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Tactual Displays for Sensory Substitution and Wearable Computers

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1. INTRODUCTION

A major challenge in building practical wearable computer systems is the development of output devices to display or transmit information to the human user. Much effort has been devoted to visual displays that are lightweight and have high resolution. Such efforts are warranted since visual displays are still the dominant output devices used by most computing systems. Auditory displays are now becoming the norm of multimedia systems in addition to visual displays. Whereas vision is best suited for perceiving text and graphics, and audition for speech and music, the sense of touch is intimately involved in nonverbal communication. Whether it is a tap on the shoulder to get someone's attention or a firm handshake to convey trust, touch enables us to exchange information directly with people and the environment through physical contact. The skin is the largest organ of our body, yet only a small portion of it (i.e., the hands) is engaged in most human–computer interactions.

For a long time, the sense of touch has been regarded as the inferior sense as compared to vision or audition. However, the potential to receive information tactually is well illustrated by some natural (i.e., nondevice related) methods of tactual speech communication. Particularly noteworthy is the so-called Tadoma method that is employed by some individuals who are both deaf and blind. In Tadoma, one places a hand on the face and neck of a talker and monitors a variety of actions associated with speech production. Previous research has documented the remarkable abilities of experienced Tadoma users (e.g., Reed, Rabinowitz, Durlach, Braida, Conway-Fithian, & Schultz, 1985). Not only can these individuals converse with both familiar and unfamiliar talkers at high performance levels, but they pick up additional features such as the speaker's accent. The Tadoma method is a living proof that high information transmission is possible through the somatosensory system.

Earlier work on wearable tactual displays has concentrated on assisting the blind to see and the deaf to hear through their sense of touch (i.e., sensory substitution). For example, the Optacon (Linvill & Bliss, 1966) was initially developed in the 1960s for the daughter of one of its inventors as a reading aid for the blind. It converted images of printed materials to vibrational patterns on the index finger. The Optacon was probably one of the first commercially successful wearable tactual displays ever developed. With sufficient training, typical reading rates of 30–50 wpm can be achieved (Craig & Sherrick, 1982). Some exceptional subjects have demonstrated rates as high as 70–100 wpm (Craig, 1977). Recently, force-feedback systems have been developed for applications in teleoperation and virtual/augmented reality systems (Burdea, 1996). These systems can simulate forces that would have been generated by remote or virtual objects during manual manipulation, thereby enhancing an operator's sense of presence and task performance. Our current work is aimed at developing wearable tactual displays for general-purpose human–computer interactions. We are exploring new ways of utilizing the wearable tactual display technology developed for sensory substitution to convey information that is as intuitive as a sense of resistive force. Wearable computing also provides a unique environment for developing paradigms to distribute human–computer interfaces across the entire body and its various sensory channels.

The organization of this chapter is as follows. Section 2 defines terms that are used throughout this chapter. Section 3 presents a brief historical review of tactual displays that have been developed for sensory substitution. Section 4 discusses the requirements for wearable tactual displays. Section 5 describes a general-purpose tactual directional display that has been developed in our laboratory for wearable computing. Section 6 provides a summary.

2. DEFINITION OF TERMS

The term *haptics* refers to sensing and manipulation through the tactual sense. The human *tactual* sensory system is generally regarded as made up of two subsystems: the tactile and kinesthetic senses (see reviews by Loomis & Lederman, 1986; Clark & Horch, 1986). The *tactile* (or *cutaneous*) sense refers to the awareness of stimulation to the body surfaces mediated by sensors close to skin surfaces such as the mechanoreceptors. For example, when you touch a loudspeaker, your hands receive tactile stimulation. The *kinesthetic* sense (or *proprioception*) refers to the awareness of limb positions, movements, and muscle tensions mediated by sensors in the muscles, skin, and joints as well as a knowledge of motor commands sent to muscles (i.e., efference copy). For example, when you touch your nose with closed eyes, you rely on the kinesthetic sense to know where your fingertip is relative to your nose. When you hold an object in your hand, you use the kinesthetic sense to estimate the weight of the object. In both the nose touching and weight estimation cases, the tactile sense is also activated since the fingertip touches the nose, and the hand is in contact with the object. However, the information that is crucial to the successful execution of these tasks is derived primarily from the kinesthetic sense. In other words, the above distinction between tactile and kinesthetic senses is functional and task dependent.

The term *haptics* is often used in the literature. In this chapter, it refers to manipulation as well as perception through the tactual sense. An example of haptic interfaces is force-feedback joysticks for video games.

The term *display* refers to a human–machine interface that mainly transmits information from a machine to a human. The term *controller* refers to a human–machine interface that is mainly used by a human to control certain processes of a machine (Figure 18.1). The term *interface* is used in this chapter either to refer to a device that is both a display and a controller, or when such distinction is not important.

