

# 18 EXPLORING THE TACTILE MODALITY FOR HMDs<sup>1</sup>

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## The Concept of Tactile Interfaces

Humans commonly are considered to have five separable named senses, called hearing, sight (vision), smell, taste, and touch, providing information about the external world. These senses, their organs, and respective modalities are listed in Table 18-1. The two most dominant senses are sight and hearing. Equipment designers understand human reliance on these two senses and have used them as the basis for most instruments and controls, as would be expected since humans manipulate and receive most feedback from their external environment based on what they see and hear. However, humans have a limited capacity to receive, hold in working memory, and cognitively process information taken from the environment through any particular sensory pathway. For operators of complex or multiple systems processing demands may be so large that the sole reliance on sight and hearing can lead to an overloading of these two sensory channels (Sorkin, 1987; van Veen and van Erp, 2001).

Table 18-1.  
Five senses providing information about the surrounding environment (Modified from Silbernagel [1979]).

Sense	Sense Organ	Sensory Modality
Hearing	Ears	Auditory
Sight (Vision)	Eyes	Visual
Smell	Nose	Olfactory
Taste	Tongue	Gustatory
Touch	Skin	Tactile *

\* Sense of touch also provides sensations of heat and pain.

When a single sensory channel is overloaded with information, and the user becomes incapable of processing all incoming information, it can result in a rapid increase in errors (Oviatt, 1999) and a decrease in situational awareness and overall user performance. One way to reduce the sensory overload is to deliver part of this information through unused or underutilized sensory modalities. A multimodal system using several sensory modalities to transmit information between the environment and the user will lessen the chance of any one sensory mode becoming overloaded (Oviatt, 1999; Wickens, 1984, 2002). Oviatt (1999) explains that the goal of multimodal systems should be to “integrate complementary modalities to yield a highly synergistic blend in which the strengths of each mode are capitalized upon and used to overcome weaknesses in the other” (p. 74). Thus, tactile displays take advantage of the sense of touch to distribute the cognitive workload among visual, auditory, and tactile sensory channels.

Smell and taste both involve the analysis of chemical molecules. Humans perceive odors via the sense of smell and the flavor of foodstuffs via the sense of taste. Smell, like vision and hearing, is a spatial telereceptor and has already been considered in virtual reality applications (Psofka, Division and Lewis, 1993). The tongue is rich with

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receptors and can discriminate five distinct tastes (salt, sweet, sour, bitter, and umami), which guide our food preferences, especially away from potentially harmful substances (Smith and Margolskee, 2006). Taste has been also reported to be successfully used by the blind as a substitute sense for navigation in space. An array of electrodes placed on a tongue has been used to help blind people to navigate or to catch moving object. (Bach-y-Rita et al., 1998). However, both smell and taste pose challenges for use as informational interfaces. Therefore, of smell, taste, and touch; touch – specifically the cutaneous (related to skin) mechanical, aspect of touch called *taction* – is the most conducive to being used as a human system interface.

Touch is the sense by which external objects or forces are perceived through contact with the body (Stedman's Medical Dictionary, 2004). It is a part of the somatic (somatosensory) system that receives external and internal information about the state of the body. Somatic senses are divided into cutaneous senses (touch), proprioception, and visceral senses. Proprioception includes the vestibular system (sense of balance) and kinesthetic senses. Kinesthetic senses inform the brain about relative positions of various body parts and their movement. Visceral senses inform the brain about the state of internal organs and overall body condition (e.g., hunger, fatigue, stomach ache).

The main operational advantages of touch over smell and taste sensory channels are a large area of possible stimulation, relatively large dynamic range, and natural directional capabilities. Touch includes sensations of pressure, heat-and-cold, and pain. The sensation of pressure is referred to as *taction* or *tactition* (from Latin *tactus*; touched) or as the tactile modality. A hierarchical taxonomy of terms related to touch and *taction* is shown in Figure 18-1. The solid lines show the “branch” of taxonomy of interest in this chapter; branches along the dotted lines are informational and not exhaustive.

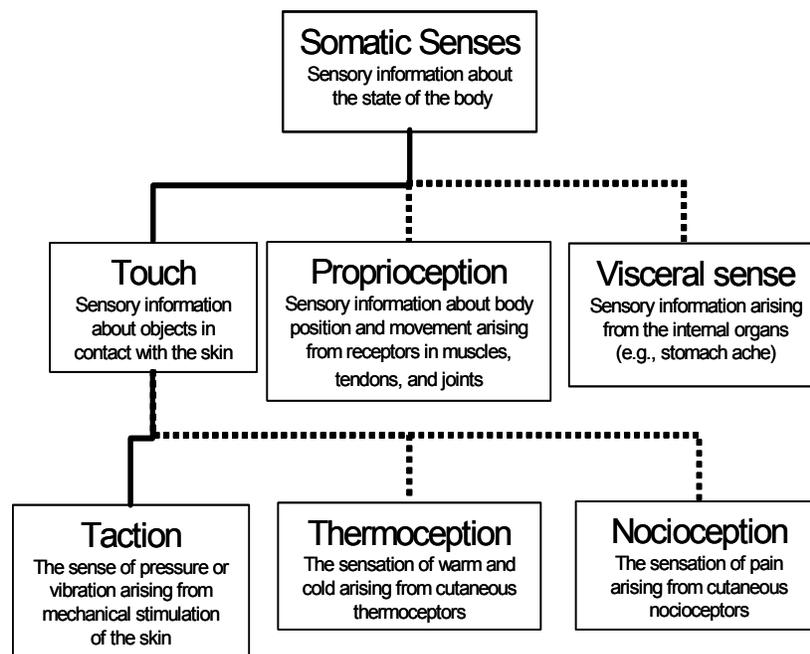


Figure 18-1. Graphical representation of a taxonomy related to touch.

One additional term that is frequently used in relation to touch is *haptics*. Most authors use the words *haptic* and *tactile* as synonymous (Stedman's Medical Dictionary, 2004). However, some authors consider haptic sensation as a combination of tactile and kinesthetic sensations resulting from the opposition to movement of the object touching the skin (Geiser, 1990; Youngblut et al., 1996). Therefore, haptic perception frequently is referred

to as the perception of three-dimensional (3-D) objects (size, weight, temperature, texture, etc.) held in or being pushed by the hand. The latter meaning of the term *haptics* is used in this chapter.

As shown in Figure 18-1, the skin responds to several types of stimulation. Receptors in the skin can be stimulated by mechanical, thermal, electrical, and chemical means. However, the latter three types of stimulation are not good candidates for interfaces, since they produce sensations that are hard to precisely localize (e.g., Mauderli et al., 2003). In addition, there are obvious issues with undesirable outcomes of a thermal, electrical, or chemical stimulation, such as pain and dermal damage. Conversely, mechanical receptors have several properties that make them good receptors of communication signals. Mechanical stimulation of the skin may have two forms: *constant stimulation*, resulting in the sensation of skin deflection, and *variable stimulation*, resulting in the sensation of skin vibration (referred sometimes to as “prickling”). The former usually is referred to as tactile or pressure stimulation and the latter as vibrotactile stimulation. An example of a constant tactile signal is a modified computer mouse which raises a piston against the finger when the mouse is positioned over an on-screen button, giving tactile feedback regarding cursor location (Akamastu, MacKenzie and Hasbrouq, 1995).

Vibrotactile stimulation can be used to send various coded signals, since it can vary in frequency, intensity, and temporal pattern. The use of the tactile or vibrotactile interface as an information channel can be beneficial in multimodal systems, especially when the visual and/or auditory channels are heavily loaded (Gemperle, Ota and Siewiorek, 2001; Raj, Kass and Perry, 2000; van Erp, 2001). Vibrotactile displays also have been proven to help fill the communication gap when the visual and/or auditory sensory modalities are weakened (Raj et al., 2000; Schrope, 2001; van Erp and van Veen, 2001). Various types of vibrotactile displays have been used successfully in a number of applications: assistance for the blind, video games, human-machine interfaces, and virtual reality enhancements. An example of a common vibrotactile display is an alert device built into pagers and cellular phones for use when an auditory signal may disturb or alert others. In summary, the tactile modality is beneficial for transmitting environmental information to the user. However, in order to design a useful tactile or vibrotactile interface, the designer needs to understand the limitations of tactile stimulation and the boundaries of useful tactile parameters.

