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Chapter 4.4

Tactile Displays

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Introduction

The work presented in this chapter focuses on potential uses of tactile displays for visually-impaired and older adults. According to the Royal National Institute for the Blind, UK (www.rnib.org) there are two million people in the UK with sight problems (with 378, 000 registered blind) and 85% of these are over 65 years of age. The ageing population in western countries means that this group will form an increasing proportion of the whole population. According to estimates from the US Census Bureau's International Database (2004), the proportion of those in the UK who are over 60 is expected to increase from 20% in the year 2000 to 27% by 2025. Gregor *et al.* (2002) note that older people are a very diverse group, with a diverse range of abilities, and it is hard to draw a simple profile or stereotype. The individual variability of physical, sensory and cognitive functions increases with age, with many people facing multiple smaller declines. These factors mean that careful consideration is required to design effective user interfaces for these important and diverse groups.

Tactile displays can offer an alternative channel through which to present information if other senses are impaired. The traditional use of encodings such as Braille is effective at presenting textual information non-visually but touch can also be used to present or enhance iconic and pictorial data for those whose sight is beginning to fade. Alternatively, for someone with hearing problems, touch can be used to present alarms or other messages that might otherwise be given in sound. One major benefit with the tactile modality is that it is private unlike audio which can be overheard by others. Another powerful aspect is the multimodal combination of touch, hearing and sight, which allows information to be presented to the sense that is most appropriate (see the previous chapter for more discussion of multimodal interactions).

Due to their compact size and power requirements, tactile displays offer a discrete, affordable means of providing access to data via the sense of touch. Displays are often small enough to be mounted on other interaction devices such as a mouse, keyboard or games controller, or portable devices such as mobile telephones and personal digital assistants (PDAs). Mobile telephones use simple vibrations to provide non-audio based indications of incoming calls or messages. Tactile information has also found widespread acceptance within the video gaming community as an inexpensive means of providing touch feedback in handheld games controllers. Tactile sensations are crucial to success in object manipulation, edge detection, palpation, and texture perception (Klatzky and Lederman, 2003). They are also implicated in more expressive and qualitative contexts such as non-visual communication (e.g. a firm handshake or a caress on the hand), and perceptions of product quality.

This chapter provides some background on the use of touch for human-computer interaction (HCI), focusing on cutaneous perception and reviewing the main research in sensory substitution, in particular Braille/raised paper, pin arrays and vibrotactile displays. It concludes with some discussion of what tactile output may offer older adults and disabled people in the future.

Design Implications of Cutaneous Perception

The human sense of touch can be divided into two separate channels. *Kinaesthetic* perception refers to the sensations of positions, velocities, forces and constraints that arise from the muscles and tendons. Force-feedback devices appeal to the kinaesthetic senses by presenting computer-controlled forces to create the illusion of contact with a rigid surface (Burdea, 1996). The *cutaneous* class of sensations arise through direct contact with the skin surface. Cutaneous stimulation can be further separated into the sensations of pressure, stretch, vibration, and temperature. Pain is sometimes also referred to as a separate sensation, though excessive stimulation of the other parameters will lead to a feeling of pain. Tactile devices generally appeal to the cutaneous senses by skin indentation, vibration, skin stretch and electrical stimulation.

It is important to know the capabilities and limits of the sense of touch when designing tactile user interfaces. This section gives a practical overview of the most important aspects of cutaneous perception from an interface designer’s perspective, with a discussion of the effects of ageing on perception. There is a great deal of work in the area of cutaneous perception and psychophysics. For a detailed review see Klatzky and Lederman (2003).

Amplitude: The fingertip is the most sensitive region for the detection of indentation, estimated by psychophysical studies to be in the region of 10 microns for step indentations (Kaczmarek et al., 1991). The highest thresholds for detection occur at low frequencies of stimulation (Lofvenberg and Johansson, 1984) and the minimum thresholds occur in the region of 250Hz. Discrimination capacity for amplitude of indentation is largely dependant on the location of stimulation, being finer at those points of the body with lower detection thresholds (Geldard, 1957). As with the vision and audition, discrimination capacity is not constant throughout the stimulation amplitude range. Indentation amplitude discrimination is lower resolution at low intensities, becomes more sensitive in the range 200-700 microns, progressively degrading with increasing stimulus amplitude (Werner and Mountcastle, 1968). Craig (as reported in Schiff and Foulke, 1982) found a difference limen of 0.2 for amplitude when 160Hz vibrations were presented to the index finger, indicating that an increase or decrease of 20% is necessary for a change in amplitude to be perceived. Discrimination capacity for amplitudes is reported to be roughly independent of frequency of stimulation (Tan, 1996).