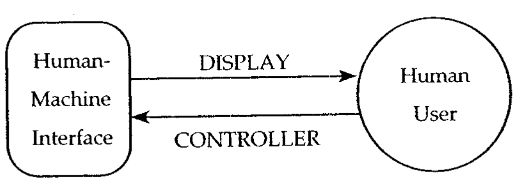

FIG. 18.1. Display vs. controller for human–machine interfaces.

3. TACTUAL DISPLAYS FOR SENSORY SUBSTITUTION

Most tactual communication systems for sensory substitution have been developed based upon two major principles: pictorial or frequency-to-place transformation. Devices for the blind tend to adopt the pictorial approach (i.e., direct translation of spatial–temporal visual information to the skin). Devices for the deaf are usually based on the cochlea model of speech (i.e., positional encoding of frequency information). Examples of pictorial tactual communication systems are the Optacon (OPtical-to-TActile-CONverter), the Optohapt (OPtical-TO-HAPTics), the TVSS (Tactile Vision Substitution System), and the Kinotact (KINesthetic, Optical and TACTile display).

The Optacon (Telesensory Corp, Mountain View, CA) is a direct translation reading aid for the blind that quantizes an area roughly the size of a letter into 144 black and white image points (24 rows and 6 columns) via photocells and displays these image points on a corresponding 24-by-6 array of vibrating pins (Linvill & Bliss, 1966). This portable system consisted of a small hand-held camera and a tactile display measuring 1.1 cm by 2.7 cm that fits under the fingertip of an index finger (Figure 18.2). Whenever a photocell detected a "black" spot, the corresponding pin vibrated. Reading speed with the Optacon varied from 10 to 100 wpm depending on the individual, the amount of training, and experience, with typical rates of 30–50 wpm (Craig & Sherrick, 1982).

The Optohapt consisted of a linear array of nine photocells that scanned vertically the output of an electric typewriter on paper and nine vibrators distributed along the body surface (Figure 18.3). The stimulation sites

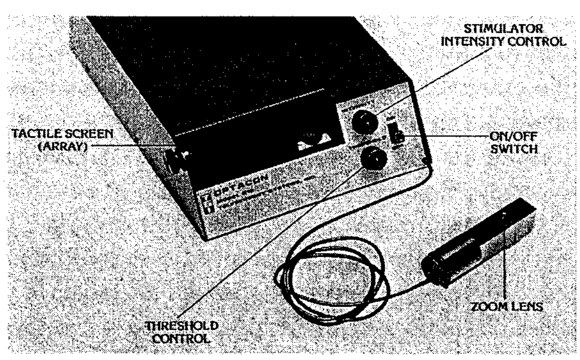

FIG. 18.2. The Optacon. Photograph courtesy of Telesensory Corp.

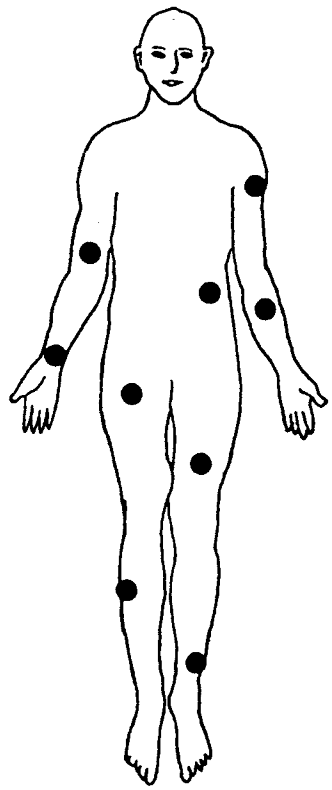

FIG. 18.3. The locations of the nine vibrators used in the Optohapt system. From Geldard (1966), reprinted by permission of Psychonomic Society, Inc.

were selected to avoid corresponding bodily points and were distributed as widely as possible over the skin surface. It was found that "raw" letters of the alphabet were not the most efficacious symbols because they lacked discriminability. It was suggested that the twenty-six most readily discriminated signals (such as the period, the colon, a filled square, etc.) be selected to encode letters of English (Geldard, 1966).