## The Physiological Basis of Tactile Stimulation

Skin is a layer of cells that protect the tissue underneath and help to maintain body temperature. Human skin has an area of 1.8 meter<sup>2</sup> (m<sup>2</sup>) (19.4 feet<sup>2</sup> [ft<sup>2</sup>]), a density of 1250 kilogram/meter<sup>3</sup> (kg/m<sup>3</sup>) (78 pounds [lb]/ft<sup>3</sup>), and a weight of 5 kg (11 lbs) (Sherrick and Cholewiak, 1986). It is classified as either glabrous (non-hairy) skin, which is found only on the plantar and palmar surfaces, or hairy skin, which is found on the rest of the body. This division is relevant to tactile displays because these skin types differ in sensory receptor systems and tactile sensitivity (Cholewiak and Collins, 1995).

The skin has two primary layers called the epidermis (outer layer) and the dermis (inner layer). In the dermal layer and at the interface of the epidermis and dermis, there are many spatially distributed free nerve endings that collect and disburse information about objects coming in contact with the skin. These free nerve endings are slowly-adapting (SA) receptors that are sensitive to mechanical, thermal, electrical, and chemical energy and convert these to neural signals, producing sensations of heat or pain (Patestas and Gartner, 2006). In addition, groupings of fast acting hair follicle receptors surround skin hair follicles and respond to skin displacement near the base of skin hair when the hair is touched (Cholewiak and Collins, 1991; Sherrick and Cholewiak, 1986).

In addition to free nerve endings and hair follicle receptors, there are four specialized types of mechanoreceptors in the skin that respond to pressure and vibration. These four types of mechanoreceptors are Pacinian corpuscles, Merkel cells (or Merkel disks), Ruffini endings (or Ruffini corpuscles), and Meissner corpuscles. Each of these cell types has a specific sensory nerve channel associated with it called P (Pacinian channel), NPI (Non-Pacinian channel I), NPPII (Non-Pacinian channel II), and NPPIII (Non-Pacinian channel III), respectively (Bolanowski et al., 1988; Cholewiak and Collins, 1991; Klatzky and Lederman, 2002). The main

difference between the channels is their frequency response. A summary of the basic properties of the four mechanoreceptors is shown in Table 18-2.

A cross-section of the skin showing the types and locations of the various mechanoreceptors is shown in Figure 18-2.

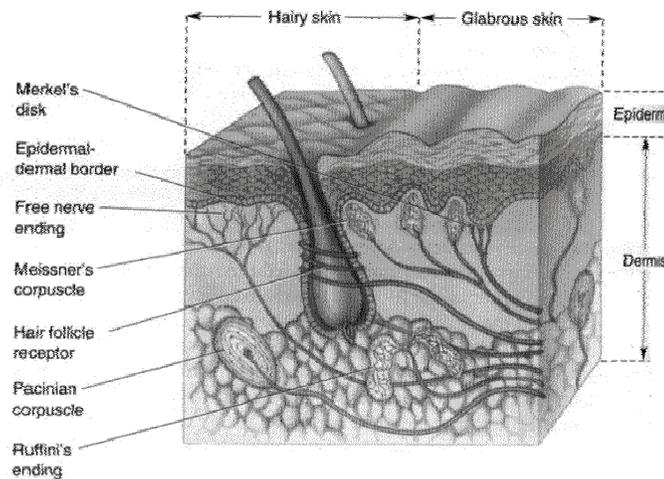


Figure 18-2. The somatosensory receptors of the skin (Kohler, 2001). Somatosensory senses ([http://www.humboldt.edu/~jgk5/cutaneous\\_senses.htm](http://www.humboldt.edu/~jgk5/cutaneous_senses.htm)).

Each mechanoreceptor type (and associated neural channel) has a specific role in the perception of vibration which extends from almost 0 Hz to greater than 500 Hz (Bolanowski et al., 1988; Cholewiak, Collins and Brill, 2001; Gemperle et al., 2003). Some of them are SA cells (pressure detectors), which respond while the stimulus is present with no decrease in firing rate, whereas others are the rapidly-adapting (RA) (change detectors), which respond with bursts of firing in response to a change in stimulation. RA change detectors discharge when the sensory cell is compressed and again when the cell is restored to its resting state. SA sustained pressure detectors discharge when the cell is compressed and continue to discharge until the stimulus ceases to act (Patesta and Gartner, 2006).

Pacinian corpuscles are the largest and the most sensitive receptors in the skin (Bear, Connors and Paradiso, 2006; Fig. 12.4, p. 391). They have an oval shape (up to 1 millimeter [mm] x 4 mm [0.04 inch [in] x 0.16 in]) and are located at a moderate depth in the skin (about 2 to 3 mm [0.08 x 0.12 in]) (Sherrick and Cholewiak, 1986). The sensitivity function of Pacinian corpuscles has a “U” shape with maximum sensitivity occurring in the 250 to 300 Hz range (Bolanowski et al., 1988; Lamore and Keemink, 1988; Verrillo, 1962, 1966). The Pacinian corpuscles are rapidly adapting and sensations for these receptors are described as deep and diffuse (Sherrick, Cholewiak and Collins, 1990). Pacinian corpuscles are located deeply in the dermis and have relatively large receptive fields, that is, regions over which skin stimulation excites a primary afferent fiber, of about 100 mm<sup>2</sup> (0.16 in<sup>2</sup>) (Youngblut et al., 1996).

Merkel cells are slowly adapting cells, which are sensitive to constant pressure. The cells have a cross-section of 10 to 15 microns (μm), are located in the upper layers of the dermis, and have a small receptive field of about 10 mm<sup>2</sup> (0.016 in<sup>2</sup>) (Youngblut et al., 1996). Meissner corpuscles are located just below the epidermis and are sensitive to low frequency vibration below 300 Hz (Sherrick, Cholewiak and Collins, 1990) but are most sensitive to frequencies of stimulation in the 20 to 50 Hz range. The Meissner corpuscles are rapidly adapting receptors having a small receptive field averaging 10 mm<sup>2</sup> (0.016 in<sup>2</sup>) (Youngblut et al., 1996). Sensations for these receptors are felt as a gentle skin flutter, sometimes called the “flutter sense” (Sherrick, Cholewiak and Collins, 1990). The size of a Meissner corpuscle is between 30 to 140 μm in length and 20 to 60 μm in width (Guinard et

Table 18-2.  
 Characteristics of the four types of mechanoreceptors in the human skin.  
 (Bear et al., 2006; Bolanowski et al., 1988; van Erp and van den Dobbela, 1998)

Location	Type of Mechanoreceptor	
	Rapidly-Adapting (RA) Receptors	Slowly-Adapting (SA) Receptors
Superficial skin (small receptive field, e.g., 1 to 3 mm [0.04 to 0.12 in])	Meissner corpuscle (RAI NPI) Operate in the 5-300 Hz range. U shaped sensitivity curve; most sensitive 20-50 Hertz (Hz). Sensitivity independent of temperature. No temporal summation. Cause "flutter" (prickling) sensation.	Merkel cell (SAI, NPIII) Operate in the 0.4-100 Hz range. Relatively flat sensitivity curve. Sensitivity slightly dependent on temperature. Sensitive to tactile form and roughness (texture).
Deeper tissue (large receptive field, e.g., 6-10 mm [0.24 to 0.4 in])	Pacinian corpuscle (RAII, P) Operate in the 10-1000 Hz range. U shaped sensitivity curve; most sensitive 250-300 Hz. Sensitivity very dependent on temperature. Spatial and temporal summation. Non-localized vibration sensation.	Ruffini ending (SAII, NPII) Operate in the 15-400 Hz range; at a much lower sensitivity. Relatively flat sensitivity curve. Sensitivity very dependent on temperature. Sustained pressure receptors. Skin stretch receptors.

al., 2000). They are particularly numerous on extremities but sparse on the skin of the back, and their number decreases with age.

Ruffini endings are slowly adapting receptors responding to constant pressure and very slow vibration. They are also thermoreceptors and are sensitive to directional skin stretch. Ruffini endings have relatively large receptive fields averaging about  $60 \text{ mm}^2$  ( $0.09 \text{ in}^2$ ) (Youngblut et al., 1996).

As the four mechanoreceptors overlap in their absolute sensitivities and receptive fields, a complex or variable vibratory stimulation will seldom activate one receptor because the energy applied to the skin will move throughout nearby skin tissues (Sherrick and Cholewiak, 1986; van Erp and van den Dobbelsteen, 1998). When constant pressure is applied to the skin, the smallest absolute threshold of sensation is about 0.03 erg and the minimum noticeable difference in stimulus intensity is about 3% (Eysenck, Arnold and Meili, 1972).

Neural stimuli caused by tactile stimulation travel through ascending neural pathways of the dorsal root ganglion, medulla oblongata, and medial lemniscus; and enter the cerebral cortex at the ventral posterior nucleus of thalamus (Bear, Connors and Paradiso, 2006). The primary somatosensory areas of the brain are located in the parietal lobe (Kohler, 2001). The ascending pathways of the neural responses to touch are shown in Figure 18-3.