Frequency: While humans can hear sounds in the range 20-20,000Hz, the practical frequency range of the skin is much smaller, ranging from 10Hz to 400Hz, with maximum sensitivity (Summers, 1992) and finer spatial discrimination (Craig and Sherrick, 1982) at around 250Hz. The resolution of temporal frequency discrimination is finer at lower frequencies. Investigations by Goff involving the stimulation of the subject's finger with a single probe showed that for lower frequencies (< 25Hz), the discrimination threshold was less than 5Hz. For frequencies greater than 320 Hz, discrimination capacities were degraded (Goff, 1967). Measures for discrimination thresholds of frequency are problematic, as perception of vibratory pitch is dependant not just on frequency, but also amplitude of stimulation. Geldard (1957) found that subjects reported a change in pitch when frequency was fixed, but amplitude of stimulation was changed. This is similar to the effect of volume on pitch perception in audio, but the effect is more pronounced for vibratory stimuli on the skin. Sherrick (1985) found that combining frequency and amplitude redundantly allowed a greater number of identifiable levels to be created. He found that people could distinguish three to five different levels of frequency, but that this range could be increased to eight by adding amplitude as a redundant parameter. The perceptual interaction between frequency and amplitude should to be taken into consideration when designing tactile user interfaces.

Waveform: Different waveforms can be generated and used to create different tactile sensations. Brown *et al.* (2005) have looked at the effects of amplitude modulation to create stimuli of different 'roughness'. A study showed that participants felt the modulations as varying levels of roughness, and that roughness increased as modulation frequency decreased (with the exception of a pure sinusoid which was perceived as smooth). They suggest that up to 3 roughnesses can be used, with a study showing that participants could recognise them with 80% accuracy.

Duration: Geldard (1957) reports that the temporal duration just noticeable difference (JND) increased from 50 to 150 ms. with increasing stimulus duration from 0.1 to 2.0 sec. Gescheider (as reported in Tan, 1996) measured the time difference between the onset of two tactile “clicks” on the fingertip, necessary for them to perceived as two separate sensations. The minimum threshold reported was 10 ms., although this estimate could have been limited by the experimental apparatus. When using duration in tactile interface design it is important to ensure that stimuli are detectable, but not so long as to make information transfer too slow. Interactions between duration and perceived amplitude should be considered when using duration as it has been shown that short intense signals can be confused with longer, lower intensity signals. Gunther (2002) suggests that stimuli lasting less than 0.1 seconds may be perceived as taps or jabs, whereas longer stimuli may be perceived as smoothly flowing tactile phrases. Craig and Sherrick (1982) warn that durations which are too short may result in sensations such as pokes or jabs which might be undesirable.

Rhythm: Building on single pulse durations more complex stimuli can be formed. Rhythms are created by grouping together pulses to create temporal patterns which are similar to rhythms in music. Summers (2000) encoded speech information by modulating vibration frequency and amplitude, and by presenting the temporal pattern of the speech. Users obtained most information from the temporal pattern and very little from the frequency/amplitude modulation. This result suggests that rhythm could be an effective parameter in tactile displays.

Location on the Body: Different body locations have different levels of sensitivity and spatial acuity. The most sensitive part of the human body is the fingertip. The two point of contact discrimination threshold is 0.9mm when the stimuli are placed against the subject's finger in the absence of any movement lateral to the skin's surface. Two points of contact closer than this threshold cannot be resolved in to distinct stimuli. Experimental evidence suggests that active exploration marginally increases sensitivity, decreasing the threshold to 0.7 mm (Phillips and Johnson, 1985).

The fingers are often used for tactile displays because of their high sensitivity. However, they are often required for interaction and manipulation tasks. Other body locations may be more suitable, or several sites may be needed for a complex display. An important factor to consider is whether stimuli are presented to glabrous (non-hairy) or hairy skin, as sensitivity differs greatly between them (Summers, 1992) and might require more discriminable stimuli. Certain body locations are less suitable for use, for example transducers should not be placed on or near the head, as this can cause leakage of vibrations into the ears, resulting in unwanted sounds (Gunther et al., 2002).