Whereas the Optacon and the Optohapt were aimed toward the transmission of text material, the TVSS was designed to transmit general visual images. It consisted of a television camera controlled by the user, and a 20-by-20 matrix of solenoid vibrators (spaced 12 mm apart) mounted in the back of a dental chair (Figure 18.4). Each solenoid would vibrate when the corresponding region in the camera's viewfinder was illuminated. Initial results showed that both sighted and blind subjects learned to recognize

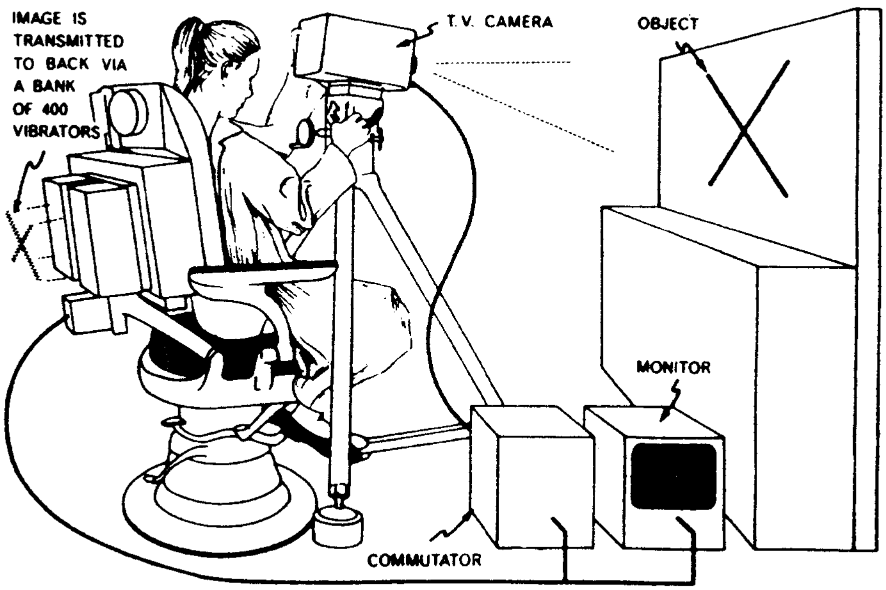

FIG. 18.4. The TVSS. From White et al. (1970), reprinted by permission of Psychonomic Society, Inc.

common objects (e.g., telephone, cup, etc.) and their arrangements in three-dimensional space. When given the control of the camera, the subjects also learned to externalize the objects presented tactually on their backs as being in front of them (Bach-y-Rita, 1972; White, Saunders, Scadden, Bach-Y-Rita, & Collins, 1970). Further investigation showed, however, that subjects had considerable difficulties in identifying internal details of a pattern, thus casting doubts on the skin's ability to identify complex visual patterns (White, 1973).

The Kinotact was very similar to TVSS in construction. It consisted of a 10-by-10 array of photocells, 100 switching circuits, and a corresponding 10-by-10 array of vibrators mounted on the back of a chair. Cutting off light to a particular photocell would switch on a corresponding vibrator. Block letters of the alphabet were used as stimuli in experiments during which subjects were required to identify letters based on the vibration patterns presented on their back. It was found that subjects could perform almost equally well whether or not the correspondence between columns of photocells and those of vibrators were in the same order (i.e., column 1 of photocells was connected to column 1 of vibrators, column 2 of photocells was connected to column 2 of vibrators, and so forth) or randomized (e.g., column 1 of photocells was connected to column 7 of vibrators, column 2 of photocells was connected to column 6 of vibrators, etc.), as long as there was a one-to-one correspondence between columns of photocells and vibrators. The amount of additional training for the subjects to learn the random mapping was minimal (Craig, 1973).

The results of studies with the Optohapt and Kinotact systems suggest that whereas a direct spatial–temporal mapping of visual images to vibrational patterns seems to be the most natural approach to take, encoding visual information in a way that results in highly discriminable vibrational patterns warrants higher performance levels at very little additional cost on training (Geldard, 1966; Craig, 1973).

In a typical tactual hearing aid using the frequency-to-place transformation model, the acoustic signal of speech is sent through an array of bandpass filters with increasing center frequencies. The outputs of these filters are rectified and used to modulate the amplitudes of a corresponding array of vibrators (Keidel, 1973). Examples of such systems range from the "Felix" system developed by Dr. Nobert Wiener in the early 1950s at the Research Laboratory of Electronics at MIT (Figure 18.5) to the modern day wearable version of Tactaid VII. The Tactaid VII system (Audiological Engineering Corp., Somerville, MA) consists of a small processing unit with an embedded microphone, which can be clipped to a belt or fit into a shirt pocket, and a harness with seven resonant vibrators (Figure 18.6). The harness can be worn on the forearm, the chest, the abdomen or around the neck. When used alone, it can convey useful information such as environmental sounds, but understanding speech is difficult. When used in conjunction with speechreading (i.e., lipreading), Tactaid VII provides a limited improvement to sentence reception accuracy with a typical increase of around 10% (the so-called ceiling effect) (Reed & Delhorne, 1995).