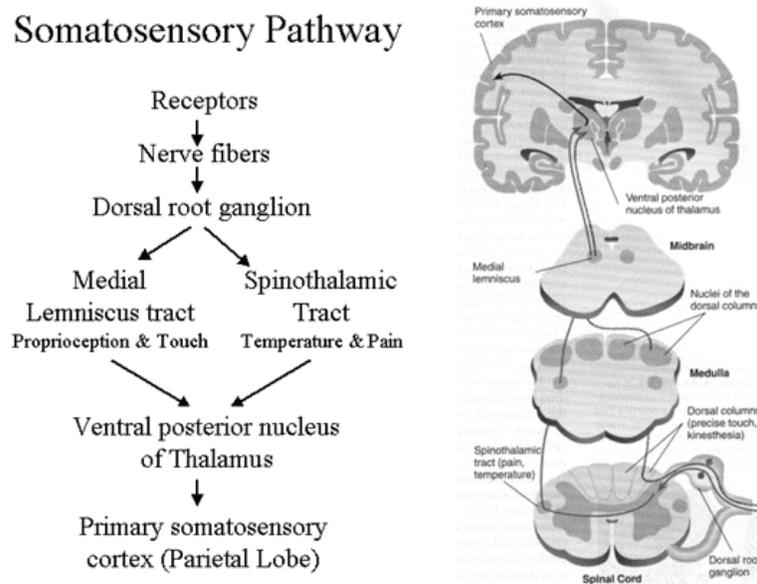


Figure 18-3. Basic ascending pathways of the touch neural impulses (Kohler, 2001) Somatosensory senses ([http://www.humboldt.edu/~jgk5/cutaneous\\_senses.htm](http://www.humboldt.edu/~jgk5/cutaneous_senses.htm)).

## Elements of Vibrotactile Perception

Head-mounted tactile displays, especially vibrotactile displays, are relatively new and sparsely applied; therefore, much of the discussion of vibrotactile perception and interface design included in this chapter is based on knowledge gained from the tactile interfaces designed for other areas of the body. This knowledge nonetheless gives insight regarding vibrotactile sensitivities, spatial resolution, and other parameters of touch to be considered in designing helmet-mounted and head-mounted systems.

Weber's (1834/1978) and Weinstein's (1968) early research on tactile perception provides the basis for what is currently known about relative tactile sensitivity for various body sites. Basic parameters that must be considered in designing head-mounted vibrotactile systems include frequency- and location-dependent pressure sensitivities (vibrotactile thresholds), stimulation localization accuracy, and spatial resolution. Additionally, temporal

resolution is of interest to designers so that signals will not be presented so closely in time as to be indistinguishable.

## Sensitivity

Similar to the relationship found for the visual and auditory modalities, the threshold of vibrotactile sensation is inversely proportional to the amount of energy applied to the skin (Verrillo, 1966). However, skin sensitivity and mechanical impedance vary in different areas of the body due to differences in skin “thickness, vascularity, density, electrical conductivity, and more derived properties, such as moduli of shear and elasticity” (Sherrick and Cholewiak, 1986; Weber, 1834/1978). Skin vibrations are detected best on hairy, bony skin but are not detected as well on soft, fleshy areas of the body (Gemperle et al., 2003). This means that the head and scalp are parts of the body that are relatively sensitive to vibrotactile stimulation. In addition, skin sensitivity decreases as you move from distal to proximal portions of extremities (Sherrick, Cholewiak and Collins, 1990; Van Erp and van den Dobbelen, 1998; Wilska, 1954).

Weinstein (1968) investigated whether tactile sensitivity differed for gender and for the left and right sides of the body (for various locations on the body). He found that women were more sensitive than men to skin stimulation and that skin sensitivity was generally the same for both the left and right sides of the body. For specific body location, the forehead (face), trunk, and fingers were most sensitive and the lower extremities least sensitive to mechanical stimulation (Figures 18-4 and 18-5).

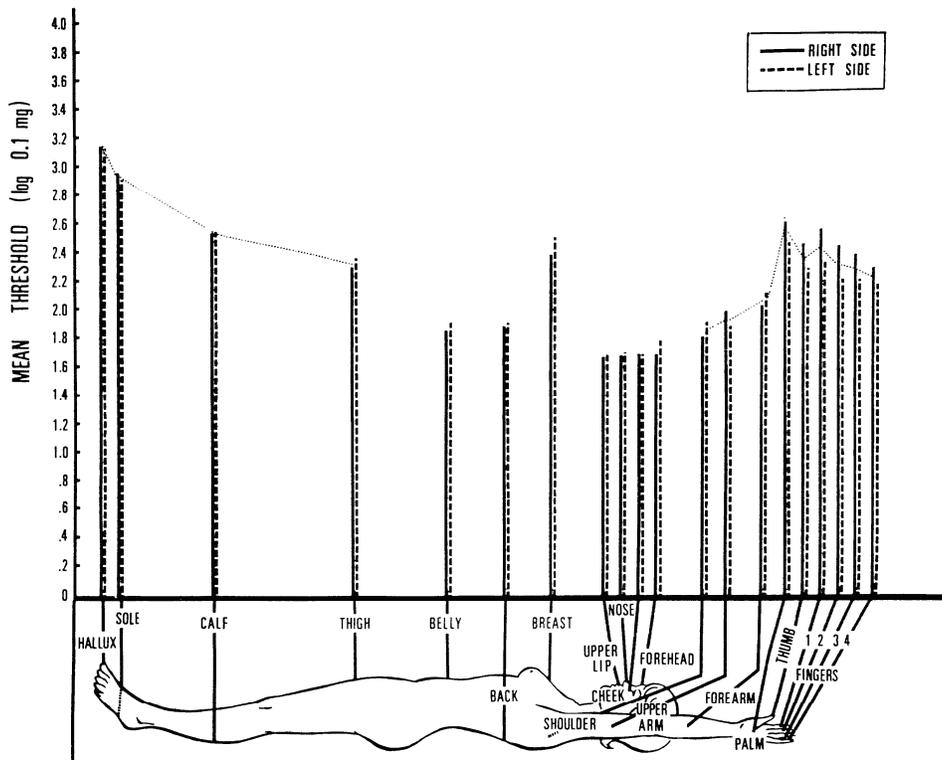


Figure 18-4. Pressure sensitivity thresholds for females for different areas of the body (Weinstein, 1968).

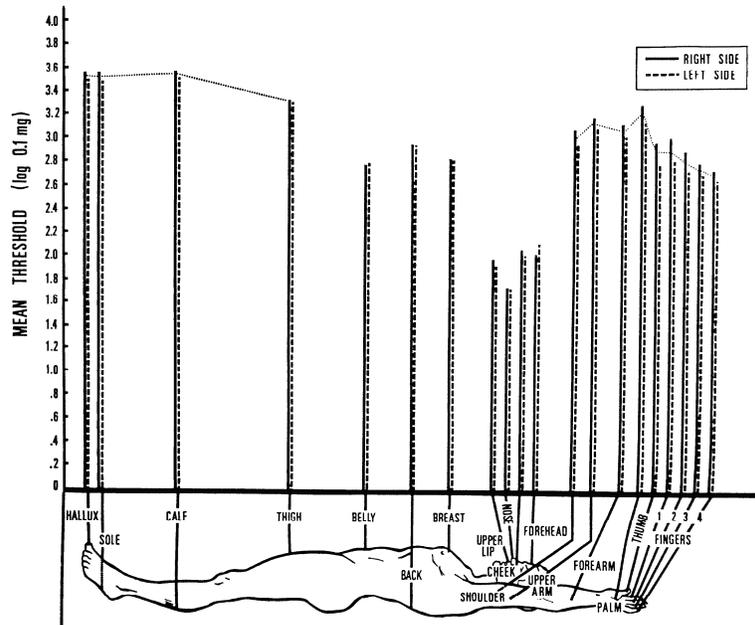


Figure 18-5. Pressure sensitivity thresholds for males for different areas of the body (Weinstein, 1968).