Craig and Sherrick (1982) suggest the back, thigh and abdomen as suitable body locations. They report that, once subjects have been trained in vibrotactile pattern recognition on the back, they can almost immediately recognise the same patterns when they are presented to the thigh or abdomen. This transfer also occurs to some extent when patterns are presented to different fingers after training on one finger, but is not so immediate. Cholewiak and Collins (2003) investigated tactile localization on the forearm using seven actuators. They found that when a stimulus was close to an anatomical reference point, and in particular a point of mobility such as the wrist or elbow, performance was greatest. Cholewiak *et al.* (2004) conducted a study on the abdomen, where the main anatomical references are the spine and navel, and found again that localization was most precise when the stimuli occurred at these reference points. They also found that people were unlikely to mistake stimulation at another point for stimulation at one of the reference points.

Effects of Ageing: Sensitivity to tactile stimulation is reduced with age (in line with the other senses). There are many reasons for this, including diabetes, skin trauma and physiological changes in the skin itself. Stuart *et al.* (2003) investigated the reductions in sensitivity to sinusoidal vibrations on different areas of the body, comparing people up to the age of 27 to a group between 55 to 90 years old. They compared detection thresholds at the fingertip, forearm, shoulder and cheek. The older group showed significantly increased detection thresholds in all areas, except for the fingertip. The oldest participants showed the greatest declines in sensitivity. Similar research by Goble *et al.* (1996) looking at the palm and fingertip found that there were differences between older and younger people's detection thresholds. One reason for the differing results is the different methods used to stimulate the skin in both studies. The results of both studies do suggest that the intensity of stimulation would need to be increased to ensure older users could detect the stimuli being presented. Tactile user interface should include an intensity control, much like a volume control in an audio interface.

Sensory Substitution

The previous section has shown the main parameters of cutaneous perception and some guidance for tactile display. This section presents a review of the work on the applications of tactile displays and, in particular, the key topic of sensory substitution. The process of sensory substitution involves the sensing of stimuli by electronic means, transformation of the stimulus via signal processing, and presentation of the transformed stimulus in another sensory modality. The main application of these systems is increasing accessibility for those with sensory impairments. As early as the 1920s, researchers were interested in using vibration as a means of information transfer (for example, Gault in 1926, cited by Craig and Sherrick, 1982). The earliest sensory substitution devices converted visual stimuli to tactile representations for blind and visually impaired people.

Traditionally, information was presented to the skin via printed Braille or raised paper diagrams. These can be very effective but are non-dynamic and slow to produce. Dynamic, refreshable displays offer greater flexibility and independence. The most commonly used tactile displays evoke sensations using mechanical perturbation of the skin. This is commonly done by vibrating a small plate pressed against the skin, or via a pin or an array of pins on the fingertip. Other types of actuator technology are available, including pneumatic and electrotactile, but these tend to be lower resolution, harder to control, with few commercial products an interface designer can use. For a full review see Kaczmarek *et al*. (1991).

This section outlines some of the key ways in which information is displayed to the skin and outlines the main technologies used and their application. It is structured around the three main methods of presenting information: Braille/raised paper, pin arrays and vibrotactile displays. Each method is described with examples of its use.

Braille and Raised Paper Diagrams

Braille is the most common tactile presentation method used by visually impaired people. Each Braille character consists of a three row by two column “cell”, with combinations of raised dots allowing 64 individual patterns. The patterns represent the letters of the alphabet, punctuation and various contractions that stand for frequently recurring letter groups. Inspired by the work of William Wait in the late 19th century (cited in (Schiff and Foulke, 1982)), experimental evidence gradually built up that demonstrated the superiority of Braille codes over embossed letters in terms of reading speed and comprehension of text. The main drawback of Braille is that reading speeds are much slower than for vision, at around 104 words per minute for experienced adult users (Schiff and Foulke, 1982) (in comparison, the average reading speed for sighted high school students is 250-300 wpm, with some adults reaching two or three times that speed).

Raised paper diagrams are most commonly used to present pictorial information. They are produced via embossing or heat raised paper and have been employed for presentation of pictorial information including illustrations, photographs, graphs, and maps. The NOMAD (Parkes, 1988) allowed the use of traditional tactile diagrams augmented with audio information. This overcomes the traditional drawbacks inherent in the static nature of tactile diagrams, and allows information to be presented in speech that would otherwise clutter the diagram with Braille. Embossed diagrams still possess many advantages over more technological solutions – they are cheap to produce, have no moving parts, and can be quickly and easily explored with the whole of both hands to provide a good overview of the information being displayed. They are, however, limited in size, can become easily cluttered with information, are subject to wear and tear and are inherently non-dynamic in nature, plus they often require sighted assistance to produce.