In general, performance levels with artificial tactual speech communication devices do not reach anywhere near that demonstrated by Tadoma users (Reed, Durlach, Delhorne, Rabinowitz, & Grant, 1989). Previous research has documented that these individuals can understand everyday speech at very high levels, allowing rich two-way conversation with both familiar and unfamiliar talkers (Figure 18.7). The information transfer rate for the Tadoma method has been estimated to be roughly 12 bits/sec, which is about half the rate of daily conversation conducted by hearing individuals (Reed, Durlach, & Delhorne, 1992). In contrast, the typical reading rates with the Optacon is about 30–50 wpm, or about 4–6.7 bits/sec in information transfer rate. The conversion from word rate to information transfer rate

FIG. 18.5. Dr. Norbert Wiener with the "Felix" system. Photograph by Alfred Eisenstaedt, 1950.

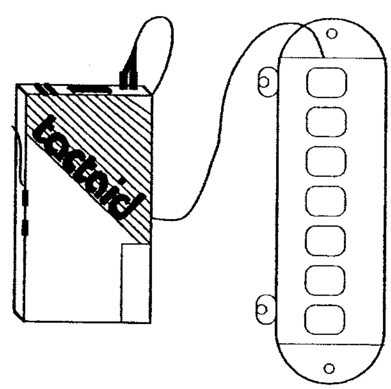

FIG. 18.6. The Tactaid VII with its processor and the seven-vibrator array. Reprinted by permission from Weisenberger & Percy (1994). ©1994 Alexander Graham Bell Association for the Deaf, Inc.

FIG. 18.7. Two experienced Tadoma method users who are deaf and blind (Leonard Dowdy on the left and Raymond Boduch on the right) communicate with each other and Senior Research Scientist Nathaniel I. Durlach (center). Photograph by Hansi Durlach, 1980.

is based on two assumptions. First, according to Shannon (1951, Fig. 4), the uncertainty for strings of eight letters (including the 26 letters of the English alphabet and space) or more has an upper bound of 2 bits/sec. For simplicity, it is assumed that the test material is longer than eight letters. Second, it is assumed that the average word length is 4 letters. It follows that the information content in words is 2 bits/letter × 4 letter/word, or equivalently, 8 bits/word. The information rate for 30 wpm is, therefore, 8 bits/word × 30 words/minute, or equivalently, 4 bits/sec.

One problem with tactile aids is that they are composed of multiple stimulators that deliver "homogeneous" high-frequency vibrations to the tactual sensory system. In contrast, a talking face for Tadoma is perceptually rich, displaying various stimulation qualities (e.g., mouth opening, airflow, muscle tension around the cheeks, laryngeal vibration, etc.) that engage both the kinesthetic and tactile sensory systems. Recognition of the need

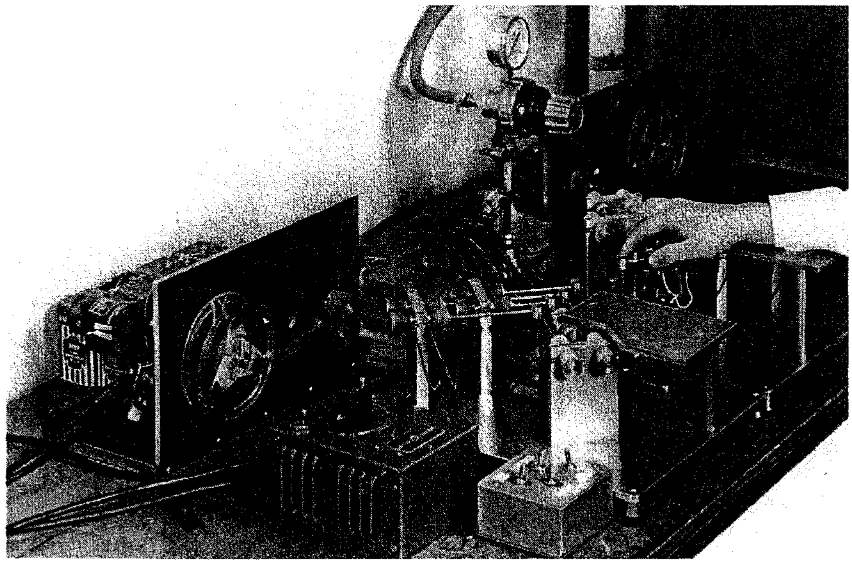

FIG. 18.8. The "reverse-typewriter" system. Photograph by James Bliss.

to develop devices that engage both the tactile and the kinesthetic senses is now prevalent. Examples of such displays are the "reverse-typewriter" system, the "OMAR" system, the MIT Morse code display, and the Tactuator, all of which stimulate the fingers.