In an attempt to describe vibration sensitivity associated with different regions of the body, Wilska (1954) used a vibrator driven by a sinusoidal alternating current and placed it against the skin of various body regions. He found the hands and soles of the foot to be most sensitive and the gluteus region to be the least sensitive. Body sites including the head, throat, and abdomen were moderately sensitive in comparison to these endpoints. It appears to be no coincidence that most of the body sites involved in tactile parameter estimation in the literature are also those areas of the body that are most sensitive to pressure and stimulus discrimination [finger, Cholewiak and Collins, (1995); Cholewiak and Collins (1997); Goble, Collins and Cholewiak (1996); Horner, 1992; Lamore and Keemink, 1988; Rabinowitz et al., (1987); hand, Bolanowski et al., 1988; Cholewiak and Collins, (1995); Verrillo, 1962; arm, Cholewiak and Collins, 2003; Lamore and Keemink, 1988; Verrillo, 1966]. Some of the lesser-sensitive regions also investigated are the thigh (Cholewiak and Collins, 1995) and torso (Cholewiak, Brill and Schwab, 2004; Cholewiak, Collins and Brill, 2001).

Laidlaw and Hamilton (1937) also explored vibration thresholds for different regions of the body. They found significant variability in threshold measurements across participants within certain regions with specifically higher thresholds among the elderly and obese. These results are in agreement with others who also found an age-related increase in thresholds (Goble, Collins and Cholewiak, 1996; Stuart et al., 2003). For the older group of participants, Stuart et al. (2003) found an increase in threshold for the forearm, shoulder and cheek when compared to younger participants. However, thresholds for the finger were the same for both groups. This finding is not surprising since both Weber (1834/1978) and Weinstein (1968) found this area to be most sensitive to pressure and stimulus discrimination reflecting a high receptor density and making it more resistant to loss of sensitivity with age (Stuart et al., 2003).

### Spatial resolution

Two-point discrimination is a measure that represents how far apart two pressure points must be before they are perceived as two distinct stimulation points on the skin (Gemperle et al., 2003). Information about spatial

resolution is important for determining the minimum distance between two adjacent points of stimulation. If two factors (mechanical transducers providing pulse, continuous, or vibrotactile stimuli) are placed too close together and each factor delivers a unique signal in the scheme of some complex, tactile pattern, the observer will not differentiate between the signals and will miss the underlying message generated with the use of the two signals.

Weber (1834/1978) studied two-point discrimination thresholds for various areas of the body. Using a metal compass (dividers), he touched various areas of the skin with the two points some distance apart and recorded judgments of the distance between the two points. From his findings, Weber (1834/1978) put forth five general propositions, of which the first two stated: (1) various parts of the body are not equally sensitive to the spatial separation of two simultaneous points of contact; and (2) if two objects touch us simultaneously, we perceive their spatial separation more distinctly if they are oriented along the transverse rather than the longitudinal axis of the body. In order of decreasing sensitivity for two-point discrimination, the tongue was found to be most sensitive, followed by the lips, fingers/palm, toes, and forehead. More recently, Gemperle et al. (2003) found that two-point discrimination acuity is 39 mm (1.5 in) for the back, less than 1 mm (0.04 in) for the fingers, 15 mm (0.6 in) for the forehead, 35 mm (1.4 in) for the forearm and 45 mm (1.8 in) for the calf. These observations agree with an earlier report by Weinstein (1968) who found the fingers, forehead, and feet to be most sensitive for two-point discrimination (Figures 18-6 and 18-7).

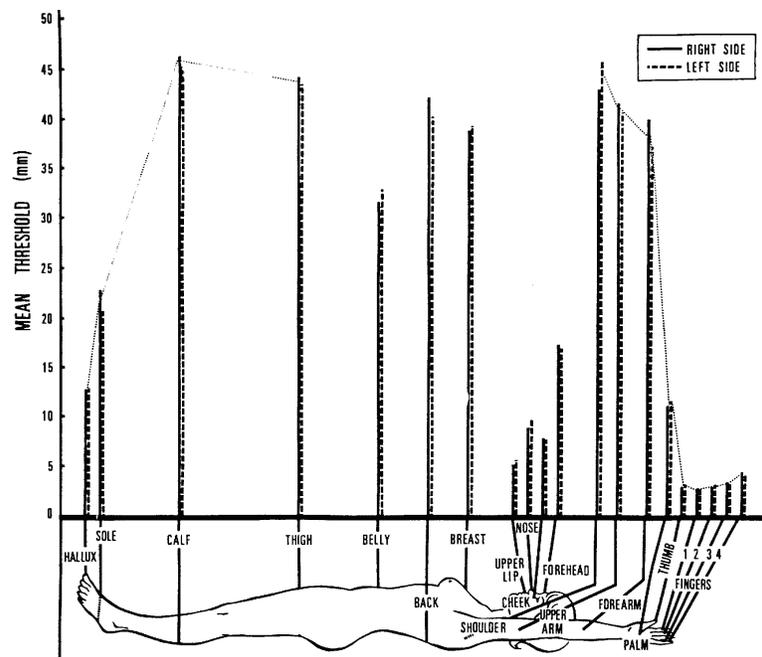


Figure 18-6. Two-point discrimination thresholds for females for different areas of the body (Weinstein, 1968).

### Localization accuracy

Localization is defined in this chapter as the ability to identify where on the skin stimulation has occurred. Localization accuracy is typically measured by presenting a stimulus through one factor among many present on the body site (such as the abdomen) and asking the experimental participant which factor had been excited. Cholewiak, Brill and Schwab (2004) investigated the vibrotactile localization accuracy for the abdomen using 12, 8, and 6 equidistant factors, 72 mm (2.8 in), 107 mm (4.2 in), and 140 mm (5.5 in) apart, respectively, arranged circumferentially around the body at abdominal height. They observed that localization accuracy increased as the

number of possible locations decreased and reported 74, 92, and 97% identification accuracy for 12, 8, and 6 factors, respectively. They also found that when the factor placement included the navel and spine, localization was better than when the factors were oriented with the navel and spine centered in a gap between factors. This reflects other studies which indicate that the ability to localize improves when the stimuli are at or near body anchor points, such as joints (Cholewiak and Collins 2003, Weber 1826/1978). Cholewiak and Collins (2003) found that sites on the forearm near the elbow were better localized than those sites farther from the elbow. When increasing factor spacing from 25 to 50 mm (0.98 to 1.97 in), localization accuracy for the forearm also increased. Hawes and Kumagai (2005) found that soldiers were able to localize an eight-factor array around the head, with a mean distance of 7.1 centimeter [cm] (2.8 in) (center-to-center) between the factors. Weinstein (1968) found that the forehead, the fingers, and hallux (big toe) were most sensitive for point localization (Figures 18-8 and 18-9).

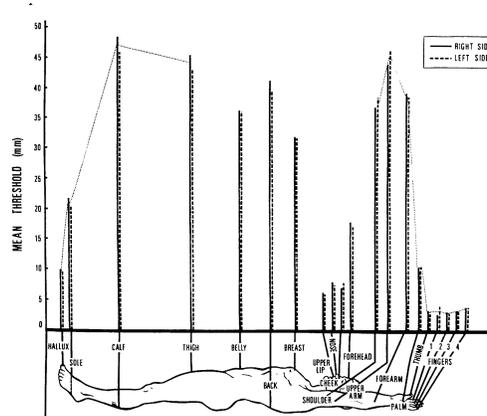


Figure 18-7. Two-point discrimination thresholds for males for different areas of the body (Weinstein, 1968).

## Tactile Displays: Factors

A tactile display consists of one or more factors and a mounting structure or harness that positions the factors on the appropriate part of the body. Important decisions that need to be made in designing tactile helmet-mounted display (HMD) systems or other types of tactile displays are the selection of type of tactile transducer and the number of transducers to be used in the design. Decisions regarding the type of factor involve its size, weight, and power handling capabilities. Especially important are the geometrical properties of the element touching the skin. This element is commonly referred to as a contactor. It has been shown that contactor area and the diameter of the contactor can significantly affect tactile detection thresholds on the skin (Verrillo, 1962). To maintain a proper coupling between the contactor and the skin (especially bony parts of the body such as the skull) it is also important to provide sufficient static force pressing the contactor against the reception area.

In the case of multi-channel tactile interfaces presenting messages in a form of coded patterns, a larger number of factors on the skin can increase the accuracy of the transmitted information (FreePatentsOnline.com, 2006). However, the designer must determine the maximum number of factors beyond which no further increase in perceptual ability can be measured (FreePatentsOnline.com, 2006) as the placement of too many factors can significantly distort the ability to discriminate between signals. In the case of single-channel tactile interfaces either a single factor or multiple factors can be used. Single factor devices can be a simple on-off buzzer or a more complex device that provides a number of signals that carry various types of information. The latter device usually requires large, high powered factors that are heavy and may become hot during some types of operations. Therefore, they may be replaced by a number of parallel transducers working simultaneously. These multiple factor single-channel devices are usually used to provide directional information to the user. For such devices,

several factors are placed around the body and used sequentially to indicate specific direction. There are four types of electromechanical transducers that are currently used as factors: moving coils (magnetolectric, dynamic) transducers, DC motors with an eccentric weight (e.g., cell phone technology), piezoelectric transducers, and electro-pneumatic transducers (van Erp, 2002).