Pin Arrays

This type of display uses a pin or array of small pins to stimulate the fingertip (see Figure 1 or the displays produced by Summers *et al.* (2002)). One of the most common uses for this type of display is for presenting Braille. Dynamic Braille displays are made up of a line of cells (often 40 or 80), each with 6 or 8 pins that move up and down to represent the dots of a Braille cell. The user can read a line of Braille cells by touching the pins of each cell as they pop up (for more information see www.tiresias.org). Summers and colleagues have developed a much higher resolution array with a 10 by 10 matrix of pins over an area of $1cm^2$ (Summers and Chanter, 2002). Such devices can present fine cues for surface texture, edges and lines for pictorial information.

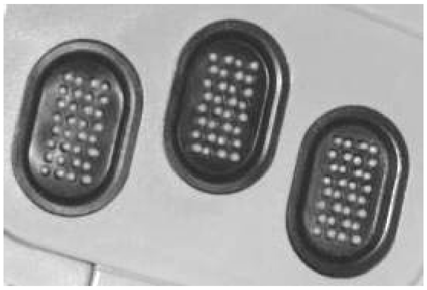

Figure 1. A tactile pin array for fingertip display, consisting of three 4 x 8 arrays of pins.

Tactile-vision substitution systems were the earliest to be developed, in order to present visual information to blind people. In a typical system, a camera receives visual information that is converted to a tactile representation on a two dimensional pin array. The Optacon (Figure 3) was one of the first devices to employ a matrix of pins for tactile-vision substitution and was the first device of this kind to be developed as a commercial product. It converted printed letters into a spatially distributed vibrotactile representation on the fingertip using a miniature handheld camera (Craig and Sherrick, 1982). The input to the device is a 6 by 24 array of photosensitive cells, which detects patterns of light and dark as material is moved underneath. The display part of the device is a 6 by 24 array of pins on which the user places their fingertip. The output of the camera is represented by vibrating pins on the tactile display. The pins vibrate at a frequency of 230Hz, which is close to the maximum sensitivity of the skin. Reading speeds with the Optacon are around 10 to 12 wpm (words per minute) after the initial 9 day training period, reaching 30 to 50 wpm after further training and experience (Craig and Sherrick, 1982).

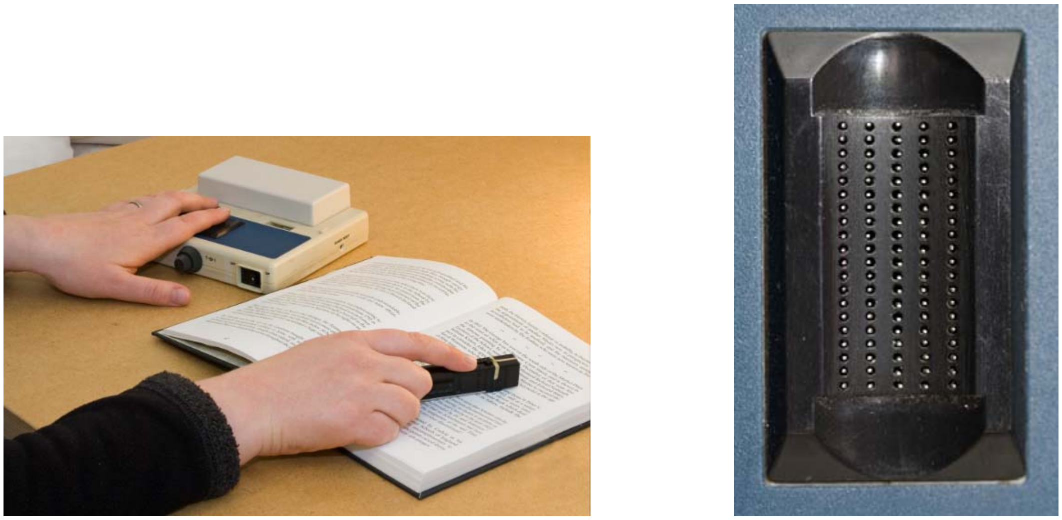

Figure 3. Using the Optacon device to read text. The image on the right shows a close-up of the pin array.

