movements of the user's hand and arm. In any application, the choice between a haptic or tactile interface depends, to a large extent, on the nature of the task that needs to be supported.

Tactile displays take many different forms and are developed for a variety of purposes, including spatial orientation and guidance, notifications and alerts, feedback on the success of control actions in human-computer interaction, and sensory substitution. They are employed in a number of application domains in which other communication channels, such as vision and audition, are heavily taxed already or in which visual displays are inconvenient or less appropriate. Examples of such domains include car cockpits, surgical instruments, and navigation aids in military operations. Tactile signals are also increasingly included in the design of multimodal interfaces, where they complement visual and auditory feedback.

The goal of the present paper is to assist designers in deciding when and how to employ the sense of touch to present information. It focuses on vibrotactile displays and their applications and does not cover haptic or thermal display technology. It provides an overview of vibrotactile perception and of the processes underlying tactile and multimodal information processing. Next, tactile display technologies are reviewed. Various applications of tactile displays are discussed, and the role of touch in the context of multimodal information presentation is examined. Finally, important research needs in the area of tactile information presentation are highlighted. This information is expected to benefit researchers from diverse fields – such as mechanical engineering, cognitive ergonomics, experimental psychology, systems physiology, and computer science – who often collaborate on the design of tactile interfaces.

VIBROTACTILE PERCEPTION

Vibrotactile stimulation activates numerous mechanoreceptors in the skin, and their responses depend on the frequency, amplitude, and duration of vibration and the area of the contactor stimulating the skin. Five main types of mechanoreceptors have been identified in hairy skin, two of which are slowly adapting and three that are rapidly adapting. An understanding of the functional characteristics of these mechanoreceptors is essential to the development of effective tactile displays. This section will primarily focus on vibrotactile sensation in hairy skin, as most of the tactile displays considered in this review are mounted on either the torso or the arms. However, information regarding tactile sensation in the glabrous skin on the hand will be discussed as appropriate.

Frequency of Vibrotactile Stimulation

The function that describes the relation between the amplitude required to detect vibration and the frequency of stimulation represents the upper bounds of sensory resolution on the skin and is used as the basis for specifying the stimulation characteristics (e.g., vibration frequency and amplitude) of a tactile display. This relation has been measured at numerous sites on the body at frequencies ranging from 0.4 to 1000 Hz (Bolanowski, Gescheider, & Verrillo, 1994; Gescheider, Bolanowski, Pope, & Verrillo, 2002; Sherrick, 1953; Verrillo, 1963) and is shown in Figure 1 for the fingertip, forearm, and abdomen, three regions of the body often used to display tactile cues.

Optimal sensitivity is achieved at frequencies between 150 and 300 Hz for all sites, and at lower and higher frequencies the displacement of the skin must be greater to be detected. The amplitude for detecting vibration at any given frequency does, however, vary considerably over the body, with the lowest thresholds (i.e., highest sensitivity) being measured on the fingertips (0.07 μm at 200 Hz) and the highest thresholds in the abdominal and gluteal regions (4–14 μm at 200 Hz; Wilska, 1954). The thresholds for detecting vibration as a function of body site are illustrated in Figure 2.

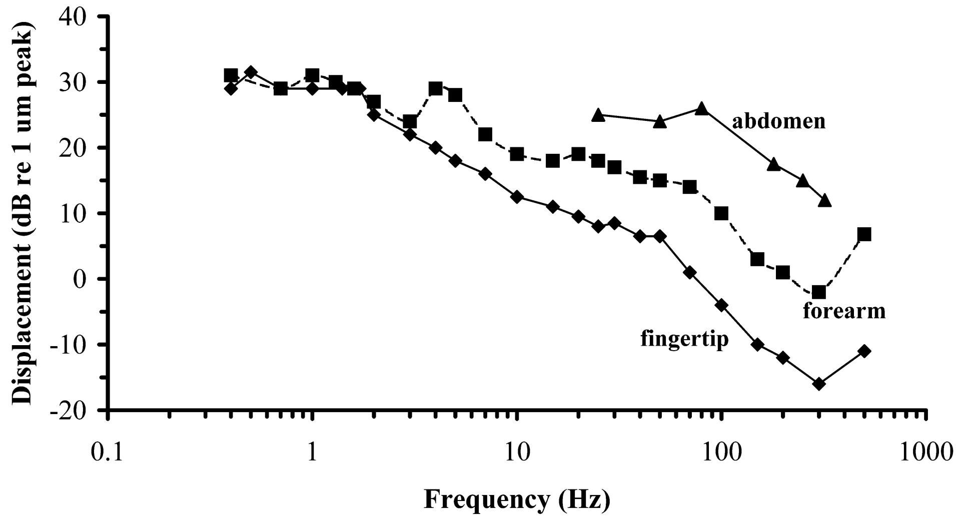

Figure 1. Threshold frequency characteristics measured on the fingertip (diamonds) with a contactor measuring 72 mm^2 (from Gescheider et al., 2002), on the forearm (squares) with a contactor measuring 290 mm^2 (from Bolanowski et al., 1994), and on the abdomen (triangles) with a contactor measuring 39 mm^2 (from Cholewiak et al., 2004).

Despite this wide variation in sensitivity, there is not a significant change in vibrotactile thresholds as one moves circumferentially around the torso from the navel to the spine (Cholewiak, Brill, & Schwab, 2004), and so a vibrotactile stimulus at a given frequency should be perceived similarly at any locus around the waist.

In using the skin as a communication channel it is important to know how sensitive people are to changes in vibration frequency, as frequency appears to be a very natural parameter to use to encode information. For example, a sense of urgency could be conveyed by increasing the frequency of the tactile signal, whereas caution could be represented by progressively decreasing the frequency of the tactile input.

In contrast to the extensive number of studies that have been conducted on vibrotactile thresholds

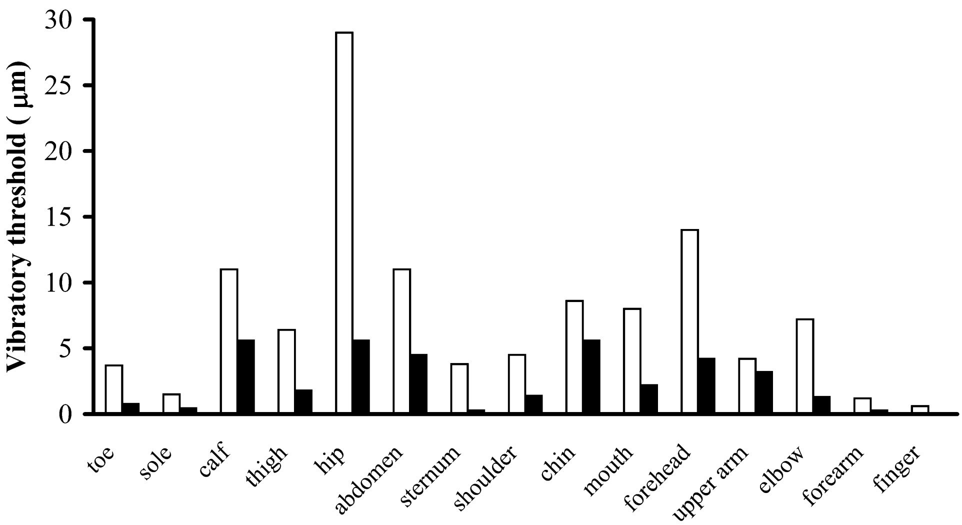

Figure 2. Thresholds for detecting vibration at 100 Hz (white bars) and 200 Hz (black bars) at various sites on the body. Data are taken from Table 1 in Wilska (1954).

as a function of frequency (e.g., Bolanowski et al., 1994), there have been relatively few studies on vibrotactile frequency discrimination, perhaps because of the interaction of frequency and amplitude in vibrotactile frequency discrimination. As the amplitude of vibration increases (at a constant frequency), the perceived frequency of the signal (i.e., pitch) also increases, although the rate at which perceived frequency changes varies considerably across people (Békésy, 1959; Morley & Rowe, 1990).

Furthermore, the relation between the perceived and actual frequency of vibrotactile stimulation varies in different regions of the body, presumably because of variations in the innervation density of mechanoreceptors and the damping effects of underlying soft tissue. In regions with high innervation densities, such as the fingertips, perceived frequency increases more rapidly with increases in frequency than it does in areas with lower densities, such as the arm (Békésy, 1962).

Mowbray and Gebhard (1957) used a handheld vibrating rod to measure the differential thresholds for frequencies ranging from 1 to 320 cycles per second. They determined that the threshold was small at low frequencies (2%–4%), increased slightly at higher frequencies (6%–8%), and averaged 4.6% across the range of frequencies tested. They did not attempt to control for pitch-frequency interactions and claimed that these interactions did not affect their findings, particularly at low frequencies. Their values are, however, considerably smaller than the differential thresholds measured on the finger pad by Goff (1967), who did control for changes in perceived intensity. She reported threshold values that varied from 18% to 50% for frequencies ranging from 25 to 200 cycles per second.

In two more recent studies (Mahns, Perkins, Sahai, Robinson, & Rowe, 2006; Rothenberg, Verrillo, Zahorian, Brachman, & Bolanowski, 1977) in which frequency discrimination was measured on the forearm and fingertip using equal-sensation stimuli, the Weber fraction (differential threshold divided by reference frequency expressed as a percentage) was reported to change as a function of frequency. Rothenberg et al. (1977) noted that it increased from around 18% at 20 Hz to approximately 30% at 300 Hz, whereas Mahns et al. (2006) reported that it decreased from 30% at 20 Hz to 13% at 200 Hz. In the later study, the authors noted there was no difference between the fingertip and the forearm in terms of the ability to discriminate vibrotactile stimuli.

These results, together with those from other studies on vibrotactile frequency discrimination, are summarized in Figure 3. These high and varying threshold values measured on the skin stand

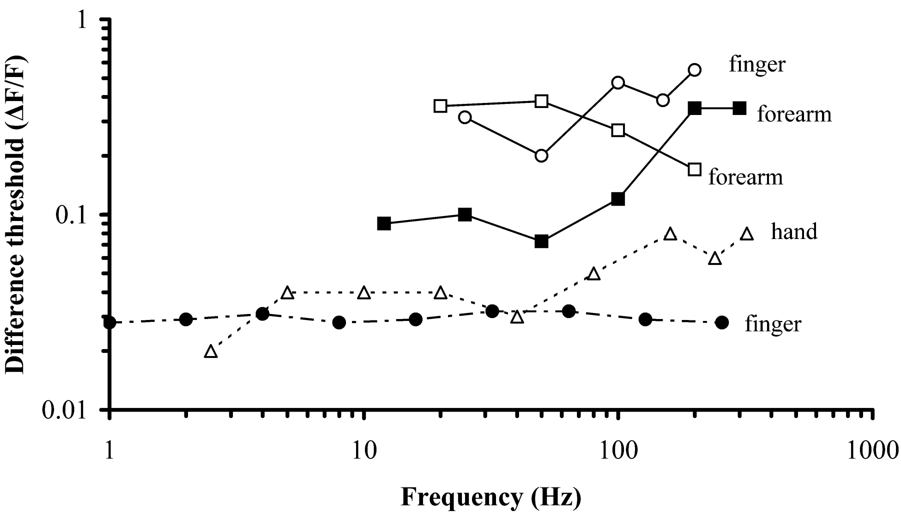

Figure 3. Difference thresholds as a function of frequency for pulses delivered to the forearm (filled squares, Rothenberg et al., 1977; open squares, Mahns et al., 2006), the finger (filled circles, Franzen & Nordmark, 1975; open circles, Goff, 1967), and the hand (triangles, Mowbray & Gebhard, 1957). The results are plotted as $\Delta F/F$, the Weber fraction.

in contrast to the exquisite sensitivity of the ear, which can discriminate frequency differences in the order of 0.3%.