The "reverse-typewriter" system was developed by Bliss (1961) prior to his invention of the Optacon. It was a pneumatic display that consisted of eight finger rests arranged in two groups on which the user could place the fingers of both hands in a manner similar to that of the "home" position of a typewriter (Figure 18.8). Each stimulator was capable of generating motions corresponding to the active movements of a typist's fingers in reaching the upper and lower rows on a keyboard. One experienced typist was trained to receive sequences of 30 symbols (the alphabet, comma, period, space, and upper case) and reached a maximum information transfer rate of 4.5 bits/sec (Bliss, 1961).

The "OMAR" system was a two-degree-of-freedom (up–down and front–back) finger stimulator that used motion, vibration, and stiffness cues to encode speech information (Figure 18.9). Initial experiments demonstrated that subjects were able to judge onset asynchronies of vibration and movement with this system (Eberhardt, Bernstein, Barac-Cikoja, Coulter, & Jordan, 1994).

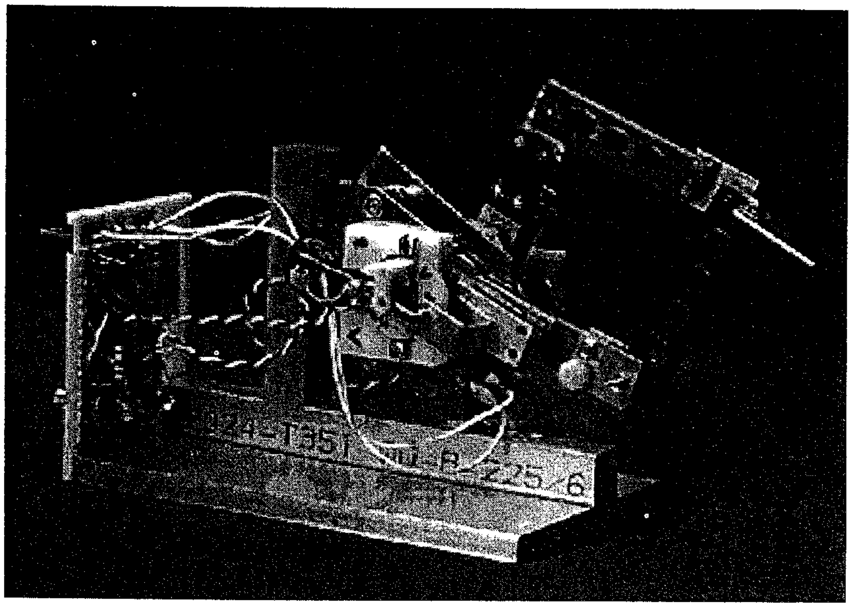

FIG. 18.9. The "OMAR" system. Photograph courtesy of Dr. Lynne E. Bernstein. ©1998 House Ear Institute.

The MIT Morse code display was designed to move the fingertip of one finger up and down in a way that was similar to the motions generated by ham radio operators using the straight keys for sending the code (Figure 18.10). The ability of two experienced Morse code operators to receive the code of everyday English sentences through this device was estimated to be around 20 wpm, or 2.7 bits/sec (Tan, Durlach, Rabinowitz, Reed, & Santos, 1997).

The Tactuator consisted of three independent, point-contact, one-degree-of-freedom actuators interfaced individually with the fingerpads of the thumb, the index finger, and the middle finger (Figure 18.11). Each movement channel is capable of delivering stimuli from absolute detection threshold (i.e., the smallest displacement that can be detected by a human observer) to approximately 50 dB SL (Sensation Level, defined relative to detection threshold) throughout the frequency range from near DC to above 300 Hz, thereby encompassing the perceptual range from gross motion to vibration (Tan & Rabinowitz, 1996). Information transfer rate with the Tactuator was estimated to be about 12 bits/sec, which is roughly the same as that achieved by Tadoma users in tactual speech communication (Tan, Durlach, Reed, & Rabinowitz, 1998). This promising result was mainly

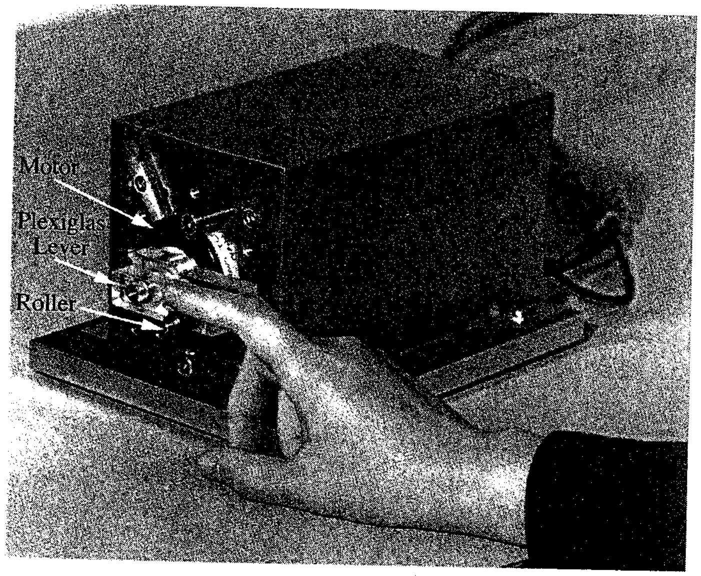

FIG. 18.10. The one-degree-of-freedom (up and down) stimulator used in the MIT Morse code study. From Tan et al. (1997), reprinted by permission of Psychonomic Society, Inc.