Early pioneering work in tactile vision substitution (TVSS) was also performed by Bach-y-Rita and colleagues in the late 1960s. Early systems displayed visual information captured by a tripod mounted TV camera to a vibrotactile display on the user's back. Due to limited spatial resolution, tactile masking effects and a low dynamic range, the system was not suitable for day-to-day navigation. However, subjects could easily recognize simple shapes and discriminate orientation of lines. It was also reported that experienced users could perform more complex tasks, such as recognition of faces, or electronic assembly using the system (Kaczmarek and Bach-y-rita, 1995).

To allow exploration of a larger tactile image with a device limited to the size of one or two fingertips, several researchers have adopted a strategy of mounting a tactile display on a computer input device, such as a mouse (see Figure 4) or graphics tablet stylus. This allows the motion of the user's fingertips to be tracked within the limits of a certain workspace and the tactile display to be updated accordingly, dependant on where the user is on a “virtual image”. They can be distinguished from devices such as the Optacon in that they are most commonly employed to represent information that is stored digitally on a computer, rather than present in the user’s distal environment. Active exploration is necessary to perceive the entirety of the image being displayed.

Figure 4. The VTPlayer tactile mouse. A commercially available virtual tactile display with two arrays of 4 by 4 pins from VirTouch (www.virtouch2.com).

Researchers are currently investigating how best to employ tactile displays like these to present pictorial information. Potential applications include making graphs and maps more accessible to visually impaired users. Wall and Brewster (2006b) investigated the identification of positive and negative gradients relative to a horizontal line using a VTPlayer mouse (see Figure 4). They found that blindfolded participants were correctly able to identify positive and negative gradients within ±4.7 degrees of the horizontal, compared to ±3.25 degrees for a force-feedback mouse, and ±2.42 degrees for raised paper representations. Using the raised paper diagram provides the richest combination of tactile cues. Improving the size, resolution and bandwidth of tactile displays could potentially move discrimination closer to that observed for raised paper.

Jansson and Pedersen looked at performance in a map-browsing task using the VTPlayer. They noted that the tactile feedback had no beneficial effects over the performance that could be achieved with audio feedback. This was due to the difficulty that the visually impaired people had using a mouse. The information available through the pin arrays is very limited compared to the rich, distributed cues of vision, or those available with a raised paper map (Jansson and Pedersen, 2005).

Wall and Brewster (2006a) also conducted a more qualitative experiment using the VTPlayer to represent bar charts. Many of the blind users consulted were also uncomfortable with mouse use, so the tactile cues were presented to the non-dominant hand to supplement navigation with a graphics tablet used in the other hand. The graphics tablet provided an absolute position reference that allowed users to plan their exploration better. A tangible overlay was used to disambiguate resources such as the graph's axes, so that they could quickly be apprehended by the user. The pins of the display were raised if the user was on a bar, and lowered if not, thus supporting navigational information (e.g. "am I on a bar?" "how many bars have I crossed") and indirect access to information ("how high is the bar?"). Supplementary audio cues were used for contextual information as to position on the graph, and provided details on the titles and values of bars.

This research shows that the needs of users can still outstrip the capabilities of current tactile displays for some applications. Improving the pin spacing and amplitude of pin movement would allow more complex information to be displayed. Performance in feature identification has been shown to increase with decreasing pin separation, and would also allow more pins on the display (Kammermeier and Schmidt, 2002). Improving the range and resolution of pin movement would allow height to be used as a filtering mechanism to disambiguate different picture elements, such as edges and texturing (Challis and Edwards, 2001). Wall and Brewster suggest presenting information through other modalities to avoid cluttering the tactile representation, and using a tangible relief to provide persistent, unambiguous guidance using static interface elements such as axes and gridlines (Wall and Brewster, 2006a).

Vibrotactile Displays

Most vibrotactile actuators use electromagnetic actuation to drive a mass in either a linear or rotational fashion to provide vibrotactile stimulation to the skin. Two typical vibrotactile devices, the TACTAID VBW32 (www.tactaid.com) and the EAI C2 Tactor (www.eai.com), are shown in Figure 2. Both of these devices are resonant at 250Hz with much reduced response at other frequencies (which reduces the usefulness of frequency as a parameter for vibrotactile interfaces). Vibrotactile cues are much lower resolution than pin arrays but can exert more force (so can be felt through clothing); they can also be distributed over the body to give spatial cues (often mounted in a vest on the user's back or in a belt around the waist). For a more detailed review of vibrotactile devices see Summers (1992).