Based on these findings, it is difficult to specify the change in vibrotactile frequency that could be reliably distinguished by people using a tactile display for communication. From their results, Rothenberg et al. (1977) suggested that there might be at least seven potentially differentiable steps in vibrotactile frequency on the forearm that could be used in a tactile display. Using an information analysis of data on the perceived rates of vibration presented to the finger, Sherrick (1985) proposed that only three to five rates can be distinguished over the range of 2 to 300 pulses per second but that when intensity is added as a redundant cue, the number of recognizable rates increases to five to eight.

In the context of a tactile display that presents information to an operator engaged in a number of tasks, it is unclear whether vibration frequency is a useful parameter to vary, given the bandwidth of the tactile system and the complex interactions between frequency and amplitude in vibrotactile frequency discrimination. Several years ago Geldard (1960) cautioned that frequency "would have to be handled gingerly in a [tactile] communication system, especially if intensity were simultaneously manipulated as a variable" (p. 1586).

Duration of Vibrotactile Stimulation

A further variable that can be used to encode information in a tactile display is temporal variation in the stimuli presented. Three temporal components to vibrotactile stimuli have been studied: the burst duration of the stimulus, the pulse repetition rate, and the number of pulses. In most tactile displays the duration of the stimulus ranges from 80 to 500 ms, typically repeated in a sequence of on/off pulses. Not surprisingly, it has also been shown that as the duration of a tactile stimulus increases from 80 to 320 ms, the ability to identify a tactile pattern improves (Summers et al., 1997). When the tactile signal is functioning as a simple alert, people prefer that the duration of the tactile pulses be between 50 and 200 ms, as stimuli of longer durations are perceived as annoying (Kaaresoja & Linjama, 2005).

It is also possible to group vibrotactile pulses of varying durations together so as to create rhythms that encode information (e.g., urgency of message, proximity of vehicle). Brown, Brewster, and Purchase (2005) have shown that participants can identify three different rhythms with an accuracy of 93%. In this study both the tactile rhythm and complexity of the waveform were independently varied to create tactile patterns called tactons.

The capacity to perceive vibrotactile frequency appears to be largely attributable to temporal cues rather than spectral properties, as the human tactile system seems to be relatively insensitive to variations in waveform, in marked contrast to the perception of timbre by the auditory system (Cholewiak et al., 2004; Summers et al., 1997). However, variations in waveform can be perceived if the complexity of a waveform is varied by using amplitude-modulated sinusoids, in which the amplitude of a base signal (e.g., 250 Hz) is modulated by a second sinusoid (e.g., 30 Hz). As the modulating frequency changes, so too does the perceived "roughness" of the resulting waveform. For a base signal of 250 Hz the roughness increases as the modulation frequency decreases from 50 to 20 Hz (see Figure 7, later in this paper), so by modulating a 250-Hz signal at different frequencies it is possible to create waveforms that vary in "roughness" (Brown et al., 2005). Signals such as these could be used to convey cues about traffic flow in a handheld or vehicle-based device.

Vibrotactile Intensity

Changes in the intensity or amplitude of vibration can also be used to convey information, such as the proximity of a vehicle to an obstacle during driving or of a restricted area during flight. The change in intensity that is reliably discriminated (i.e., the difference threshold) depends on the amplitude of the vibration, but it does not follow Weber's law. At moderate to high intensities of vibration the threshold is smallest, and estimates range from 5% to 30% with an average around 16% (Craig, 1972). As noted previously, changes in intensity at a constant frequency influence not only the perceived amplitude of the signal but also its perceived frequency (Békésy, 1959), and so it would be advisable to vary only one of these variables (i.e., intensity or frequency) when communicating via the skin.

The combination of frequency and intensity that results in judgments of equal subjective magnitude has been determined for a range of vibrotactile frequencies, as shown in Figure 4 (Verrillo, Fraioli, & Smith, 1969). From these curves it is possible to ascertain the intensity of vibration that

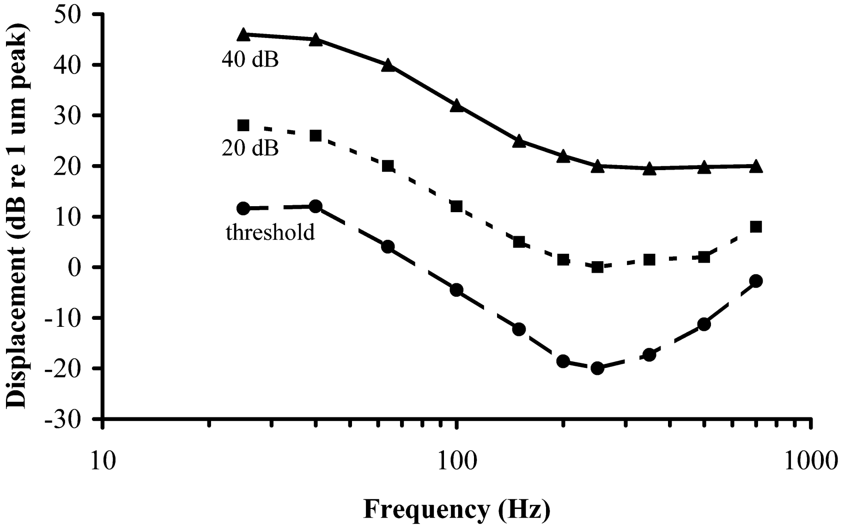

Figure 4. Contours of equal-sensation magnitude for vibration derived from data obtained by the method of numerical magnitude balance. The sensation levels are threshold (circles) and 20 dB (squares) and 40 dB (triangles) above threshold for a signal at 250 Hz. The data are taken from Verrillo et al. (1969).

is required to equal the subjective intensity of a vibration at another frequency. This matching of subjective magnitudes would be required if information in a display was being encoded in terms of only vibrotactile frequency, not in combination with any other encoding variable.

The absolute and differential thresholds for vibrotactile intensity can be used to determine how much stimulus intensity should be varied in a tactile display for an observer to detect a change. In addition, it is important to understand how suprathreshold stimuli are perceived so that the perceptual effect of doubling or halving stimulus intensity is known. The psychophysical function that relates the amplitude of a vibrotactile stimulus to its perceived intensity has been measured in a number of experiments (e.g., S. S. Stevens, 1968; Verrillo & Chamberlain, 1972; Verrillo et al., 1969).

The results from these studies indicate that the perceived intensity of vibration increases as a power function of the physical intensity of the vibration with an exponent ranging from 0.45 to 0.95, depending on the site tested (Verrillo & Chamberlain, 1972) and the frequency of vibration (S. S. Stevens, 1968). The slope or exponent of this psychophysical function relating physical to perceived magnitude is inversely related to the density of neural innervation at the skin site tested (see Figure 5), which means that the perceived magnitude of vibration increases more rapidly as the sensitivity to vibration decreases (Verrillo, 1973; Verrillo & Chamberlain, 1972). In the context of a tactile display, this means that changes in vibrotactile intensity are perceived to be greater if they are presented to a site such as the torso or arm, rather than to the fingers.

In all these studies on the perception of vibrotactile intensity, the amplitude of a single vibratory stimulus was varied. The perceived intensity of vibrotactile stimulation can also be manipulated by varying the number of vibrating motors (called tactors) used to present the stimulus. Cholewiak (1979) mounted a tactile display on the thigh and found that as the number of active tactors increased from 1 to 64, there was a linear increase in the perceived intensity of the vibrotactile stimulation for frequencies above 40 Hz. This suggests that the intensity of a vibrotactile stimulus on the body can be varied by changing the number of tactors concurrently active. If this were the only cue available, then probably only three widely spaced intensity values are usable in a display (Geldard, 1960).

Locus of Vibrotactile Stimulation

The spatial coordinates of a stimulus applied to the skin are accurately represented in the central nervous system, and so it has been proposed that spatial information about the external world may be communicated via tactile stimulation of the skin (e.g., van Erp, 2001). In several proposed

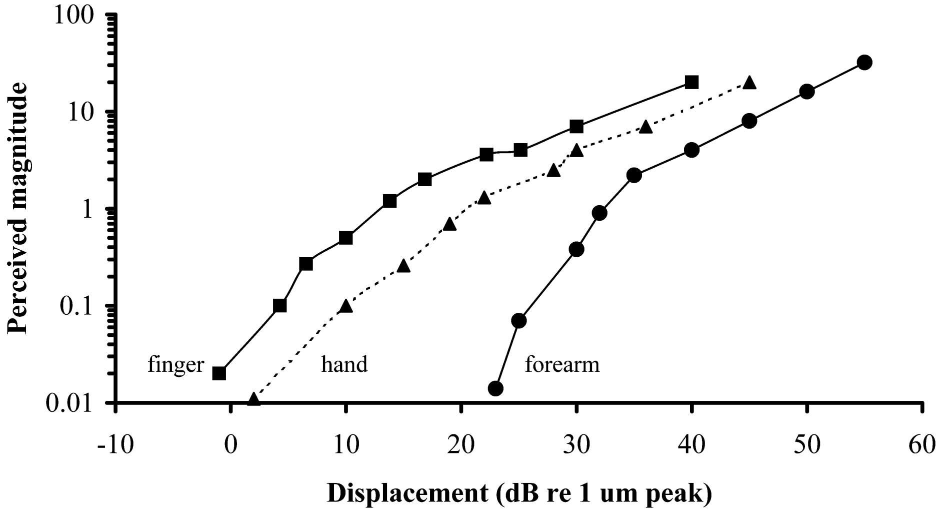

Figure 5. Relation between perceived and physical magnitude of a 250-Hz vibratory stimulus delivered to the finger (squares), the thenar eminence on the hand (triangles), and the forearm (circles). The data are from Verrillo and Chamberlain (1972). Subjective magnitude functions were determined by the method of numerical magnitude balance.

applications of tactile displays, users have to identify where an event occurs in 3-D space using the location of vibrotactile stimulation on their body as the cue (e.g., van Erp, 2001, 2005) or direct their attention to a visual target on a screen based on a spatially congruent tactile cue (Tan, Gray, Young, & Traylor, 2003). It appears to be very intuitive to perceive an external direction from a single point of stimulation on the body (van Erp, 2001). In general, the ability to localize a point of vibrotactile stimulation on the body is best when it is presented near anatomical points of reference such as the wrist, elbow, spine, or navel (Cholewiak & Collins, 2003; Cholewiak et al., 2004; van Erp, 2001).

One common method of referencing space around the torso uses the 12 hours of the clock as spatial landmarks. Using a cylindrical keyboard as a response device that represented the 3-D surface of the waist, Cholewiak et al. (2004) determined the number of sites around the waist at which participants could accurately localize vibrotactile stimulation. The tactile array comprised a belt with 12 (intertactor spacing of 72 mm), 8 (spacing of 107 mm), or 6 (spacing of 140 mm) tactors equidistantly spaced. Localization accuracy averaged 74% correct with 12 tactors, and it improved to 92% with 8 tactors and to 97% when 6 tactors were used. Cholewiak et al. (2004) also reported that performance was better (by 2%–5%) if anchor points such as the spine or navel were used as stimulation sites.

Consistent with these findings, van Erp (2005) found that localization accuracy was highest for stimuli presented in the midsagittal plane of the body and that errors were higher for stimuli presented on the side of the torso. In his experiment, participants were required to position a remotely controlled cursor to indicate the external direction of a localized vibration applied around the torso, a task resembling the conditions associated with using tactile spatial cues for navigation or vehicle control.