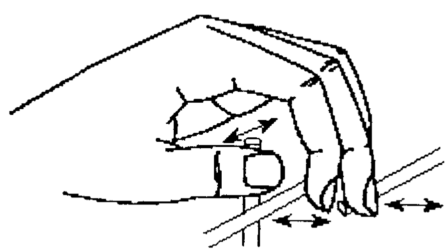

FIG. 18.11. A diagram of the Tactuator. Reprinted by permission of the ASME from Tan & Rabinowitz (1996).

attributed to the relative richness of the Tactuator as a tactual display (i.e., it used features such as finger location, motional and vibrational stimulation, etc. to convey tactual information).

Despite the recent promising results in the research laboratories, however, much work still remains before these experimental apparatus become practical for the daily use by individuals with sensory impairments.

The above review, although brief and incomplete [e.g., we did not discuss electrocutaneous stimulation at all because of its tendency to induce pain and discomfort (Rollman, 1973)], brings several conclusions that can be drawn from work in the area of sensory substitution. First of all, among the above-reviewed tactual communication systems developed for sensory substitution, the Optacon and the Tactaid VII (including its earlier versions) are the only commercially available, portable aids for the blind and the deaf, respectively. Laboratory apparatus are usually developed with the aim of precise stimulus control, not necessarily the device portability. Second, both the Optacon and the Tactaid VII require intensive and extensive training for their users. Only those individuals with severe sensory impairments are motivated enough to go through the training. Third, performance with tactile aids for the blind and/or the deaf do not match that achieved by people with normal sensory capabilities as far as pictorial and speech communication are concerned. Fourth, there remains much work in developing displays that deliver rich stimulation to the tactual sensory systems, and in devising coding schemes that best match the information content of stimulating signals with the capability of the somatosensory system.

4. CONSIDERATIONS FOR WEARABLE TACTUAL DISPLAYS

The development of tactual interfaces in general requires advancement in two areas. On the one hand, an understanding of the human somatosensory system enables us to associate physical stimulation parameters with well-defined percepts. On the other hand, advances in technologies make it possible for us to design apparatus that can deliver desired stimulation patterns. The development of wearable tactual displays presents additional challenges and opportunities.

The first consideration is the wearability of wearable tactual displays. Desktop-based displays such as the Tactuator and the PHANToM™ (Massie & Salisbury, 1994) are unlikely candidates for a wearable computer. Portable haptic displays, such as the exoskeleton system developed by EXOS Inc. for NASA astronauts, requires the user to carry the weight of the structure and absorb the excessive force at body sites strapped to the device. One human factor study recommends that such devices be worn for no more than an hour or two due to user fatigue (Tan, Srinivasan, Eberman, & Cheng, 1994). Given the state of current technology, vibrotactile displays are good candidates for wearable tactual displays for their light weight and low power consumption.

The second consideration is the body site to be stimulated by wearable tactual displays. The desire for high spatial resolution should be balanced with the accessibility and size of contact area. For example, the hands (especially the fingertips) are the best candidates for tactual displays in terms of sensory resolution. However, the hands are already engaged in many daily tasks, especially those involving human–computer interactions. The back has poorer spatial resolution, yet it is usually not engaged by any human–computer interfaces and can be easily accessed. Its relatively poor spatial resolution can be compensated for by its relatively large contact area.

The third consideration is the intended users of wearable tactual displays. We believe that with proper design, tactual displays should be useful for all users of wearable computers, whether they are sensory impaired or not. A good example of a well-designed universal adaptive structure is the street curb. Although originally conceived to provide access for individuals on wheelchairs, curbs are used by mothers with baby strollers, students on roller blades, and couriers with dollies. Tactual displays should be developed to enhance the functionality of wearable computers for all users.

The fourth consideration is the amount of training associated with the use of wearable tactual displays. A good wearable tactual display should minimize training by displaying information that is salient, intuitive, and easy to interpret through the sense of touch. For example, a buzzing on one's shoulder can attract immediate attention from the user. Increased pressure on one's back can signal something approaching from behind.

The fifth issue concerns the long-term wearability of tactual displays. For example, it is well known that all sensory systems adapt to the stimulation environment. For example, we cease to notice our clothes after we have put them on for a while although they are in constant contact with the skin surfaces. Static stimulation (such as a constant vibration) tends to "numb" the skin and "fades" after a short while. Dynamic stimuli (such as pulsing) are more likely to evoke the same perceptual intensity time after time.