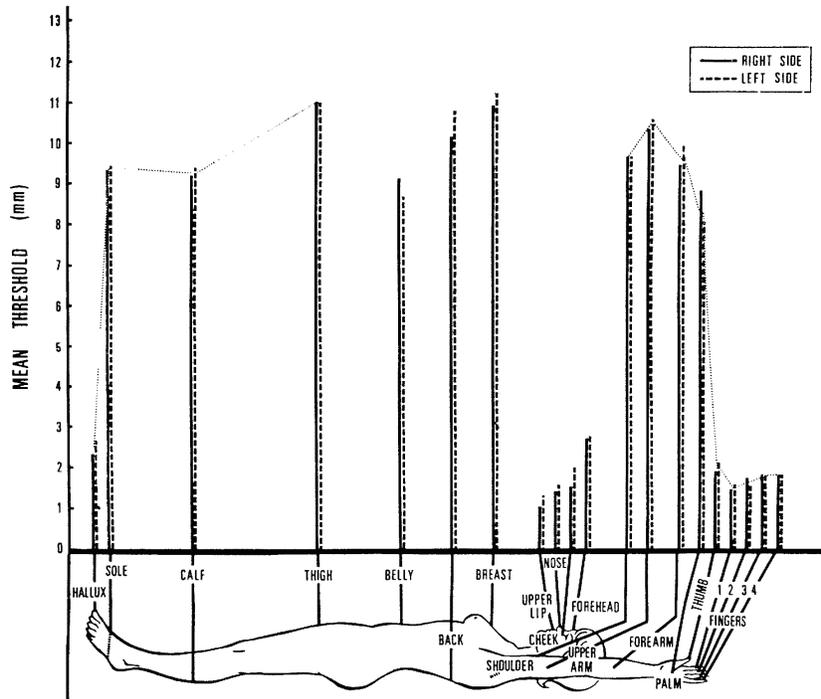


Figure 18-8 Point localization thresholds for females (Weinstein, 1968).

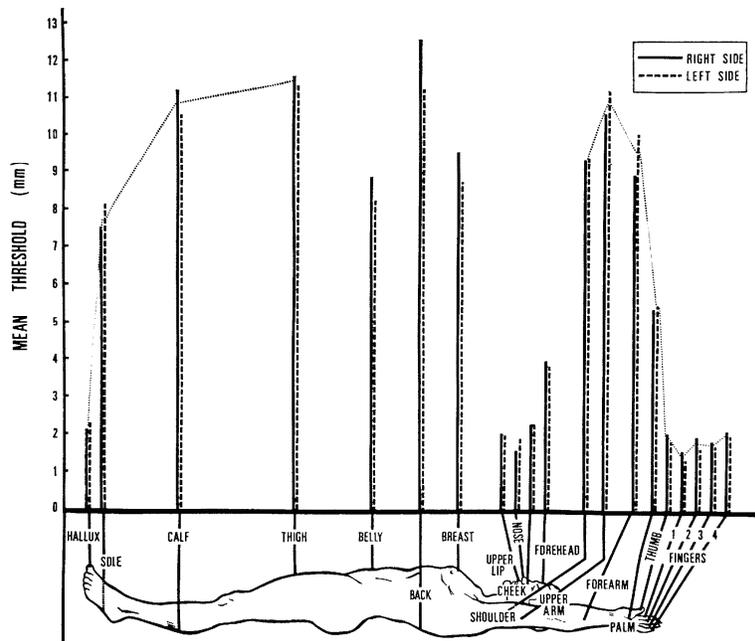


Figure 18-9 Point localization thresholds for males (Weinstein, 1968).

## Moving coil transducers

A moving coil transducer is an electromechanic transducer with a stationary magnet and a moving wire coil passing an alternate current. Such transducers are also known as magnetoelectric or dynamic transducers. (Tran, Amrein and Letowski, 2009). An example of a moving coil factor is the C-2 tactor designed by Engineering Acoustics, Inc. (EAI) ([www.eaiinfo.com](http://www.eaiinfo.com)) and shown in Figure 18-10. The tactor has a moving piston-like element with an attached electric coil. Current passing through the coil creates the contactor movement with displacement proportional to the intensity of the electrical current passing through the coil (Engineering Acoustics, Inc. [EAI], 2006; van Erp, 2002). The contactor displaces the skin with movement similar to a constant pricking or tapping of the skin while additional housing of the contactor shields the surrounding skin from vibration. The housing is used to keep the tactile signal as localized as possible and prevent the signal from radiating to unintended skin surfaces.



Figure 18-10. The C-2 Tactor (EAI) (<http://www.eaiinfo.com/EAI2004/Tactor%20Products.htm>), 2006.

## Direct current (DC) motors

Direct current (DC) motor technology is used in tactors built in cell phones and pagers to alert the user via vibration of an incoming call, text message, calendar alert, etc. The motor produces vibration by rotating an off-center (i.e., eccentric) mass. The rotating mass “creates a centrifugal force that is transmitted through the entire motor as a vibration” (Gemperle, Ota and Siewiorek, 2001). An increase in DC voltage applied to the motor produces an increase in vibration intensity (Cohen et al., 2005; Gemperle et al., 2001). There are two commonly used DC motors: the cylindrical motor and the disk-shaped pancake motor (Figure 18-11). Both motors use an off-center mass to produce vibration. The pancake motor rotates the mass in a plane parallel to the mounting surface and the cylindrical motor rotates the mass in a plane normal to the mounting surface (Piateski and Jones, 2005). The cylindrical motor was found to provide better tactile pattern recognition and to be more reliable than the pancake motor (Bloomfield and Badler, 2006; Piatieski and Jones, 2005). However, there are several limitations to using both types of the DC motor to drive the tactors. One limitation is that the off-center mass on the motors is easily impeded by minimal resistance or pressure from fingers or fabric (Gemperle et al., 2001). A second limitation is the tendency for the vibration frequency to be affected by extraneous factors such as how the tactor is mounted and posture changes (Cohen et al., 2005).

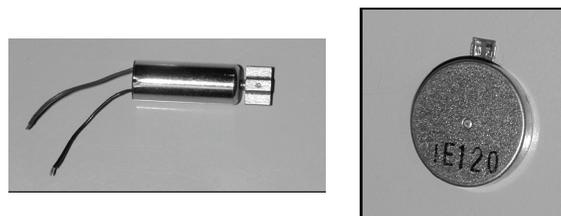


Figure 18-11 The cylindrical (left) and pancake (right) motors often used in cell phones and pagers (<http://www.cis.upenn.edu/~aaronb/docs/tactorsuit.pdf>).

## Piezoelectric transducers

Piezoelectric transducers, also called piezoelectric benders, are electromechanical transducers which convert electrical power into mechanical vibration by bending a piezoelectric bimorph (Andersen, 2002; Chilibon et al., 2005). An example of a piezoelectric transducer is shown in Figure 18-12.

The piezoelectric effect is a property of certain crystals to produce static electricity in response to mechanical force (stress) (Andersen, 2002; Phillips, 2000). The effect is reversible. Typical piezoelectric transducers operate when two rectangular piezoelectric plates (and a metallic electrode fixed between them) are glued together and applied pressure (i.e., rubbing) drives one plate to expand while the other plate contracts, forcing the transducer to bend (i.e., deformation), thus creating an out-of-plane motion and vibrations in the range of tens of micrometers (Chilibon et al., 2005).



Figure 18-12. Piezoelectric bender actuators (<http://www.physikinstrumente.com/en/products/prdetail.php?&sortnr=103000>).

The piezoelectric benders used for vibrotactile applications are usually not made with crystals but with more effective ceramic materials such as lead zirconium titanate (PZT). The configuration of a piezoelectric transducer can vary depending on the application (GlobalSpec.com, 2006), so these transducers can be designed to fit the system requirements. Other advantages to using piezoelectric bender transducers include: “the ability to generate electrical signals from mechanical and acoustic sources of low impedance”; and “the ability to develop relatively large motions and low forces with small electrical excitation” (Chilibon et al., 2005). Limitations to using piezoelectric bender transducers include the brittleness of the ceramic, which make it prone to breakage over time (Andersen, 2002; Niezrecki et al., 2001), and the unwanted change in displacement over time which may hinder the accuracy of the transducer (Andersen, 2002).