When two-dimensional tactile arrays are used to determine localization accuracy, performance appears to be highly dependent on intertactor spacing. Lindeman and Yanagida (2003) placed a 3 × 3 array on the back with a 60-mm intertactor spacing and found that participants were able to identify the location of a single vibrotactile stimulus with an 84% correct identification rate. However, when a 3 × 3 array with an intertactor spacing of 25 mm was tested on the dorsal surface of the forearm, participants were able to identify the location of the vibrotactile stimulus on only 53% of the trials (Oakley, Kim, Lee, & Ryu, 2006). In the latter situation, one of the constraints in using a tactile display is the limited skin surface available, particularly if the display dimensions are kept constant across participants. These results clearly indicate that intertactor spacing, array configuration, and the specific location on which the display is mounted all influence localization accuracy and must be considered carefully in the design of a tactile display used to communicate spatial information.

In addition to providing cues about the location of events in the environment, spatial cues can also be represented in the pattern of vibrotactile stimulation. In these applications, a series of tactors in the tactile display are sequentially activated and the pattern of activation represents a specific command: for example, "move to the left" (Jones, Lockyer, & Piateski, 2006). The effective design of a tactile display requires that the spacing of the tactors on the body is greater than the two-point threshold for vibrotactile stimulation (i.e., the minimal distance at which two points of stimulation are reported). On the back the two-point threshold for discriminating vibratory stimuli is approximately 10 to 11 mm, and it is the same regardless of whether the stimuli are delivered simultaneously or successively (Eskildsen, Morris, Collins, & Bach-y-Rita, 1969). These thresholds are considerably smaller than static two-point thresholds on the back, which are around 20 to 40 mm (Weinstein, 1968), and indicate that dynamic stimuli enhance the spatial acuity of the torso.

It is possible to augment the information presented at a number of sites on the skin by making use of various illusory phenomena. One tactile illusion that has been studied at several different locations on the body is sensory saltation (Geldard, 1975), a tactile illusion of displacement. This illusion can be demonstrated by placing three stimulators at three equally spaced locations on the skin – for example, on the forearm or back (Cholewiak & Collins, 2000; Tan, Gray, et al., 2003) – and then delivering three brief pulses at the first stimulator, followed by three pulses at the middle stimulator, and finally three pulses at the most distant stimulator. Rather than feeling three successive taps at three distinct locations, most people perceive that the mechanical pulses are essentially evenly distributed across the skin surface, as if the stimulus were hopping from one location to the next (hence the term "cutaneous rabbit").

The parameter that appears to determine the perceived spatial layout in sensory saltation is the temporal separation between the bursts of vibration. When the interstimulus intervals are between 20 and 300 ms (optimally near 50 ms), the stimuli are perceived as being spatially distributed across the skin surface. On the back, the tactors need to be placed at distances no greater than 100 mm, and the optimal number of pulses delivered to each tactor is between three and six (Geldard, 1975; Geldard & Sherrick, 1972). This phenomenon means that it would be possible to simulate a higher spatial density of tactors than is actually present in a display by using appropriate tactor spacing and interstimulus intervals. Cholewiak and Collins (2000) have indeed shown that when salutatory presentations are compared directly with veridical presentations of vibrotactile stimuli on the back, the sensations produced by the salutatory mode are indistinguishable from those presented veridically most of the time.

Summary

Of the encoding parameters available for a vibrotactile stimulus – namely frequency, intensity, locus, and duration – the latter two hold the most promise for encoding information in a tactile display. Frequency and intensity appear to be the least exploitable dimensions, primarily because the skin is rather poor at discriminating differences in frequency, and stimuli of the same intensity applied to different loci on the body are perceptually different.

Although it has been proposed that there are at least seven distinguishable steps in vibrotactile frequency and 15 different intensities that can be discriminated on hairy skin (Rothenberg et al., 1977), it seems most unlikely that identifying these numbers of stimulus levels could be achieved without a substantial amount of training. In many of the contexts in which tactile displays will come to be used, it is anticipated that the user will be involved in other activities, such as driving a vehicle or analyzing information presented on a computer screen, which makes it even more unlikely that an individual could identify which of 15 vibrotactile intensities was being presented. Similarly, it seems doubtful that people could perceive up to nine different levels of vibrotactile frequency, as recommended by the European Telecommunications Standards Institute (2002).

TACTILE DISPLAY TECHNOLOGIES

Devices that are used to stimulate the skin in wearable tactile communication systems must be lightweight and small, and if the tactile display is to be worn by mobile users, it must minimize power consumption. Other factors that are often considered when choosing a tactor for a tactile display are its durability, cost, reliability, and wearability.

Tactile displays can be divided into two broad classes, vibrotactile and electrotactile, which are distinguished on the basis of the mechanism used to stimulate the skin. Vibrotactile displays mechanically stimulate the skin using an actuator that converts electrical energy into a mechanical displacement of either the whole actuator or a contactor pad at frequencies ranging from 10 to 500 Hz. Electrotactile displays stimulate the skin by passing a current through surface electrodes (e.g., typically gold, platinum, silver, or stainless steel) that directly stimulate afferent nerve fibers, in contrast to the mechanoreceptors activated by vibrotactile displays. The sensations evoked by electrotactile stimulation are described qualitatively as a tingle, itch, buzz, or sharp and burning pain, depending on the stimulating voltage, current and waveform, and the electrode size, skin location, and degree of hydration of the skin (Kaczmarek, Webster, Bach-y-Rita, & Tompkins, 1991).

In addition to these two categories of tactile displays are static displays, which either statically indent the skin or apply shear forces to the skin surface. This technology is typically used in displays fabricated for presenting tactile cues to the fingers, such as in displays embedded in handheld devices (e.g., Poupyrev, Maruyama, & Rekimoto, 2002) and in virtual Braille displays (Lévesque, Pasquero, Hayward, & Legault, 2005).

A number of different actuator technologies have been used in vibrotactile displays, such as electromagnetic motors (e.g., Tactaid: Audiological Engineering Corp., Somerville, MA, http://www.tactaid.com; C2 tactor: Engineering Acoustics Inc., Casselberry, FL, http://www.eaiinfo.com) and arrays of pins (e.g., Optacon: Bliss, Katcher, Rogers, & Shepard, 1970; Braille Note BN32: KGS Corp., Saitama, Japan, http://kgs-jpn.co.jp) that indent the skin when activated by piezoelectric bimorphs.

The Tactaid, developed to assist speech comprehension in hearing-impaired individuals, has a usable frequency range from 100 to 800 Hz, with a nominal peak frequency of 250 Hz. The C2 tactor also has a nominal frequency of 250 Hz and can be programmed to display a range of tactile inputs that vary in frequency. Both of these tactors (see Figure 6) have been used in tactile displays developed for navigation and orientation and as sensory aids for the impaired. Tactile displays that are based on pin arrays, such as the Optacon and Braille Note, a refreshable Braille display, were designed to display letters on the finger pads, and so the arrays are small and dense.

A recent novel development in finger-based tactile displays is the fabrication and evaluation of displays that use lateral skin deformation instead of normal indentation to stimulate the skin to produce

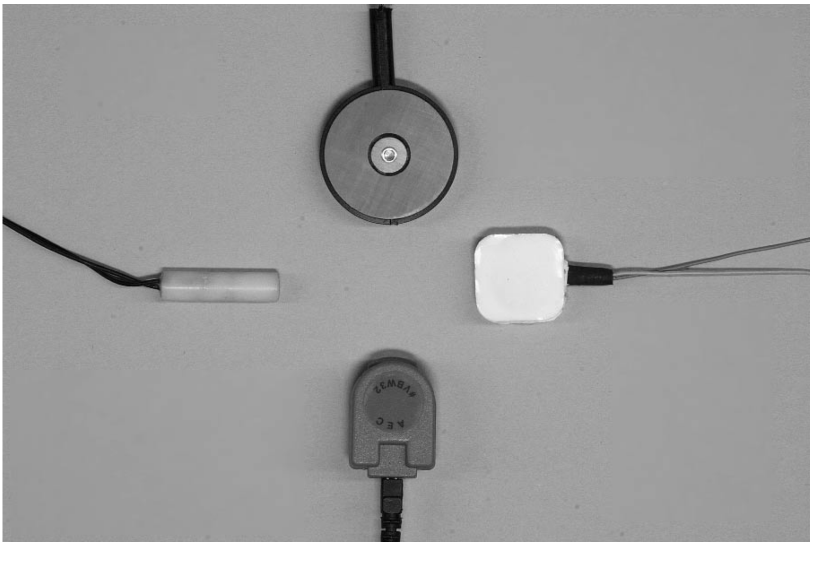

Figure 6. Electromechanical actuators used as tactors in tactile displays. From top clockwise: C2 tactor (Engineering Acoustics Inc.), encased pancake motor, Tactaid tactor (Audiological Engineering Corp.), and rototactor (Steadfast Technologies).

sensations similar to those felt when moving a finger across a line of Braille dots (Lévesque et al., 2005; Wang & Hayward, 2006). The Virtual Braille Display is composed of a 10 × 6 matrix of piezoelectric bender motors that apply tangential forces to the skin to simulate contact with Braille characters (Lévesque, Pasquero, & Hayward, 2007).

Over the past decade, a variety of small DC motors have been used in a number of contexts to provide tactile stimulation to the torso (Jones et al., 2006; Lindeman, Yanagida, Noma, & Hosaka, 2006; van Erp, van Veen, Jansen, & Dobbins, 2005). These motors (see Figure 6) typically vibrate by using an off-axis weight on their rotor. The frequency of vibration is directly proportional to the motor's speed, which is a function of the driving voltage. If the rotor and attached weight are exposed, the motor is encased so that movement of the rotating mass is not impeded (Piateski & Jones, 2005).

The advantages of these motors are that they are simple to control and can produce vibrations on the skin that are readily perceptible. They do, however, have limited power-to-mass ratios, and in general the frequency and amplitude of the vibration is difficult to control independently, unlike some of the electromagnetic motors (e.g., C2 tactor) described previously. The small DC motors are activated at a fixed frequency (typically between 80 and 250 Hz) and amplitude, and the number and location of the motors simultaneously active are used to convey information. Some tactile displays have been designed so that they can be controlled wirelessly using communication technologies such as IEEE 802.11b (Wall, Weinberg, Schmidt, & Krebs, 2001), Bluetooth (Jones et al., 2006; Lindeman et al., 2006), and infrared wireless (Gemperle, Ota, & Siewiorek, 2001).

Several electrotactile displays have been developed for use as sensory aids for those with hearing (Summers et al., 1994) and visual disabilities (Kaczmarek & Haase, 2003; Saunders, 1973). These systems typically comprise an array of electrodes that is stimulated with brief (50–100 μs), constant-current pulses (0.1–10 mA). Variations in the intensive and temporal parameters of stimulation and in the spatial sequence of electrodes activated can be used to convey information. The intensity of electrotactile stimuli can be modulated by varying either the pulse duration or current amplitude. However, both the absolute threshold and subjective magnitude of electrotactile stimulation increase rapidly with changes in current amplitude (Rollman, 1973), and so stimulation current must be controlled carefully to avoid painful sensations.

One further disadvantage of constant-current stimulation is that if there is poor contact between the skin and an electrode, the decrease in effective area results in a higher current density and a much stronger sensation of a sudden, sharp pain (Kaczmarek et al., 1991). A limitation of electrotactile displays in general is the small dynamic range available to present cues. The range from threshold to a maximal level that is comfortable and not painful depends on the individual, stimulation site, and type of electrodes and waveform used; when expressed as a ratio of the maximum to minimum it varies from 1.2 (1.6 dB) to 10 (20 dB; Kaczmarek et al., 1991). The equivalent vibrotactile range is about 40 dB.