Finally, a new paradigm is needed to seamlessly integrate tactual interfaces with visual and auditory displays. Given the existing well-developed visual and auditory interfaces, tactual interfaces would be most useful when used to supplement visual and auditory information, or to clarify it when vision or audition is overloaded. An example of such a system would be a tactile vest that redirects a driver's visual attention when a collision-warning alarm goes off.

In summary, a good wearable tactual display should be not only portable but wearable, should not interfere with the user's daily activities, should be useful for people with all degrees of sensory capabilities, should require minimum amount of training, should be resistant to sensory adaptation, and should be well integrated with existing visual and auditory interfaces.

5. A TACTILE DIRECTIONAL DISPLAY

Recently, a wearable tactile directional display has been developed at our research laboratory. It consists of an array of micromotors embedded in the back of a vest that delivers vibrational patterns to the back of the wearer. The display elicits salient and vivid movement sensations that are resistant to sensory adaptation. Informal tests with first-time users indicate that it requires no training and the interpretation of directional signals is highly consistent. Because the directional information is presented relative to the user's body coordinates, it eliminates the need to transform coordinates as is often the case with maps and building layouts. What's more, the perceived spatial resolution of the display can be manipulated by the signals delivered to the individual actuators and is not limited by the physical layout of actuator arrays.

All this is accomplished by taking advantage of a perceptual illusion called sensory saltation (also known affectionately as the "rabbit"), discovered by Dr. Frank Geldard and his colleagues at the Princeton Cutaneous Communication Laboratory in the early 1970s (Geldard, 1975). In a typical setup for eliciting the "rabbit," three mechanical stimulators are placed with equal distance on the forearm (Figure 18.12). Three brief pulses are delivered to the first stimulator closest to the wrist, followed by three more at the middle stimulator, followed by another three at the stimulator near

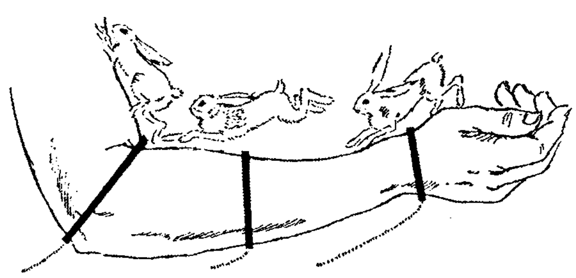

FIG. 18.12. A Norwegian cartoonist's illustration of sensory saltation. From Geldard (1975), reprinted by permission of Lawrence Erlbaum Associates, Inc. Publishers.

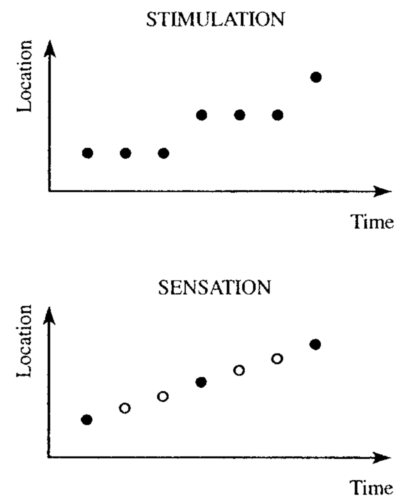

FIG. 18.13. An illustration of sensation vs. stimulation pattern for sensory saltation. Open circles indicate perceived pulses at phantom locations between stimulators. Reprinted by permission from Tan & Pentland (1997). ©1997 IEEE.

the elbow. The pulses are evenly spaced in time. Instead of feeling the successive taps localized at the three stimulator sites, the observer is under the impression that the pulses are distributed with more or less uniform spacing from the wrist to the elbow (as illustrated in Figure 18.13). The saltation effect can be elicited with mechanical, electrocutaneous, or thermal stimulation. The sensation is discontinuous and discrete as if a tiny rabbit was hopping up the arm from the wrist to the elbow, leading to the nickname "cutaneous rabbit." The same vivid hopping sensation can also be elicited in vision and audition (Geldard, 1975).