## Electro-pneumatic transducers

Electro-pneumatic transducers use air pressure to generate a vibrating sensation on the skin (Figure 18-13). They use devices such as small air jets or air bladders to convert air pressure changes to vibration. When the air jets or bladders are activated by a pneumatic pump the resulting sensation on the skin is perceived as a touch (Enriquez et al., 2001; FreePatentsOnline.com, 2006). Contrary to DC motors, pneumatic jets and bladders do not shake the entire transducer but produce stimulation only within a specific area under the transducer (Enriquez et al., 2001). Drawbacks of electro-pneumatic transducers include possible air leaks in the equipment and the limited range of frequencies available for use (Enriquez et al., 2001). Also, the mechanical aspects of the system (pumps, valves, etc.), mean “all pneumatic tactile systems have an inherently slow response time, which limits the operating bandwidth of these devices, and hence the types of signals that can be sent to the user” (FreePatentsOnline.com, 2006).

Information about selected factors commercially available at the time of publication is included in Table 18-3. Recently Mortimer, Zets and Cholewiak (2007) described a new class of factors, which performance is fairly independent of the static pressure acting on the skin.

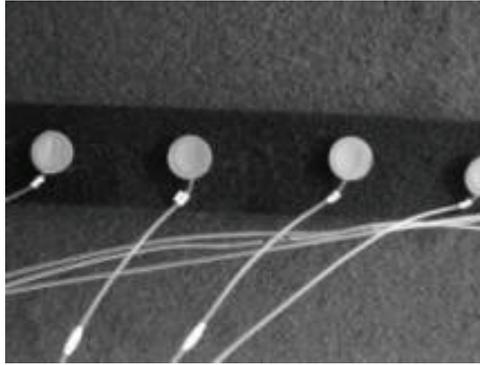


Figure 18-13. Pneumatic factors (<http://www.tactileresearch.org/rcholewi/TRLFactorArrays.html>).

General recommendations for using factors as communication devices were published by van Erp (2002). The author focused on single factor displays such as those used in mobile phones and computer mice and multiple-element factor displays worn on the body or used as finger displays. Examples of the later systems are tactile Braille finger displays. van Erp (2002) based his recommendations on broad neurophysiologic and psychophysical data available for human tactile perception. Presented recommendations were divided into stimulus detection guidelines and tactile information coding guidelines. For optimal stimulus detection van Erp recommended factor placement on glabrous as opposed to hairy skin, 200 to 250 Hz frequency range, and long stimulus duration for frequencies above 60 Hz. For tactile information coding van Erp recommended up to four levels of intensity coding, up to nine levels of frequency, and at least 4 cm (1.6 in) separation between multiple factors. The difference between the frequencies of the tone signals should exceed 20% and the minimal duration of the signals and the pauses between the signals should exceed 10 milliseconds (ms). However, it has to be stressed that both sets of the above recommendations apply only to body-worn and hand-held tactile displays and are not appropriate for tactile HMD systems where both tactile perception and auditory perception via bone conduction need to be considered together. Tactile signals used in HMDs are discussed in the final part of the chapter.

### Tactile Interfaces: Applications

A sensory channel can be used to substitute, reinforce, or add other sensory channels in providing information to the user. Examples include a scanner and pad which convert written material to Braille (substitution); a threat indicator that shows a target on a visual display and also alerts the user via an auditory display (reinforcement); or an auditory alarm for an equipment malfunction (additional channel).

The tactile modality can be used as an operational interface in all these ways. It can be used as an additional, independent input modality to convey information to the user or as a redundant modality to increase information salience of the visual and auditory modalities (Sherrick and Cholewiak, 1986; Sorkin, 1987). For visual- and hearing-impaired users the tactile modality can be used as a substitute channel and can become either the primary or a supplementary channel for the receipt of information. Outside of the visually impaired population, the military has been one of the leading pioneers in the development and use of tactile systems. In military applications, the vibrotactile channel is being used to deliver threat warnings and as an additional sensory input

Table 18-3.  
Parameters of selected commercially available factors.

Tactor/Transducer	Specifications	Cost	Use
 <p>C-2 Tactor <a href="http://www.ealinfo.com/EAI2004/Tactor%20Products.htm">www.ealinfo.com/EAI2004/Tactor%20Products.htm</a></p>	<ul style="list-style-type: none"> <li>• Diameter = 30.5 mm (1.2 in)</li> <li>• Height = 7.9 mm (0.31 in)</li> <li>• Weight = 17 grams (0.6 ounces [oz])</li> <li>• Stimulus Amplitude = &gt; 0.64 mm (&gt; 0.025 in) peak at 230 Hz with 0.25 A RMS drive</li> <li>• Impedance = approx. 7 ohms</li> </ul>	On request	<ul style="list-style-type: none"> <li>• Mount directly on the skin, in a chair, or in clothing</li> <li>• Supplement audio or visual input</li> <li>• Place factors individually, sequentially, or in groups</li> <li>• Have been used in military, medical, and commercial applications</li> </ul>
 <p>VPM2 Vibrating Disk Motor <a href="http://www.solarbotics.com/products/in dex.php?search_id=1056">www.solarbotics.com/products/in dex.php?search_id=1056</a></p>	<ul style="list-style-type: none"> <li>• Diameter = 12.7 mm (0.5 in)</li> <li>• Height = 3.4 mm (0.134 in)</li> <li>• Standard Voltage: DC 3.0V</li> <li>• Operating Voltage Range: DC 2.5 to 3.5V</li> <li>• Power Supply, Voltage Source: DC Power Supply or Battery 3.0V</li> </ul>	\$3.95	<ul style="list-style-type: none"> <li>• Mount on skin</li> <li>• Mount in clothing</li> <li>• Place factors individually, sequentially, or in groups</li> </ul>

Table 18-3 (continued).  
Parameters of selected commercially available factors.

Factor/Transducer	Specifications	Cost	Use
<p><b>Tactors</b></p>  <p>Encased Piezo Element  <a #34:_dia_x_0.13"#34:_encased_piezo_element_.html"="" href="http://www.allelectronics.com/cgi-bin/item/PE-54/search/0.89">www.allelectronics.com/cgi-bin/item/PE-54/search/0.89"#34:_DIA_X_0.13"#34:_ENCASED_PIEZO_ELEMENT_.html</a></p>	<ul style="list-style-type: none"> <li>• Diameter = 22.6 mm (0.89 in)</li> <li>• Height = 3.3 mm (0.13 in)</li> </ul>	<p>\$0.75</p>	<ul style="list-style-type: none"> <li>• Mount on skin</li> <li>• Mount in clothing</li> <li>• Place factors individually, sequentially, or in groups</li> </ul>
 <p>Coin/Pancake Vibration Motors  <a href="http://www.vibratormotor.com/guide-table.htm">www.vibratormotor.com/guide-table.htm</a></p>	<ul style="list-style-type: none"> <li>• Diameter = 10 mm (0.4 in)</li> <li>• Length = 3 mm (0.12 in)</li> <li>• Frequency Range: 10 to 55 Hz</li> <li>• Operating Voltage Range: 2.5 to 4V DC</li> <li>• Operating Voltage: 3V DC</li> </ul>	<p>On request</p>	<ul style="list-style-type: none"> <li>• Mount directly on the skin, in a chair, or in clothing</li> <li>• Place factors individually, sequentially, or in groups</li> </ul>

Table 18-3 (continued).  
Parameters of selected commercially available factors.

Tactor/Transducer	Specifications	Cost	Use
<p><b>Vibrotactile Transducers</b></p>  <p>Silver TST229 <a href="http://www.clarksynthesis.com/home-products.php">www.clarksynthesis.com/home-products.php</a></p>	<ul style="list-style-type: none"> <li>• Diameter = 20.3 cm (8 in)</li> <li>• Height = 5.7 cm (2.25 in)</li> <li>• Weight = 0.57 kg (20 oz)</li> <li>• Tactile Freq. Response = 15 Hz to 800 Hz</li> <li>• Maximum Power = 200W</li> <li>• Tactile Force Peak = 216 lb-ft</li> <li>• Transduction Force = 1.6 lb-ft/watt</li> <li>• Impedance = 4 ohms</li> </ul>	<p>\$300</p>	<ul style="list-style-type: none"> <li>• Home theater</li> <li>• Commercial theater</li> <li>• Virtual reality</li> <li>• Gaming</li> <li>• Amusement parks</li> <li>• Hearing impaired</li> <li>• Studio monitoring</li> <li>• Stage monitoring</li> <li>• Simulators</li> </ul>
 <p>Gold TST329 <a href="http://www.clarksynthesis.com/home-products.php">www.clarksynthesis.com/home-products.php</a></p>	<p>Diameter = 20.3 cm (8 in) Height = 5.7 cm (2.25 in) Weight = 0.57 kg (20 oz)</p> <p>Tactile Freq. Response = 10 Hz to 800 Hz</p> <p>Maximum Power = 200W</p> <p>Tactile Force Peak = 378 lb-ft</p> <p>Transduction Force = 2.8 lb-ft/watt</p> <p>Impedance = 4 ohms</p>	<p>\$500</p>	<ul style="list-style-type: none"> <li>• Home theater</li> <li>• Commercial theater</li> <li>• Virtual reality</li> <li>• Gaming</li> <li>• Amusement parks</li> <li>• Hearing impaired</li> <li>• Studio monitoring</li> <li>• Stage monitoring</li> <li>• Simulators</li> </ul>

Table 18-3 (continued).  
Parameters of selected commercially available factors.