Summary

Vibrotactile and electrotactile displays have been implemented in a number of environments in which the skin is used as a medium of communication. The limitations of electrotactile displays in terms of their restricted dynamic range, concern for user comfort when contact between the display and the skin is not maintained, and the need to adjust the comfortable stimulation range for each individual have meant that this type of display has been used less extensively. Vibrotactile displays have achieved success in a number of domains, as detailed in the following section. The availability of small, low-cost, low-power motors has been a major factor in contributing to this success.

TACTILE DISPLAY PURPOSES AND APPLICATIONS

Sensory Substitution

Tactile displays have been used to support a variety of functions, such as sensory substitution for those with visual or hearing impairments (Kaczmarek & Bach-y-Rita, 1995) and the provision of cues about the properties of objects in computer-generated virtual environments (Burdea & Coiffet, 2003). In these applications, the sense of touch is used to compensate for deficiencies in other senses or to provide information that is best represented using the tactile modality (e.g., surface texture). A summary of the properties of a number of tactile displays is provided in Table 1. Sensory substitution systems that present tactile stimuli to the torso or hand were first developed for the visually impaired in the 1970s. In general these systems use a camera and computer to capture the visual information, which is then presented via a tactile array to the skin as a pictorial representation.

One such system is the Optacon (*op*tical to *ta*ctile *con*verter), which was first marketed in 1970 as an electronic device that permitted blind people to read printed material (Bliss et al., 1970). It comprises a lens module that is moved by the user across a line of print and a tactile array onto which the blind person places his or her index finger. As the lens is moved across a line of print, an image roughly the size of one print letter is felt moving across the tactile display under the user's finger. The tactile display is composed of a 24 × 6 array of pins actuated by piezoelectric bimorphs that vibrate at 230 Hz and cause the pins to indent the skin.

The reading rate achieved with this system after training ranges from 50 (typical) to 100 (maximal) words per minute (wpm), which is considerably slower than the typical reading rates for English text of 300 wpm (600 wpm maximal) and 100 wpm (250 wpm maximal) for Braille (Reed & Durlach, 1998). Despite these limitations, more than 15,000 Optacon devices were sold by Telesensory Systems Inc. between 1970 and 1990, but by the mid-1990s page scanners with optical character recognition became the tool of choice for people with visual impairments, as the scanners were less expensive and easier to learn to use.

TABLE 1: Characteristics and Applications of Tactile Displays

Device	Function	Actuators	Display Location	Display Dimensions
Optacon[a]	Reading device for those with visual impairments	Piezoelectric bimorphs	Fingertip	24 × 6 pin array, vibrating at 230 Hz
Videotact[b]	Mobility aid for those with visual impairments	Titanium electrodes	Torso	768- and 32-electrode arrays
Tactaid 7[c]	Assists speech comprehension in those with hearing impairments	Inertial actuators	Sternum, neck, abdomen, or forearm	7 tactors, vibrating over 100- to 800-Hz range
Balance prosthesis[d]	Provides feedback of body tilt	Tactaid tactors (inertial actuators)	Torso	3 × 16 array of tactors around torso, vibrating at 250 Hz
Vibrating insoles[e]	Balance control and postural stability	Linear actuators (C2, Engineering Acoustics Inc.)	Insoles of shoes	3 tactors in each sole, vibrating at 250 Hz
TSAS[f]	Navigation aid for pilots	Pneumatic and electromechanical (rototactors)	Torso (vest)	22 pneumatic tactors, vibrating at 50 Hz; electromechanical tactors vibrating at 150 Hz
Personal tactile navigator[g]	Navigation aid in unfamiliar environments	DC pager motors	Waist belt	8 tactors vibrating at 160 Hz
CyberTouch[h]	Interaction with virtual environments	Electromechanical actuators	Hand	6 tactors, one on each finger, one on the palm, vibrating at 0 to 125 Hz

[a]Bliss et al., 1970. [b]ForeThought Development, LLC. [c]Audiological Engineering Inc. [d]Wall et al., 2001. [e]Priplata et al., 2003. [f]TSAS = Tactile Situation Awareness System; Rupert, 2000. [g]Van Erp et al., 2005. [h]Immersion Corp.

The torso has also been used as a site for tactile displays for people with visual impairments. In these systems a visual image is presented to the skin using an array of vibrotactile or electrotactile stimulators in which the intensity (pulse width or amplitude) of the stimulus delivered by each stimulator is controlled by the light intensity at a single camera pixel. Early studies with these tactile visual substitution systems (TVSSs) demonstrated that participants could identify the orientation of lines presented tactually on the back using an array of 400 vibrators and that experienced users could identify tactile images of common objects (Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969).

More recently, an array of 768 titanium electrodes called the Videotact has been fabricated and marketed as a tactile visual substitution device (ForeThought Development LLC, Madison, WI; http://www.4thtdev.com). This display is worn on the abdomen and shows promise as an aid for navigation in simple, high-contrast visual environments. In more cluttered visual environments TVSS systems are ineffective, as complex patterns need to be scanned sequentially, which significantly slows object recognition (Kaczmarek & Bach-y-Rita, 1995). However, a 96-element version (ETV 4) of the Videotact has been used successfully by operators to control a robot as it navigated through a 3-D maze (Segond, Weiss, & Sampaio, 2005).

A number of auditory prostheses have been developed that use electrotactile or vibrotactile inputs to assist with speech perception and production in deaf individuals and others with severe hearing impairments. Most of these systems are based on a cochlea model of speech with positional encoding of frequency information in the speech signal. Saunders, Hill, and Franklin (1981) developed an electrotactile auditory prosthesis known as the Teletactor, which transformed the acoustic spectrum of a speech sound into a tactile pattern that was presented using a belt of 32 electrodes worn around the abdomen. It was found to improve the speech clarity of deaf children and assist in auditory discrimination and comprehension in some older individuals (Szeto & Riso, 1990).

A vibrotactile aid known as the Tactaid (Audiological Engineering Corp.) has been commercially available for over 15 years and is used by deaf individuals and others with severe hearing impairments who are unable or do not want to use a cochlear implant. One version of this device uses seven tactors (Tactaid 7) that are in contact with the skin (usually on the sternum, neck, abdomen, or forearm), and variations in the amplitude, location, duration, and frequency (100–800 Hz) of the vibrotactile inputs are used to encode properties of the acoustic signal. The acoustic signal is initially processed to derive an estimate of the spectral location and amplitude of the first two formant regions of speech, which are then presented through the tactor array (Reed & Delhorne, 1995). Studies with this device in individuals with hearing impairments indicate that the Tactaid does facilitate the comprehension of some speech sounds (improvements in sentence comprehension average 25%) and the identification of environmental sounds (Galvin et al., 1999; Reed & Delhorne, 1995, 2003).

Tactile signals have also been shown to be of use in sound localization. In an early study, Békésy (1955) reported that with training, participants could localize sound sources accurately when the only cue regarding their origin was vibrotactile stimulation delivered to each forearm. In a later study using a similar system, Gescheider (1965) showed that the average error of sound localization was indeed very similar for the skin and the ears, at 10.3° and 8°, respectively.

A final and relatively recent innovation in the application of tactile displays as sensory substitution systems is in their use as balance prostheses for people with vestibular dysfunction (Priplata, Niemi, Harry, Lipsitz, & Collins, 2003; Wall et al., 2001). In one application, body tilt information is presented via a tactile display to improve postural stability, and hence prevent falls, in people with balance impairments (Wall & Weinberg, 2003). The vibrotactile display is worn around the torso and comprises a 3 × 16 array of tactors that vibrate at 250 Hz. Micro-Electro-Mechanical Systems inertial sensors are used to estimate body tilt angle, and the 16 circumferential columns of tactors indicate tilt direction, with each column having three rows that indicate tilt magnitude. Preliminary tests showed that use of the display significantly reduced the magnitude of body sway in participants with vestibular dysfunction (Wall & Weinberg, 2003).

A second application involves using tactors (three per foot) that are embedded in gel insoles worn on the feet and present "tactile noise" to the somatosensory system as a means of improving postural control. Priplata et al. (2003) found that postural sway was substantially reduced in healthy older individuals when vibration was applied to the feet and hypothesized that this resulted from enhanced sensory feedback from the feet when vibration was applied during standing.

Spatial Orientation and Navigation

A number of tactile displays have been designed to assist in spatial orientation and navigation in situations in which the human operator can become disoriented because of an absence of stable reference frames, such as when "cloud flying" or flying under high G-load conditions (Rupert, 2000; van Veen & van Erp, 2003), working in weightless environments in space (Rochlis & Newman, 2000; Traylor & Tan, 2002), or moving through unfamiliar terrain (Gilson, Redden, & Elliott, 2007; Jones et al., 2006; Lindeman, Sibert, Lathan, & Vice, 2004). In this application of tactile displays, vibrotactile stimuli are used to present information about the intended direction of personal or vehicle movement, the pitch and roll of an aircraft, and the location of way points in the environment.

A torso-based display known as the Tactile Situation Awareness System (TSAS) has been developed as a navigation aid for navy pilots (Rupert, 2000). Several prototypes of the TSAS have been developed and tested, some with pneumatically driven tactors and others with electromechanical stimulators. One prototype comprised 22 pneumatic tactors that were mounted in a vest worn under a flight suit and activated using oscillatory compressed air that forced the membrane on the tactor to vibrate at 50 Hz. The tactors were sequentially activated to provide information about the aircraft being controlled.

In one set of experiments the TSAS was used to provide pilots with information about helicopter velocity direction (tactor location) and velocity vector magnitude (pulse pattern) so that they could control hovering (motionless flight over a reference point) in the helicopter. A computer connected to the altitude and velocity sensors on the helicopter translated its position and movement into tactile signals. Test flights involving 4 pilots flying UH-60 helicopters were conducted and showed that the aircraft could be controlled using predominantly tactile cues (with visual cues significantly reduced), that there was improved control of the aircraft during these complex flight maneuvers, and that the TSAS facilitated situational awareness and reduced workload (McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004; Rupert, 2000).

The TSAS and other torso-based displays indicate that tactile signals presented to the torso can be used to control a vehicle and maintain spatial orientation. These displays can also be used to alert a human operator and provide information about the location of key features in an unknown environment.

A number of studies have demonstrated that tactile displays can assist in navigation in unfamiliar environments (Gilson et al., 2007; Jones et al., 2006; van Erp et al., 2005). In these contexts it has been important to ascertain the optimal configuration of the tactors in the display (e.g., a belt, a dorsal and/or ventral vest, arm bands) and determine how direction and distance information can be conveyed effectively.

Van Erp et al. (2005) used eight tactors worn in a belt around the waist to provide navigation cues, in which the specific tactor activated and the rate at which it vibrated was determined by the location of the next way point that the participant had to walk toward. They observed that participants could readily use the display as an effective navigation device (100% of way points achieved) but found that providing feedback about the distance to the next way point did not have any significant effect on walking speed. The tactile belt was also tested as a navigation aid for a helicopter pilot and a boat operator (rigid inflatable boat), and both individuals were able to use tactile cues effectively to navigate their vehicles through a series of waypoints. Consistent with Rupert's (2000) findings, van Erp et al. (2005) found that there did not appear to be any difficulty in interpreting vibrotactile signals in a vibrating environment.