An important feature of the cutaneous rabbit is its ability to simulate higher spatial resolution than the actual spacing of stimulators, yet mimic the sensation produced by a veridical set of stimulators with the same higher-density spacing (Cholewiak & Collins, 1995; Collins, 1996; Cholewiak, Sherrick, & Collins, 1996). The perceived spacing of adjacent taps is inversely proportional to the number of pulses sent to each stimulator. In theory, only two stimulators are needed in order to produce the sensory saltation effect. Additional stimulators add redundancy and robustness to the overall setup. Thus a sparse stimulator array can be effectively used to produce a dense perception. Another important feature of the sensory saltation phenomenon is that the sensation remains vivid and

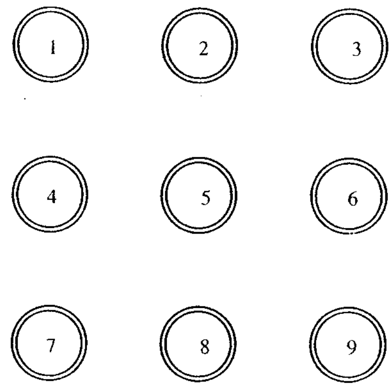

FIG. 18.14. Layout of the 3-by-3 two-dimensional "rabbit" display. Reprinted by permission from Tan & Pentland (1997). ©1997 IEEE.

does not fade away after repeated stimulation due to its discontinuity and discreteness.

Our wearable rabbit displays are implemented on the back of vests. An initial protocol consisted of 9 actuators arranged in a 3-by-3 array that measured 18 cm by 18 cm (Figure 18.14). The final version consisted of 16 actuators arranged in a 4-by-4 array covering an area of 18 cm by 18 cm. The main reasons for using a 4-by-4 array are to avoid direct stimulation to the spine area and to provide some additional redundancy. Each actuator is based on a micromotor with a biased load (MicroMo, Clearwater, Florida) that weighs 3.2 grams. The micromotor is mounted inside a square plastic tubing. The tubing is then attached to the garment with elastic bands. The state of the actuator (on or off) and its timing can be controlled by the parallel port of a personal computer through additional circuitry.

To test the effectiveness of our rabbit display, observers who are not aware of the sensory saltation phenomenon have been asked to wear the vests and report on the sensations associated with several stimulation patterns. One typical pattern consisted of three pulses sent to stimulator #8 (see Figure 18.14), followed by three pulses sent to #5, and followed by another three sent to #2. Most observers commented on a sensation of something "hopping" or "crawling" up the spine. When asked how many pulses were felt, most gave an answer between 6 and 8, thus indicating a perception of pulses in between stimulator locations. This is quite consistent with the classical definition of the sensory saltation phenomenon. In a two-dimensional pattern, three pulses of each were sent sequentially to stimulators in the order of #1, #2, #3, #6, #9, #8, #7, and #4. Instead of feeling a square, most observers reported that they felt a circular pattern. This was an interesting finding and its interpretation awaits further investigation of the sensory saltation phenomenon, especially in the case of a two-dimensional stimulator array.

In general, novice observers find it intuitive to perceive the directional information indicated by these patterns, and their interpretations of the signals are highly consistent. The signals can elicit vivid movement sensations (up, down, left, right, along a line of 45° or −45° incline). Because the directional cues are relative to the user's own body coordinate, no additional coordinate transformations are necessary. The fact that a circular pattern can be perceived suggests that other patterns might be "drawn" as well.

In an implementation of a navigational guidance system, the rabbit vest has been integrated with a driving simulation software system to provide directional cues to a driver. The overall system consists of an SGI, a PC, the vest, and input hardware that simulated the steering wheel, acceleration petal, and brake petal. The SGI is dedicated to the traffic simulation software SIRCA (Nissan Cambridge Basic Research, Cambridge, Massachusetts). The PC is used to interface with the hardware. The driver controls the steering wheel and acceleration and brake petals. The positions of these input devices, read by the game port of the PC and transmitted to the SGI through a serial link, are used to control a virtual car in SIRCA simulation. Depending on the location of the virtual car, surrounding traffic condition, road configuration, and the driver's intended destination, SIRCA generates one of the following directional commands: turn left, turn right, or go straight at the next intersection. This command, sent to the PC through a serial connection, triggers a preprogrammed signal pattern at the parallel port of the PC that controls the micromotors in the rabbit vest. The driver wearing the vest feels a left, right, or upward arrow on the back. Such a system demonstrates the feasibility and effectiveness of wearable tactile displays for navigation guidance.

6. SUMMARY

This chapter has presented a general review of tactual displays for sensory substitution and a description of a tactile directional display designed for wearable computing. The two-dimensional "rabbit" display has many features that make it an attractive candidate for displaying directional information in applications such as navigation guidance. One implementation has already demonstrated the usefulness of simple directional signals for providing directional cues to a driver. The possibilities of displaying more complicated patterns and using them to encode useful information have yet to be explored.

As wearable computing becomes more ubiquitous and distributed, a new generation of interfaces for wearable computers is emerging. In the future, smart clothing and furniture will become part of human–computer interfaces through contact sensing and display. By presenting our current efforts toward that goal, we hope to stimulate similar work on new and novel haptic displays that can work in concert with wearable visual and auditory displays.

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