Factor/Transducer	Specifications	Cost	Use
<p>Vibrotactile Transducers</p>  <p>Platinum TST429 <a href="http://www.clarksynthesis.com/home-products.php">www.clarksynthesis.com/home-products.php</a></p>	<p>Diameter = 20.3 cm (8 in) Height = 5.7 cm (2.25 in) Weight = 0.57 kg (20 oz)</p> <p>Tactile Freq. Response = 5 Hz to 800 Hz</p> <p>Tactile Force Peak = 932 lb-ft</p> <p>Transduction Force = 6.9 lb-ft/watt</p> <p>Impedance = 4 ohms</p>	<p>\$700</p>	<ul style="list-style-type: none"> <li>• Home theater</li> <li>• Commercial theater</li> <li>• Virtual reality</li> <li>• Gaming</li> <li>• Amusement parks</li> <li>• Hearing impaired</li> <li>• Studio monitoring</li> <li>• Stage monitoring</li> <li>• Simulators</li> </ul>
 <p>VX-GH72 <a href="http://www.vidsonix.com/vx3/vx_inwall.html">www.vidsonix.com/vx3/vx_inwall.html</a></p>	<ul style="list-style-type: none"> <li>• Diameter = 7.6 cm (3 in)</li> <li>• Height = 2.54 cm (1 in)</li> <li>• Weight = 0.5 kg (1.2 lbs)</li> <li>• Freq. Response = 20 Hz to 20,000 Hz</li> <li>• Maximum Power = 50W</li> <li>• Impedance = 8 ohms</li> </ul>	<p>\$69.95</p>	<ul style="list-style-type: none"> <li>• Tactile therapy</li> <li>• Home theater</li> <li>• Museum exhibits</li> <li>• Spas</li> <li>• Bathtubs</li> <li>• Pools</li> </ul> <p>** Device can be placed in water</p>

Table 18-3 (continued).  
Parameters of selected commercially available factors.

Factor/Transducer	Specifications	Cost	Use
 Rolen Star Audio Transducer <a href="http://www.invisiblestereo.com">www.invisiblestereo.com</a>	<ul style="list-style-type: none"> <li>• Diameter = 10.2 cm (4 in)</li> <li>• Height = 4.4 cm (1.75 in)</li> <li>• Weight = 1 kg (2.2 lbs)</li> <li>• Freq. Response = 20 Hz to 20 kHz</li> <li>• Maximum Power = 100W</li> <li>• Impedance = 8 ohms</li> </ul>	On request	Home Theater <ul style="list-style-type: none"> <li>- Mount on chairs, recliners, love seats, small couches</li> </ul>
 Aura Interactor Vest <a href="http://www.combatsim.com/html/mar99/aura2.htm">www.combatsim.com/html/mar99/aura2.htm</a> <a href="http://www.avsim.com/pages/0604/aura/aura_interactor.htm">www.avsim.com/pages/0604/aura/aura_interactor.htm</a> <a href="http://migman.com/hw/sound/AuraInteractor/AuraInteractor.htm">migman.com/hw/sound/AuraInteractor/AuraInteractor.htm</a>	<ul style="list-style-type: none"> <li>• Diameter = 7.6 cm (3 in)</li> <li>• Height = 1.7 cm 0.6875 in.</li> <li>• Maximum Power = 25W</li> <li>• Impedance = 3 - 4 ohms</li> </ul>	\$150	<ul style="list-style-type: none"> <li>• Video game market</li> </ul> Aura no longer offers this vest but it can be purchased from other sources over the internet.

Table 18-3 (continued).  
Parameters of selected commercially available factors.

Factor/Transducer	Specifications	Cost	Use
 <p>Crowson Tech TES 100 <a href="http://www.crowsontech.com/go/crowsontech/3342/en-US/DesktopDefault.aspx">www.crowsontech.com/go/crowsontech/3342/en-US/DesktopDefault.aspx</a></p>	<p>Size = 14.5 cm x 12.2 cm x 2.8 cm (5.7 in x 4.8 in x 1.1 in) Weight = 1.6 kg (3.5 lbs)</p> <p>Freq. Response = 1 Hz to 500 Hz Minimum Power = 50W Maximum Power = 500W Impedance = 6 ohms</p>	<p>\$349</p>	<p>Home Theater</p> <ul style="list-style-type: none"> <li>- Mount on chairs, recliners, love seats, small couches</li> </ul>
 <p>Aura Pro Bass Shaker <a href="http://www.partsexpress.com/pe/showdet.cfm?&amp;Partnumber=299-028">www.partsexpress.com/pe/showdet.cfm?&amp;Partnumber=299-028</a></p>	<p>Size = 15.7 cm dia x 6.4 cm H (6.2 in dia X 2.5 in H) Weight = 1.7 kg (3.75 lbs)</p> <p>Freq. Response = 20 to 80 Hz Power = 50W RMS/100W max. Force Peak = 30 lbs. per ft. Impedance = 4 ohms</p>	<p>\$38.88</p>	<ul style="list-style-type: none"> <li>- Enable movement from music, movies, video games</li> <li>- Video game chairs</li> </ul>

facilitating human orientation, navigation, and communication capabilities (Castle and Dobbins, 2006; Chaisson, McGrath and Rupert, 2002). Some of the specific applications are discussed below.

### Spatial orientation

Several tactile vests and belts have been developed in various countries to enhance spatial orientation under adverse operational conditions. Examples of such systems include TNO Tactile Torso Display (van Erp et al., 2003), Carnegie Mellon University (CMU) Wearable Tactile Display (Gemperle et al., 2001), and MIT Wireless Tactile Control Unit (Jones, Nakamura and Lockyer, 2004). The most widely known tactile vest is the Tactile Situation Awareness System (TSAS). The TSAS was developed at the U.S. Naval Aerospace Medical Research Laboratory (NAMRL) to minimize the occurrence of spatial disorientation in rotary-wing pilots, thereby reducing aircraft mishaps (Griffin, Pera, Cabrera and Moore, 2001; McGrath et al., 2004; Nordwall, 2000). The TSAS also helped to ease the visual overload naturally placed on pilots from the visual instruments in the aircraft. The TSAS is a vest filled with 32 tactors, worn on the torso of the pilot and assists the pilot in determining the aircraft's orientation with respect to the ground (Ryan, 2000). The location of a vibration on the torso directly relates to out-of-envelope excursions in aircraft attitude where corrective action is required (Schrope, 2001). For example, a vibration signal applied to the front of the torso indicates a correction is needed to raise the nose of the aircraft (Schrope, 2001). The system has been shown to increase pilot performance over a visual cockpit indicator alone. One pilot even wore the vest while blindfolded with no significant degradation in flight performance (Ryan, 2000). The TSAS confirms the efficient use of tactile systems for the orientation domain.

The success of the TSAS motivated its developers to expand the TSAS tactile vest concept to other applications. The U.S. Navy SEALs have shown interest in the system for use underwater for swimmer navigation and reduction of spatial disorientation, especially at night (Castle and Dobbins, 2006). The system has also been implemented as the Tactor Locator System (TLS) to reduce spatial disorientation for astronauts in the International Space Station (Rochlis and Newman, 2000) and as a ground navigation aid in the Tactile Situation Awareness System for Special Forces (TSAS-SF) (Chaisson, McGrath and Rupert, 2002).

### Navigation aids

The TSAS has been applied in air (parachutist), land (dismounted), as well as underwater (diver) navigation (McTrusty and Walters, 1997; Chaisson, McGrath and Rupert, 2002). The results indicated that overall, using tactile feedback for navigation was feasible and beneficial. As an indication of the visual load during land navigation using the TSAS-SF, participants were asked to locate objects placed along the navigation path. Participants located about 80% more objects navigating with the TSAS-SF versus using a Global Positioning System (GPS) with a visual display. A similar system is a tactile belt for the torso, designed for infantry Soldiers to aid in navigation on the battlefield (Elliott et al., 2006; Krausman and White, 2006; Redden et al., 2006).