Using a different navigation task, in which the direction of movement outdoors was signaled by a vibrotactile pattern delivered by a 4 × 4 tactor array mounted on the back, Jones et al. (2006) determined that participants had no difficulty in interpreting the vibration pattern to determine the path that they should follow. Moreover, they found that of the eight patterns presented, seven were always correctly responded to (100% accuracy), and only one error was made in response to the eighth pattern. These results, together with those from van Erp et al. (2005), indicate that with minimal training a tactile display mounted on the torso configured as either a belt or a vest can effectively convey navigation cues. Perception of vibrotactile signals is not impeded when observers are in vibrating vehicles and is still possible during high G-load (up to 6 G) conditions (van Veen & van Erp, 2000).

Exploration of Virtual Environments

Tactile feedback devices have also been built for exploring computer-generated virtual environments, in particular for presenting collision information during interaction with virtual objects or for providing rumble vibration in driving simulators. These devices vary from displays affixed to chairs that stimulate the back (Lindeman & Yanagida, 2003) to gloves that track the movements of the fingers and represent these together with contact in a virtual environment.

The CyberTouch glove developed by Immersion Corporation (San Jose, CA, http://www.immersion.com) for use in virtual environment applications has six individually programmable vibrotactile actuators, one mounted on the back of each finger and one on the palm. The configuration of the hand is recorded from 22 sensors that are located over the finger joints and the wrist, and the measurements from these sensors are used to drive the position and configuration of a virtual hand presented to the user on a visual display. The vibrotactile actuators attached to the glove are activated whenever the virtual hand interacts with a virtual object, which provides information about which fingers are in contact with the object.

At present, these tactile displays deliver rather simple vibrotactile inputs to the hand at single frequencies that are within the range of maximal sensitivities. The use of patterns of vibrotactile stimuli to convey information about objects or events in a real or simulated environment holds promise and is starting to be implemented in new mobile phones (e.g., Immersion Corp. and Sanyo Seimitsu's VibeTonz).

Communication of Complex Concepts and Messages

One particular form of tactile signals, so-called tactons or tactile icons, represents structured abstract messages that are designed to convey complex concepts and ideas (Brewster & Brown, 2004; MacLean & Enriquez, 2003; Rinker, Craig, & Bernstein, 1998; Roberts & Franklin, 2005). They are the tactile equivalent of visual icons and auditory earcons, which have been defined as an image, picture, symbol, or sound representing a specific event, object, or concept (Shneiderman, 1998). Pasquero (2006) proposed that in order to bring added value to an interaction, tactile or haptic or icons must be (a) easy to learn and memorize, (b) carry meaning or emotional content, and (c) be universal and intuitive, and, at the same time, support increasing levels of abstraction for expert users. The challenge in creating tactons is in identifying which stimulus parameters map most effectively onto which concept.

Tactons encode information by simultaneously manipulating several of the parameters of vibrotactile stimuli described previously (see the Vibrotactile Perception section) and illustrated in Figure 7. One critical but difficult aspect of designing tactons is in selecting those parameters and determining the range across which they can be varied. Early efforts focused primarily on first order dimensions, such as stimulation frequency, amplitude, and duration. Limitations associated with using some of these parameters were first noted by Geldard (1957, 1960) in his efforts to develop a tactile alphabetic code. Psychophysical studies of vibrotactile perception provide a framework for determining which stimulus dimensions and what range of values are most likely to be perceived, and they indicate how some of these dimensions, such as amplitude and frequency, interact.

It seems clear that stimuli that vary along a number of dimensions hold the most promise for the development of tactons that convey abstract concepts. MacLean and Enriquez (2003) used multidimensional scaling techniques to determine how haptic icons can be created from signal parameters such as waveform, frequency, and force. They found that for the ranges of parameters that they implemented in a handheld knob, frequency played a dominant role in distinguishing between the multidimensional stimuli and that waveform and force were less salient. As described earlier (see the Duration of Vibrotactile Stimulation section), temporal variations encoded in different rhythms can be readily identified and used to represent different tactons. Brown et al. (2005) found that by changing the modulation frequency of a base signal, waveforms were created that were perceived as varying in roughness (see Weisenberger, 1986). Rhythmic patterns were also found to be very effective by Summers (2000), who used temporal patterns as well as frequency and amplitude variations to encode speech information.

Another application of temporal pattern variations is the vibrotactile progress bar that Brewster and King (2005) developed as part of a desktop

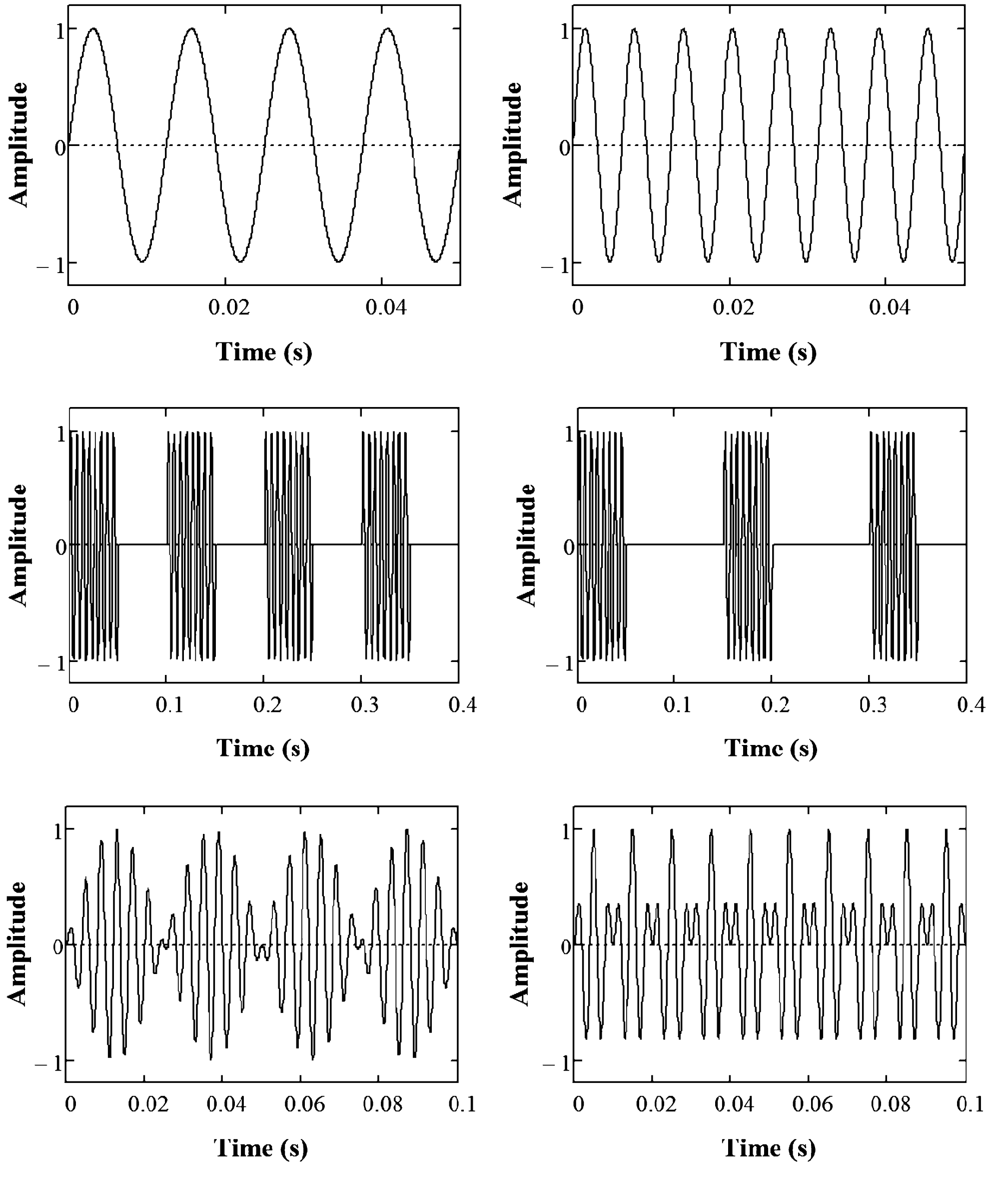

Figure 7. Types of signals that can be used to create tactons. Top panels: variations in signal frequency. Middle panels: variations in signal duration and repetition rate. Bottom panels: variations in complexity of waveform; 250 Hz signal modulated by 20 Hz (left) and 50 Hz (right).

interface design. In this situation, the time remaining is represented by variations in the time between vibrotactile pulses. The closer the pulses are presented in time, the nearer the system is to completing the download. Participants in the evaluation of this design not only preferred the tactile progress bar over the traditional visual one but also performed better in terms of tracking download progress in parallel with performing a main visual task.

Brewster and Brown (2004) have proposed three different types of tactons: compound tactons, hierarchical tactons, and transformational tactons. Compound tactons consist of a combination of two or more simple tactons (such as a high- vs. a low-frequency pulse). Hierarchical tactons represent nodes at various levels of a so-called tacton tree, in which tactons at lower levels inherit properties from tactons at higher levels. Transformational tactons encode several properties or pieces of information using different parameters. For example, if a transformational tacton is used to represent a computer file, the file type can be encoded by rhythm, the file size by frequency, and the creation date by body location.

Another approach to developing tactile or haptic icons involves identifying the basic elements, called haptic phonemes, and using these to create different haptic icons. With this method, Enriquez, MacLean, and Chita (2006) created a set of nine haptic icons that varied in terms of waveform and frequency. They then trained participants to associate each haptic icon with an arbitrary concept, such as the name of a fruit. They found that participants learned these associations after about 25 min of training and achieved higher identification rates with stimuli that varied in frequency (81% correct), as compared with those that varied in waveform (73% correct).

Tactons have been developed as a means of supporting attention and interruption management in complex, event-driven domains. In this case, several properties of an interrupting task or event are encoded in a vibrotactile signal to support people in determining whether or not to reorient their attentional focus immediately or after some delay (Woods, 1995). Tactons have been implemented as alerts on handheld devices such as pagers and mobile phones. Brown and Kaaresoja (2006) evaluated nine tactons that were used to communicate the type of alert (voice call, text message, or multimedia message, represented by rhythm) and the priority of the alert (low, medium, or high, represented by roughness or intensity). Overall recognition rates of 72% were achieved, with rhythm and intensity being highly recognizable but roughness showing significantly lower recognition rates.

Tactons can also be employed in the context of large-scale supervisory control environments. For example, Hameed, Ferris, Jayaraman, and Sarter (2006) developed an interface to support water control engineers in task scheduling and prioritization. They encoded the nature, urgency, and duration of a pending task by mapping this information on the location, characteristic frequency, and duration of the tactile signal, respectively (see Figure 8). The information encoded in these signals was correctly interpreted in 94%, 90%, and 83% of all cases, respectively. Based on this partial information about a pending task, participants were able to make more informed and appropriate decisions about attention switching than with traditional rather uninformative interruption cues. They were able to do so without incurring performance costs on their main visual task.

Other research has shown that complex tactile signals are, in principle, feasible and useful but that their success is highly context dependent. Chan, MacLean, and McGrenere (2005) found that seven haptic icons could easily be learned in the absence of workload and with minimal training. The authors also demonstrated that an increase in workload resulted in detection times that were significantly longer but still acceptable in most task contexts. The specific designs of the different icons used in this research did, however, influence their susceptibility to workload effects.

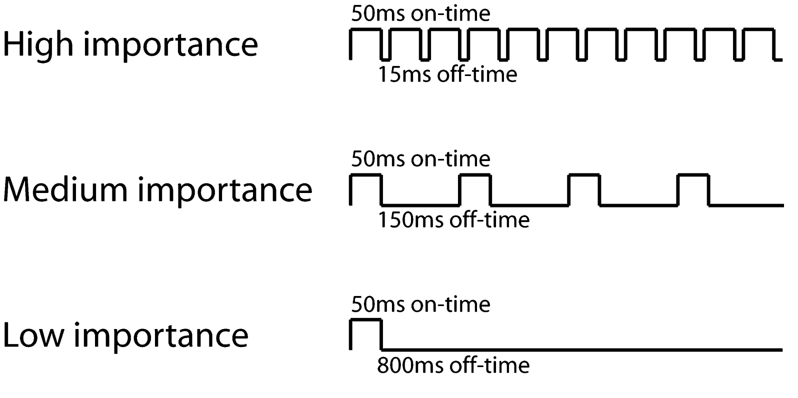

Figure 8. Graphical representation of cue duration and frequency representing different levels of importance. (Reproduced with permission from *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*. Copyright 2006 by the Human Factors and Ergonomics Society. All rights reserved.)

Summary

Vibrotactile displays have achieved some success as sensory substitution systems and, with new wireless communication systems, are being evaluated as aids to navigation in unfamiliar and hazardous environments. Their use in virtual environments has grown with the range of interfaces available to present tactile cues and clearly will expand further as devices become lighter and less cumbersome to use.

The optimal characteristics of a tactile display in terms of the minimum number of tactors required to present information and their spacing and location across the skin surface clearly depend on the nature of the information being transmitted. A display configured as a belt with eight tactors can effectively provide directional cues that are accurately perceived (van Erp et al., 2005), and the seven tactors worn by people with profound hearing impairments to assist in speech comprehension and the identification of environmental sounds have also been shown to be effective (Reed & Delhorne, 2003). Most of the systems developed and tested to date have stimulated the skin at a fixed frequency and amplitude and have varied the location and number of tactors simultaneously active to convey information. Recent research on the development of tactons offers considerable promise in determining the properties of a tactile vocabulary that can be used to communicate both simple and more abstract concepts.

THE ROLE OF TOUCH IN MULTIMODAL INTERFACES

Tactile displays are being developed both as stand-alone systems and as part of multimodal interfaces to complement other sensory channels and support a variety of functions. There is considerable empirical evidence that they represent a valuable addition to multimodal interfaces, provided their inclusion is based on need and appropriateness considerations, rather than the feasibility and availability of tactile technologies.

One need that can be supported by adding tactile components to an interface is an increased bandwidth of information transfer in complex, data-rich environments, such as process control and aviation, in which the visual and auditory channels have traditionally been heavily relied upon (Hale & Stanney, 2004; Oviatt, 2003; Sarter, 2006; Sklar & Sarter, 1999). The sense of touch is being used to off-load these modalities and to present information that would otherwise be delayed or not available at all.

Tactile displays also support modality appropriateness – that is, they increase the designer's ability to choose among modalities and assign functions and types of information to the channel that is best suited for their presentation. For example, spatial information maps well onto the human body, thus making the sense of touch the preferred medium for information related to orientation and navigation. Tactile stimuli also represent an effective means of attracting attention in a subtle yet reliable way (Ho, Reed, & Spence, 2006; Sarter, 2002, 2006). In some cases, they are therefore preferred over auditory cues, which tend to be highly intrusive and most appropriate for critical alarms that warrant interruption of any ongoing tasks and activities.

Other reasons for including tactile cues in multimodal interfaces are synergy (i.e., the merging of information that is presented via several modalities and refers to various aspects of the same event or process), redundancy (i.e., the use of several modalities for processing the exact same information in an effort to improve detection rates and interpretation accuracy), and privacy. Privacy is important in public spaces, where a person may prefer to receive tactile notifications from personal devices such as mobile phones. It is also beneficial in workplaces such as operating rooms, where medical personnel complain about auditory clutter from the large number of false and nuisance alarms, which can be annoying or distracting and which are sometimes relevant for only one or a few members of the surgical team.

Finally, as mentioned earlier, touch is the only modality capable of simultaneously sensing and acting on the environment. People often manipulate objects in their environment and, in fact, tend to feel that they need to handle and explore an object to have "seen" it. Tactile cues are therefore added to multimodal interfaces to support (a) grasping, manipulating, and identifying objects; (b) assessing texture, temperature, weight, and other attributes of objects; or (c) exploring spaces that are not accessible to vision (Burdea & Coiffet, 2003). Support for these functions is critical, for example, in the context of multimodal interfaces with virtual environments.

The inclusion of tactile signals in multimodal interfaces requires careful consideration of their combination and synchronization with signals presented in other modalities (Sarter, 2002, 2006). To date, little guidance has been available on how to approach this challenge. Some guidelines suggest that the combination of media should be minimized as much as possible (ISO, 1998), whereas others propose that modality combinations should be based on factors such as user preference, needs, and abilities (e.g., European Telecommunications Standards Institute, 2002; ISO, 1998; Sutcliffe, 2003).

According to Reeves et al. (2004), modality integration needs to be compatible not only with user preference but also with context and system functionality (see also Sutcliffe, 2003). In current multimodal systems, an auditory alert is often followed by the visual presentation of related information, For example, route guidance systems in cars use an auditory signal to notify the driver of an upcoming turn, and a visual display then provides more detailed information about the turn (Dingus & Hulse, 1993; Mollenhauer, Hulse, Dingus, Jahns, & Carney, 1997).

A rapidly growing body of work on cross-modal links in attention (for overviews see Driver & Spence, 2004; Spence, Nicholls, Gillespie, & Driver, 1998) can inform the effective use of tactile cues in multimodal interfaces for the purpose of guiding attention in other modalities. Ho, Tan, and Spence (2005) studied the use of such vibrotactile warning signals in the context of providing spatial information to car drivers. They presented drivers with a tactile stimulus on either their abdomen or back and asked them to respond by checking the front or the rearview mirror, respectively, for a rapidly approaching car and to brake or accelerate accordingly. They found that participants responded significantly faster following spatially predictive and nonpredictive vibrotactile cues that appeared on the same side as the critical driving events, thus showing that vibrotactile warning signals can be highly effective in directing a driver's visual attention.

Tactile cues have also been shown to be effective in guiding visual attention to the location of a critical event in the context of an air traffic control simulation (Hameed, Jayaraman, Ballard, & Sarter, 2007). In this study, participants monitored a display depicting the flight paths of 40 aircraft and were presented with tactile cues indicating either the occurrence only or both the occurrence and display location of an event requiring a response. Tactile cuing, especially when combined with location information, resulted in significantly higher detection rates and faster response times to these events.

RESEARCH NEEDS IN TACTILE DISPLAY DESIGN

The design of tactile interfaces is still at a rather early stage, and a number of important research questions remain to be addressed with respect to the design and effectiveness of tactile feedback by itself as well as to its integration with information presented in other modalities.

First, with respect to the design and implementation of tactile technologies, one important issue concerns the dimensions and configuration of tactile arrays in general and how they should change for specific locations on the body and as a function of the display's purpose. Currently, the size of these arrays varies considerably and often appears to be determined by trial and error or practical considerations. High-density arrays have generally been built for communication systems that involve the fingers (e.g., the Optacon, dynamic Braille cells), whereas more spatially diffuse devices are typically used on less sensitive areas of the body, such as the torso or arm. However, even on the torso the number of elements in the displays ranges from 8 to 128 (Jones, Kunkel, & Piateski, 2007; Rupert, 2000; van Veen & van Erp, 2000).

Psychophysical studies have demonstrated that increasing the number of tactors in the display does not necessarily lead to superior perceptual performance in localization tasks but that using anatomical points of reference when positioning the tactile display does enhance localization accuracy (Cholewiak & Collins, 2003; Cholewiak et al., 2004; van Erp, 2001). Given the range of body sizes that these displays will be mounted on, it will be important to determine whether it is better to use the available sensory area by adjusting intertactor distances to cover the skin surface or to maintain the same dimensions of the display for all users in a specific application.

Other challenges in tactile display design include the need for tactors that have a wide dynamic range, are power efficient, and are physically robust. In many of the environments in which it is envisaged that tactile displays will be employed, the human user will be active and assume a range of different body positions (e.g., crawling or climbing). Displays will need to be designed that can maintain continuous contact with the skin under these conditions and can present tactile signals of sufficient magnitude that they are readily attended to but not aversive.

A second challenge for tactile display design relates to real-world domains and the selection of appropriate sites for presenting tactile signals. The most sensitive body regions for tactile perception – the tongue, lips, and fingers – are off limits in most of these environments because of intrusiveness and interference with user tasks. Thus, each new tactile display design requires a trade-off decision between cutaneous sensitivity and feasibility/acceptance. Tactile patterns that are presented across a large sensory surface, such as the back, are easier to recognize than similar patterns presented on a smaller surface, such as on the forearm (Jones et al., 2006), but for both body sites high recognition accuracy is obtained with the judicious selection of tactile patterns (Jones, Kunkel, & Piateski, 2007).

One promising approach for creating wearable displays is to integrate tactile technologies with devices that users are wearing on a regular basis, such as headsets or seatbelts. It is also becoming increasingly feasible to integrate sensor and actuator technology into garments made with woven conductive fabrics that can be used for power and data transmission (Wade & Asada, 2006).

Research on tactile patterns and tactons has focused on their use in human-computer interactions and, in particular, on facilitating interactions with graphical interfaces (Brewster & Brown, 2004). A third research need is the development of tactons for navigation and communication in hazardous environments (Jones, Kunkel, & Torres, 2007). The number of tactons that are potentially available for communication in these contexts will need to be determined from analyses of how the basic parameters of vibrotactile signals can be combined to create unique icons. Stimulus parameters, such as stimulus waveform, that may be useful for tactons displayed in handheld devices (Brown et al., 2005) may be ineffective in displays mounted on other sites on the body. It seems clear that the number of tactons that can be accurately identified at any location depends on the degree of similarity among the various tactons presented (Enriquez et al., 2006; Jones, Kunkel, & Piateski, 2007).

A fourth issue that will need to be addressed is the effect of aging on tactile perception and how it impacts the design of tactile displays that are intended for a wide range of users. Overall, a reduced spatial acuity for most body locations has been reported for older people (J. C. Stevens & Choo, 1996). In addition, a recent study on cross-modal attentional narrowing by Hess and Sarter (2007) found that under conditions of high visual load, older drivers were significantly more likely to miss tactile cues than were their younger counterparts – a finding with important implications for the design of in-vehicle interfaces.

It appears that tactile cues are less affected by cross-modal spatial links and thus can be decoupled from other attentional processes easily and effectively (Eimer, 1999). Gray, Tan, and Young (2002) have shown that whereas visual and auditory stimuli have to be presented in close spatial proximity to produce performance benefits, proximal haptic cues can be used to reorient visual attention to areas in distal space.

Also, Ferris and Sarter (2008; this issue) found that ipsilateral cuing resulted in slower response times for visually cued tactile targets (compared with uncued tactile targets) but faster response times for auditorily cued visual targets (as opposed to uncued visual targets). Significantly faster responses were found for contralateral tactile cuing of auditory targets but not for contralateral auditory cuing of tactile targets. These findings clearly indicate the relevance of a fifth area for additional research concerned with cross-modal sensory interactions. Asymmetries in interactions and the effects of different modality pairings will need to be elucidated. The results from this research should then inform the design of multimodal interfaces that include a tactile component.