Researchers from the US Army Natick Soldier Research, Development, and Engineering Center (NSRDEC) and the US Army Research Institute of Environmental Medicine (Mahoney et al., 2007) have examined the effects of movement and physical exertion on vigilance in navigation tasks. Investigators used the tactile modality as a secondary communication source to the visual and auditory modes of communication. Results showed that while traversing a course with obstacles, participants covered less distance when responding to tactile signals than auditory signals.

### Command and control

In the two applications discussed above, the tactile inputs convey direct physical information. Tactile displays can also be used to impart more abstract information such as in command-and-control applications. Merlo et al. (2006) reported a study in which four signals ("halt," "rally," "move out," and "nuclear, biological, or chemical

warning”) were presented three ways: hand signals initiated from the front of the group; hand signals initiated from the rear; and transmitted via a vibrotactile display. The vibrotactile display used was an eight-tactor torso belt worn just above the navel called Tactile Communication System (TACTICS) (Brill et al., 2006). During the study, Soldiers conducted individual movement techniques over obstacles, in many different postures, and with and without combat loads. Results showed faster detection of and response to signals when they were transmitted via the vibrotactile display. Soldiers commented that they preferred the vibrotactile display because it allowed them to use their vision to maintain their situational awareness without the need to frequently check their leader for hand signals. Although four signals were used, the amount of abstract information that can be imparted via vibrotactile could be increased by varying factors such as combinations and patterns of activated tactors, tactor locations, and signal frequency and duration.

### Task reinforcement

Tactile inputs can be used to enhance performance for many tasks by reinforcement of other modalities. Akamastu, MacKenzie and Hasbrouq (1995) showed the advantage of incorporating tactile feedback when they asked participants to locate a target using a mouse-type device and to move the cursor inside the target. After the initial visual presentation of the target, participants were given auditory feedback, tactile feedback, color (visual) feedback, combined feedback, or no feedback to alert them that the cursor was placed inside the target. The authors found that the time required to correctly position the cursor was lowest for tactile feedback, showing that the addition of tactile feedback yielded a quicker motor response than other feedback systems for the task.

### Tactile Head/Helmet-Mounted Displays (HMDs)

The tactile displays discussed thus far were primarily used for torso, arm, or hand applications. However, the hands are often occupied or unsuitable for use with tactile displays. The arms or the torso as locations for tactile displays have their own limitations, such as display size, bulkiness, thermal comfort, and compatibility with equipment, such as body armor, which can degrade the utility of these displays. Most importantly, the mental mapping of tactile signals can be impacted by head orientation when the display is mounted on the torso. Ho and Spence (2007) found that when the head is not aligned with the body, the perception of the location of a tactile signal is negatively affected. Therefore, in situations where the wearer is actively looking around or when the head is not aligned with the body, applications such as navigation or target cueing could suffer. This makes the head a location of choice for tactile displays aiding in navigation or providing directional information about the environment (e.g., sniper detection).

Tactors mounted on the head can be worn on headband, harnesses, such as used on other body locations, or incorporated into many types of headgear, including helmets. This would eliminate many of the potential problems encountered with torso-mounted displays. Therefore, tactile HMD systems should be considered in applications such as navigation and target/threat cueing, where mental mapping of the stimulus to the physical world is important and head-direction errors undesired.

An analysis of Weber’s (1834/1878) data related to head sensitivity indicates that (1) various points on the head differ in tactile sensitivity, (2) the crown is less sensitive than the skin near the forehead, temples, and lower part of the back of the head, (3) spatial resolution is less for locations leading downward from the crown than for areas around the crown, and (4) forehead, and temples are best for tactile acuity. Gilliland and Schleger (1994) used various numbers of tactors ( $n = 5, 6, 8, 10,$  and  $12$ ) placed over the parietal meridian of the head (i.e., from ear to ear) and investigated tactile detection for a stimulus pulsing at a rate of 4 Hz. They reported that optimal tactile detection and localization accuracy occurred with the use of five tactors. As the number of tactors increased, localization accuracy decreased and reaction time increased.

Despite the many advantages of placing tactile displays on the head, examples of tactile HMD systems are still elusive. Borg, Neovius and Kjellander (2001) used three microphones and four transducers mounted in glasses to

provide directional information about sound source (talker) location to hearing impaired and deaf-blind people. Mounting direction sensitive tactor arrays on the head allows the user to quickly orient the head toward the incoming sound source. Cassinelli, Reynolds and Ishikawa (2006) report on a pilot study of an “artificially extended skin” concept they call “haptic radar”. In this experiment, six tactors were mounted along the rear hemisphere of the subjects’ heads at 30° increments. Collocated with the tactors were infrared proximity sensors with a range of about 80 cm. When the proximity sensors detected an object, a vibrotactile signal proportional to the object’s distance was applied to the associated tactor (the closer the object, the more intense the vibration). The experimenters then swung a foam ball at the back of the blindfolded subject’s head. The subjects were significantly successful in moving in response to the stimulus; however, they were not significantly better at avoiding contact, as compared to their performance with the system off. These early results show promise for the integration of sensors and tactile displays, and the intuitive response to vibrotactile signals felt on the head.

Another tactile HMD system involved a navigation task (Hawes and Kumagai, 2005). The authors compared the utility of three types of vibrotactile displays: an eight-tactor head-mounted display, a four-tactor head-mounted display, and an eight-tactor chest-mounted display. All of the displays were mounted on circumferential bands with the tactors being placed at essentially equal intervals around the band. The results demonstrated better task performance with the eight-tactor head-mounted variant than the other two displays. In comparing the displays, the soldier participants rated the head- and chest-mounted variants similar in many subjective areas such as ease of use.

There are a number of issues which need to be investigated before a robust understanding of appropriate applications for head-mounted tactile displays is developed. For example, Hawes and Kumagai (2005) reported that even though head-mounted tactors produced better performance in a group of soldiers on a navigation task, and the soldier participants rated the head- and chest-mounted systems similar in many subjective areas such as ease of use, the soldiers showed a preference for the chest-mounted system. In the discussion of the results, the authors note (p. 49):

“The participants found the vibration of the tactors was too strong on the head compared to the chest. Two participants reported getting headaches and the majority of the soldiers felt the system was too distracting when worn on the head. They reported that there currently tends to be too much information and equipment coming in through the head.”

However, reported poor satisfaction with tactile HMD systems were most likely related to some suboptimal conditions of the study such as mounting bands that were too tight or presented signals which were too high in intensity. The main factor, which might have had a large contribution to any dissatisfaction, was that the tactile frequency used was 160 Hz. At this frequency bone conduction response is very strong and completely masks the presence of the cutaneous response on the skin. It has to be stressed that for tactile stimuli with frequencies above 60 Hz cutaneous perception through the skin occurs together with auditory perception through bone conduction pathways. This may or may not be a desirable situation. Since bone conduction perception is more effective than cutaneous perception for higher tactile frequencies, it can mask cutaneous response of the skin. For a tactile HMD system to provide tactile information in the auditory range the system must overcome the masking effect of bone conduction transmission, which may lead to prohibitively large and potentially dangerous tactile stimulation of the head.

Current research in tactile HMD systems is geared toward determining the optimum operational parameters for tactor placement and signal intensity and frequency. One of the projects conducted at the U.S. Army Research Laboratory (ARL) is to determine the optimum synergy between tactile and bone conduction signal reception using the same array of transducers. The concept of this system is an auditory-tactile cueing system using a circumferential tactor display which can also be utilized as a bone conduction communications headset. Early results show that for frequencies above 100 Hz, the bone-conducted sound component resulting from use of vibrotactile tactors is too strong to allow the use of frequencies in that regime for tactile purposes. It appears that

the optimum tactile frequency range for head-mounted tactile displays is between 20 to 60 Hz and the shape of the tactile stimulus should have slow on and off transients to prevent generation of auditorily perceived clicks (Kalb, Amrein and Myles, 2008).

In conclusion, head mounted tactile displays offer promise in many single and multi-modal configurations for both civilian and military applications. Recent reports by Kalb, Amrein and Myles (2008) and Myles and Kalb (2009) support the use of such displays for sniper detection and tactical signal displays. By using tactile HMD systems, advantages in equipment compatibility, natural directional cueing, increased situational awareness, and integration of communications and informational displays can be achieved. With the recent explosion in research on tactile displays in general and in head-mounted displays in particular, the promise of these displays may soon be realized.

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