Finally, it is necessary to further develop possible ways of overcoming known limitations and breakdowns in tactile information processing related to factors such as masking – that is, a tactile stimulus not being perceived as a result of another tactile stimulus being presented immediately preceding or following that stimulus (Evans, 1987; Tan, Reed, Delhorne, Durlach, & Wan, 2003) – and change blindness, a failure to detect a change in a tactile pattern that is presented repeatedly in between other stimuli (Gallace, Tan, & Spence, 2006). The skin has a prodigious capacity for adaptation, and in the relatively new field of tactile displays, very little is known about the long-term effects of prolonged, but intermittent, cutaneous stimulation.

ACKNOWLEDGMENTS

Both authors would like to thank the Army Research Laboratory (Grant DAAD 19-01-2-0009; Collaborative Technology Alliance manager: Dr. Mike Strub; project manager: Sue Archer) for support of their work during the preparation of this manuscript. In addition, the second author would like to acknowledge the support of the National Science Foundation (Grant 0534281; program manager: Dr. Ephraim Glinert) in her work during the preparation of this manuscript.

REFERENCES

Bach-y-Rita, P., Collins, C. C., Saunders, F. A., White, B., & Scadden, L. (1969). Vision substitution by tactile image projection. *Nature, 221,* 963–964.

Békésy, G., von. (1955). Human skin perception of traveling waves similar to those on the cochlea. *Journal of the Acoustical Society of America, 27,* 830–841.

Békésy, G., von. (1959). Synchronism of neural discharges and their demultiplication in pitch perception on the skin and in hearing. *Journal of the Acoustical Society of America, 31,* 338–349.

Békésy, G.. von. (1962). Can we feel the nervous discharges of the end organs during vibratory stimulation of the skin? *Journal of the Acoustical Society of America, 34,* 850–856.

Bliss, J. C., Katcher, M. H., Rogers, C. H., & Shepard, R. P. (1970). Optical-to-tactile image conversion for the blind. *IEEE Transactions on Man-Machine Systems, MMS-11,* 58–65.

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

Brewster, S. A., & Brown, L. M. (2004). Tactons: Structured tactile messages for non-visual information display. In *Proceedings of the 5th Australasian User Interface Conference* (pp. 15–23). Sydney, Australia: Australian Computer Society.

Brewster, S. A., & King, A. (2005). The design and evaluation of a vibrotactile progress bar. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 499–500). Los Alamitos, CA: IEEE Computer Society.

Brown, L. M., Brewster, S. A., & Purchase, H. C. (2005). A first investigation into the effectiveness of tactons. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 167–176). Los Alamitos, CA: IEEE Computer Society.

Brown, L. M., & Kaaresoja, T. (2006). Feel who's talking: Using tactons for mobile phone alerts. In *Proceedings of the Conference on Human Factors in Computing Systems (CHI 2006),* (pp. 1–6). New York: Association for Computing Machinery Press.

Burdea, G., & Coiffet, P. (2003). *Virtual reality technology* (2nd ed.). Hoboken, NJ: Wiley-Interscience.

Chan, A., MacLean, K. E., & McGrenere, J. (2005). Learning and identifying haptic icons under workload. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 432–439). Los Alamitos, CA: IEEE Computer Society.

Cholewiak, R. W. (1979). Spatial factors in the perceived intensity of vibrotactile patterns. *Sensory Processes, 3,* 141–156.

Cholewiak, R. W., Brill, J. C., & Schwab, A. (2004). Vibrotactile localization on the abdomen: Effects of place and space. *Perception and Psychophysics, 66,* 970–987.

Cholewiak, R. W., & Collins, A. A. (2000). The generation of vibrotactile patterns on a linear array: Influences of body site, time and presentation mode. *Perception and Psychophysics, 62,* 1220–1235.

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

Craig, J. C. (1972). Difference threshold for intensity of tactile stimuli. *Perception and Psychophysics, 11,* 150–152.

Dingus, T. A., & Hulse, M. C. (1993). Some human factors design issues and recommendations for automobile navigation information systems. *Transportation Research, Part C, IC,* 119–131.

Driver, J., & Spence, C. (2004). Crossmodal spatial attention: Evidence from human performance. In C. Spence & J. Driver (Eds.), *Crossmodal space and crossmodal attention* (pp. 179–220). New York: Oxford University Press.

Eimer, M. (1999). Can attention be directed to opposite locations in different modalities? An ERP study. *Clinical Neurophysiology, 110,* 1252–1259.

Enriquez, M., MacLean, K. E., & Chita, C. (2006). Haptic phonemes: Basic building blocks of haptic communication. In *Proceedings of the 8th International Conference on Multimodal Interfaces (ICMI'06)* (pp. 302–309). Los Alamitos, CA: IEEE Computer Society.

Eskildsen, P., Morris, A., Collins, C. C., & Bach-y-Rita, P. (1969). Simultaneous and successive cutaneous two-point threshold for vibration. *Psychonomic Science, 14,* 146–147.

European Telecommunications Standards Institute. (2002). *Human factors (HF); Guidelines on the multimodality of icons, symbols and pictograms* (ETSI EG 202 048). Sophia Antipolis, France: Author.

Evans, P. M. (1987). Vibrotactile masking: Temporal integration, persistence, and strengths of representations. *Perception and Psychophysics, 42,* 515–525.

Ferris, T. K., & Sarter, N. B. (2008). Cross-modal links among vision, audition, and touch in complex environments. *Human Factors, 50,* 17–26.

Franzen, O., & Nordmark, J. (1975). Vibrotactile frequency discrimination. *Perception and Psychophysics, 17,* 480–484.

Gallace, A., Tan, H. Z., & Spence, C. (2006). Failure to detect tactile change: A tactile equivalent to the change blindness phenomenon. *Psychonomic Bulletin and Review, 13,* 300–303.

Galvin, K. L., Mavrias, G., Moore, A., Cowan, R. S., Blamey, P. J., & Clark, G. M. (1999). A comparison of Tactaid II+ and Tactaid 7 use by adults with a profound hearing impairment. *Ear and Hearing, 20,* 471–482.

Geldard, F. A. (1957). Adventures in tactile literacy. *American Psychologist, 12,* 115–124.

Geldard, F. A. (1960). Some neglected possibilities of communication. *Science, 131,* 1583–1588.

Geldard, F. A. (1975). *Sensory saltation.* Hillsdale, NJ: Erlbaum.

Geldard, F. A., & Sherrick, C. E. (1972). The cutaneous "rabbit": A perceptual illusion. *Science, 178,* 178–179.

Gemperle, F., Ota, N., & Siewiorek, D. (2001). Design of a wearable tactile display. In *Proceedings of the 5th International Symposium on Wearable Computers* (pp. 5–15). Los Alamitos, CA: IEEE Computer Society.

Gescheider, G. A. (1965). Cutaneous sound localization. *Journal of Experimental Psychology, 70,* 617–625.

Gescheider, G. A., Bolanowski, S. J., Pope, J. V., & Verrillo, R. T. (2002). A four-channel analysis of the tactile sensitivity of the fingertip: Frequency selectivity, spatial summation, and temporal summation. *Somatosensory and Motor Research, 19,* 114–124.

Gilson, R. D., Redden, E. S., & Elliott, L. R. (2007). *Remote tactile displays for future soldiers* (Tech. Rep. ARL-SR-0152.) Aberdeen Proving Ground, MD: Army Research Laboratory.

Goff, G. (1967). Differential discrimination of frequency of cutaneous mechanical vibration. *Journal of Experimental Psychology, 74,* 294–299.

Gray, R., Tan, H. Z., & Young, J. J. (2002). Do multimodal signals need to come from the same place? Crossmodal attentional links between proximal and distal surfaces. In *Proceedings of the Fourth IEEE International Conference on Multimodal Interfaces* (pp. 437–441). Los Alamitos, CA: IEEE Computer Society.

Hale, K. S., & Stanney, K. M. (2004). Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundation. *IEEE Computer Graphics and Applications, 24,* 33–39.

Hameed, S., Ferris, T., Jayaraman, S., & Sarter, N. B. (2006). Supporting interruption management through informative tactile and peripheral visual cues. In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting* (pp. 376–380). Santa Monica, CA: Human Factors and Ergonomics Society.

Hameed, S., Jayaraman, S., Ballard, M., & Sarter, N. B. (2007). Guiding visual attention by exploiting crossmodal spatial links: An application in air traffic control. In *Proceedings of the Human Factors and Ergonomics Society 51st Annual Meeting* (pp. 220–224). Santa Monica, CA: Human Factors and Ergonomics Society.

Hess, W. J., & Sarter, N. B. (2007). *Crossmodal and intramodal attentional narrowing and its interaction with aging.* Manuscript in preparation.

Ho, C., Reed, N., & Spence, C. (2006). Assessing the effectiveness of "intuitive" vibrotactile warning signals in preventing front-to-rear-end collisions in a driving simulator. *Accident Analysis and Prevention, 38,* 989–997.

Ho, C., Tan, H. Z., & Spence, C. (2005). Using spatial vibrotactile cues to direct visual attention in driving scenes. *Transportation Research Part F: Traffic Psychology and Behaviour, 8,* 397–412.

ISO. (1998). *Multimedia user interface design software ergonomic requirements: Part 3. Media combination and selection* (ISO 14915). Geneva, Switzerland: Author.

Jones, L. A., Kunkel, J., & Piateski, E. (2007). *Vibrotactile pattern recognition on the arm and back.* Manuscript submitted for publication.

Jones, L. A., Kunkel, J., & Torres, E. (2007). Tactile vocabulary for tactile displays. In *Proceedings of the Second Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 574–575). Los Alamitos, CA: IEEE Computer Society.

Jones, L. A., & Lederman, S. J. (2006). *Human hand function.* New York: Oxford University Press.

Jones, L. A., Lockyer, B., & Piateski, E. (2006). Tactile display and vibrotactile recognition on the torso. *Advanced Robotics, 20,* 1359–1374.

Kaaresoja, T., & Linjama, J. (2005). Perception of short tactile pulses generated by a vibration motor in a mobile phone. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 471–472). Los Alamitos, CA: IEEE Computer Society.

Kaczmarek, K. A., & Bach-y-Rita, P. (1995). Tactile displays. In W. Barfield & T. A. Furness (Eds.), *Virtual environments and advanced interface design* (pp. 349–414). New York: Oxford University Press.

Kaczmarek, K. A., & Haase, S. J. (2003). Pattern identification as a function of stimulation current on a fingertip-scanned electrotactile display. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11,* 269–275.

Kaczmarek, K. A., Webster, J. G., Bach-y-Rita, P., & Tompkins, W. J. (1991). Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE Transactions on Biomedical Engineering, 38,* 1–16.

Lévesque, V., Pasquero, J., & Hayward, V. (2007). Braille display by lateral skin deformation with the STReSS^2 tactile transducer. In *Proceedings of the Second Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 115–120). Los Alamitos, CA: IEEE Computer Society.

Lévesque, V., Pasquero, J., Hayward, V., & Legault, M. (2005). Display of virtual Braille dots by lateral skin deformation: Feasibility study. *ACM Transactions on Applied Perception, 2,* 132–149.

Lindeman, R. W., Sibert, J. L., Lathan, C. E., & Vice, J. M. (2004). The design and deployment of a wearable vibrotactile feedback system. In *Proceedings of the Eighth International Symposium on Wearable Computers* (pp. 56–59). Los Alamitos, CA: IEEE Computer Society.

Lindeman, R. W., & Yanagida, Y. (2003). Empirical studies for effective near-field haptics in virtual environments. In *Proceedings of the IEEE Virtual Reality Conference* (pp. 287–288). Los Alamitos, CA: IEEE Computer Society.

Lindeman, R. W., Yanagida, Y., Noma, H., & Hosaka, K. (2006). Wearable vibrotactile systems for virtual contact and information display. *Virtual Reality, 9,* 203–213.

McGrath, B. J., Estrada, A., Braithwaite, M. G., Raj, A. K., & Rupert, A. H. (2004). *Tactile situation awareness system flight demonstration final report* (USAARL Rep. 2004-10). Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory.

MacLean, K., & Enriquez, M. (2003). Perceptual design of haptic icons. In *Proceedings of Eurohaptics* (pp. 351–363). Dublin, Ireland: Trinity College.

Mahns, D. A., Perkins, N. M., Sahai, V., Robinson, L., & Rowe, M. J. (2006). Vibrotactile frequency discrimination in human hairy skin. *Journal of Neurophysiology, 95,* 1442–1450.

Mollenhauer, M. A., Hulse, M. C., Dingus, T. A., Jahns, S. K., & Carney, C. (1997). Design decision aids and human factors guidelines for ATIS displays. In Y. I. Noy (Ed.), *Ergonomics and safety of intelligent driver interfaces* (pp. 23–62). Mahwah, NJ: Erlbaum.

Montagu, A. (1971). *Touching: The human significance of the skin.* New York: Columbia University Press.

Morley, J. W., & Rowe, M. J. (1990). Perceived pitch of vibrotactile stimuli: Effects of vibration amplitude, and implications for vibration frequency coding. *Journal of Physiology, 431,* 403–416.

Mowbray, G. H., & Gebhard, J. W. (1957). Sensitivity of the skin to changes in rate of intermittent mechanical stimuli. *Science, 125,* 1297–1298.

Oakley, I., Kim, Y., Lee, J., & Ryu, J. (2006). Determining the feasibility of forearm mounted vibrotactile displays. In *Proceedings of the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 27–34). Los Alamitos, CA: IEEE Computer Society.

Oviatt, S. (2003). Multimodal interfaces. In J. Jacko & A. Sears (Eds.), *Handbook of human-computer interaction* (pp. 286–304). Hillsdale, NJ: Erlbaum.

Pasquero, J. (2006). *Survey on communication through touch* (Tech. Rep. TR-CIM 06.04). Montreal, Canada: McGill University, Department of Electrical and Computer Engineering, Center for Intelligent Machines.

Piateski, E., & Jones, L. (2005). Vibrotactile pattern recognition on the arm and torso. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 90–95). Los Alamitos, CA: IEEE Computer Society.

Poupyrev, I., Maruyama, S., & Rekimoto, J. (2002). Ambient touch: Designing tactile interfaces for handheld devices. In *Proceedings of the ACM Symposium on User Interface Software and Technology* (Vol. 4, pp. 51–60). New York: Association for Computing Machinery Press.

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.

Reed, C. M., & Delhorne, L. A. (1995). Current results of a field study of adult users of tactile aids. *Seminars in Hearing, 16,* 305–315.

Reed, C. M., & Delhorne, L. A. (2003). The reception of environmental sounds through wearable tactual aids. *Ear and Hearing, 24,* 528–538.

Reed, C. M., & Durlach, N. I. (1998). Note on information transfer rates in human communication. *Presence, 7,* 509–518.

Reeves, L. M., Lai, J., Larson, J. A., Oviatt, S., Balaji, T. S., Buisine, S., et al. (2004). Guidelines for multimodal user interface design. *Communications of the ACM, 47,* 57–59.

Rinker, M. A., Craig, J. C., & Bernstein, L. E. (1998). Amplitude and period discrimination of haptic stimuli. *Journal of the Acoustical Society of America, 104,* 453–463.

Roberts, J. C., & Franklin, K. (2005). Haptic glyphs (Hlyphs) – Structured haptic objects for haptic visualization. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 369–374). Los Alamitos, CA: IEEE Computer Society.

Rochlis, J. L., & Newman, D. J. (2000). A tactile display for International Space Station (ISS) extravehicular activity (EVA). *Aviation, Space, and Environmental Medicine, 7,* 571–578.

Rollman, G. B. (1973). Electrocutaneous stimulation. In F. Geldard (Ed.), *Cutaneous communication systems and devices* (pp. 38–51). Austin, TX: Psychonomic Society.

Rothenberg, M., Verrillo, R. T., Zahorian, S. A., Brachman, M. L., & Bolanowski, S. J. (1977). Vibrotactile frequency for encoding a speech parameter. *Journal of the Acoustical Society of America, 62,* 1003–1012.

Rupert, A. H. (2000). An instrumentation solution for reducing spatial disorientation mishaps: A more "natural" approach to maintaining spatial orientation. *IEEE Engineering in Medicine and Biology Magazine, March/April,* 71–80.

Sarter, N. B. (2002). Multimodal information presentation in support of human-automation communication and coordination. In E. Salas (Ed.), *Advances in human performance and cognitive engineering research* (pp. 13–36). New York: JAI Press.

Sarter, N. B. (2006). Multimodal information presentation: Design guidance and research challenges. *International Journal of Industrial Ergonomics, 36,* 439–445.

Saunders, F. A. (1973). Electrocutaneous displays. In F. Geldard (Ed.),

Cutaneous communication systems and devices (pp. 20–26). Austin, TX: Psychonomic Society.
Saunders, F. A., Hill, W. A., & Franklin, B. (1981). A wearable tactile sensory aid for profoundly deaf children. *Journal of Medical Systems, 5,* 265–270.
Segond, H., Weiss, D., & Sampaio, E. (2005). Human spatial navigation via a visuo-tactile sensory substitution system. *Perception, 34,* 1231–1249.
Sherrick, C. E. (1953). Variables affecting sensitivity of the human skin to mechanical vibration. *Journal of Experimental Psychology, 45,* 273–282.
Sherrick, C. E. (1985). A scale for rate of tactual vibration. *Journal of the Acoustical Society of America, 78,* 78–83.
Shneiderman, B. (1998). *Designing the user interface.* Reading, MA: Addison-Wesley.
Sklar, A. E., & Sarter, N. B. (1999). "Good vibrations": The use of tactile feedback in support of mode awareness on advanced technology aircraft. *Human Factors, 41,* 543–552.
Spence, C., Nicholls, M. E. R., Gillespie, N., & Driver, J. (1998). Crossmodal links in exogenous covert spatial orienting between touch, audition, and vision. *Perception and Psychophysics, 60,* 544–557.
Stevens, J. C., & Choo, K. K. (1996). Spatial acuity of the body surface over the life span. *Somatosensory and Motor Research, 13,* 153–166.
Stevens, S. S. (1968). Tactile vibration: Change of exponent with frequency. *Perception and Psychophysics, 3,* 223–228.
Summers, I. R. (2000). Single-channel information transfer through the skin: Limitations and possibilities. In *Proceedings of the 6th International Conference on Tactile Aids, Hearing Aids and Cochlear Implants* (pp. 105–108). Exeter, UK: University of Exeter.
Summers, I. R., Cooper, P. G., Wright, P., Gratton, D. A., Milnes, P., & Brown, B. H. (1997). Information from time-varying vibrotactile stimuli. *Journal of the Acoustical Society of America, 102,* 3686–3696.
Summers, I. R., Dixon, P. R., Cooper, P. G., Gratton, D. A., Brown, B. H., & Stevens, J. C. (1994). Vibrotactile and electrotactile perception of time-varying pulse trains. *Journal of the Acoustical Society of America, 95,* 1548–1558.
Sutcliffe, A. (2003). *Multimedia and virtual reality: Designing multisensory user interfaces.* Mahwah, NJ: Erlbaum.
Szeto, A. Y. J., & Riso, R. R. (1990). Sensory feedback using electrical stimulation of the tactile sense. In R. V. Smith & J. H. Leslie, Jr. (Eds.), *Rehabilitation engineering* (pp. 29–78). Boca Raton, FL: CRC Press.
Tan, H. Z., Gray, R., Young, J. J., & Traylor, R. (2003, June 11). A haptic back display for attentional and directional cueing. *Haptics-e, 3,* Article 1. Retrieved November 2, 2007, from http://haptics-e.org/Vol_03/he-v3n1.pdf
Tan, H. Z., Reed, C. M., Delhorne, L. A., Durlach, N. I., & Wan, N. (2003). Temporal masking of multidimensional tactual stimuli. *Journal of the Acoustical Society of America, 114,* 3295–3308.
Traylor, R., & Tan, H. Z. (2002). Development of a wearable haptic display for situation awareness in altered-gravity environment: Some initial findings. In *10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperation Systems* (pp. 159–164). Los Alamitos, CA: IEEE Computer Society.
van Erp, J. B. F. (2001). Tactile navigation display. In S. Brewster & R. Murray-Smith (Eds.), *Haptic HCI 2000* (pp. 165–173). Berlin: Springer-Verlag.
van Erp, J. B. F. (2005). Presenting directions with a vibrotactile torso display. *Ergonomics, 48,* 302–313.
van Erp, J. B. F., van Veen, A. H. C., Jansen, C., & Dobbins, T. (2005). Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception, 2,* 106–117.
van Veen, H. A. H. C., & van Erp, J. B. F. (2000). Tactile information presentation in the cockpit. In S. Brewster & R. Murray-Smith (Eds.), *Haptic HCI 2000* (pp. 174–181). Berlin: Springer-Verlag.
van Veen, H. A. H. C., & van Erp, J. B. F. (2003). Providing directional information with tactile torso displays. *Eurohaptics*, 471–474.
Verrillo, R. (1963). Effect on contactor area on the vibrotactile threshold. *Journal of the Acoustical Society of America, 35,* 1962–1966.
Verrillo, R. T. (1973). Vibrotactile intensity scaling at several body sites. In F. Geldard (Ed.), *Cutaneous communication systems and devices* (pp. 9–14). Austin, TX: Psychonomic Society.
Verrillo, R. T., & Chamberlain, S. C. (1972). The effect of neural density and contactor surround on vibrotactile sensation magnitude. *Perception and Psychophysics, 11,* 117–120.
Verrillo, R. T., Fraioli, A. J., & Smith, R. L. (1969). Sensation magnitude of vibrotactile stimuli. *Perception and Psychophysics, 6,* 366–372.
Wade, E., & Asada, H. H. (2006). DC behavior of conductive fabric networks with application to wearable sensor nodes. In *Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks* (pp. 27–30). Los Alamitos, CA: IEEE Computer Society.
Wall, C., III, & Weinberg, M. S. (2003). Balance prostheses for postural control. *IEEE Engineering in Medicine and Biology Magazine, March/April,* 84–90.
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.
Wang, Q., & Hayward, V. (2006). Compact, portable, modular, high-performance, distributed tactile transducer device based on lateral skin deformation. In *Proceedings of the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (pp. 67–72). Los Alamitos, CA: IEEE Computer Society.
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: Charles C. Thomas.
Weisenberger, J. M. (1986). Sensitivity to amplitude-modulated vibrotactile signals. *Journal of the Acoustical Society of America, 80,* 1707–1715.
Wilska, A. (1954). On the vibrational sensitivity in different regions of the body surface. *Acta Physiologica Scandinavica, 31,* 285–289.
Woods, D. D. (1995). The alarm problem and directed attention in dynamic fault management. *Ergonomics, 38,* 2371–2393.

Lynette A. Jones is a principal research scientist in the Department of Mechanical Engineering at the Massachusetts Institute of Technology, Cambridge. She obtained her Ph.D. in psychology from McGill University in 1983.

Nadine B. Sarter is an associate professor in the Department of Industrial and Operations Engineering – Center for Ergonomics at the University of Michigan, Ann Arbor. She received her Ph.D. in industrial and systems engineering from Ohio State University in 1994.

Date received: November 9, 2006
Date accepted: September 21, 2007