Poupyrev *et al.* (2003) have designed sophisticated tactile displays for handheld computers. Lee et al. (2004) have also recently developed a vibrotactile stylus to use on touch screens and handheld computers. There is commercial interest in this area, as most mobile telephones include tactile feedback to accompany ring tones. For example, Immersion's VibeTonz (www.immersion.com/vibetonz) attempt to extend this simple feedback to enhance games and ring tones. Vibrotactile displays have been incorporated into canes used by visually-impaired people. The UltraCane (www.soundforesight.co.uk) uses ultrasound to detect objects in a user's environment and displays the location and distance to targets by vibrating pads on the handle of the cane.

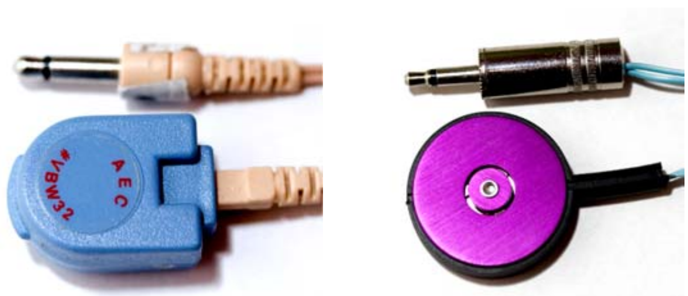

Figure 2: Left – a TACTAID VBW32 transducer, right an EAI C2 Tactor.

Work on vibrotactile displays was motivated by tactile-audio substitution for profoundly deaf people, which did not develop much until the late 1970s and early 1980s. One of the earliest devices was the Tacticon, a commercial device that adjusted the perceived intensity of 16 electrodes, each of which corresponded to a range of frequencies in the auditory spectrum, in order to improve speech comprehension, auditory discrimination, and the clarity of the users speech (Kaczmarek and Bach-y-rita, 1995). Another early device, the Tactile Acoustic Monitor (TAM), was developed by Summers (2000).

The TAM employed a single vibrotactile stimulator to provide un-encoded information about the loudness of the user's speech and other sounds in the environment. Sound is picked up by a microphone, which is then compared to a threshold level. If the microphone signal is above the threshold the vibrotactile actuator is turned on at a constant amplitude and frequency, whereas if the sound level falls below the threshold the actuator is turned off. Evaluation showed that the TAM was useful for lip reading applications, prompting a variety of experiments investigating speech perception via a single vibratory transducer (Summers, 2000). For a full review of work in this area see Summers (1992).

Significant early work in tactile displays for desktop human-computer interaction was carried out by Akamatsu and colleagues who investigated the addition of an electromagnetically controlled pin to a standard mouse. This allowed users to feel vibrations through a fingertip. Akamatsu *et al.* (1995) investigated the impact of their tactile feedback on target acquisition in a Fitts' law pointing study. They examined whether targeting was aided when sound, tactile and colour feedback were used to indicate target acquisition in a desktop type pointing interaction. Tactile feedback had a greater effect in reducing the time a user spent over a target than either sound or colour. In a second study, Akamatsu and MacKenzie (1996) examined the contribution of tactile and force-feedback on targeting. Tactile alone and force-feedback + tactile reduced targeting times by 5.6% and 7.6% respectively. Force-feedback alone resulted in slightly higher targeting times.

Cockburn and Brewster (2005) looked at combinations of different feedback modalities, including vibration feedback from a Logitech iFeel vibrotactile mouse (www.logitech.com), for selecting small targets on a computer desktop. They found that, in simple Fitt's law type tasks (where discrete targets are used, so there are no distracters), tactile and audio feedback both reduced targeting time (confirming Akamatsu's results above), but the combination of audio plus tactile was not as good as when each was used alone. However, in a more realistic task (choosing items from drop down menus) the tactile feedback caused problems and actually increased targeting time over a standard graphical display. The reason for this was the close proximity of many tactile targets (each menu item gave tactile feedback) causing feedback 'overload'.

Jacko and colleagues have looked at how tactile displays (and more generally multimodal ones) can help older adults with age-related macular degeneration (AMD) (which is a leading cause of visual impairment in individuals of 65 years and over). Their evaluations use drag-and-drop type interactions with the Logitech Wingman force-feedback mouse (www.logitech.com) which is vibrated to produce tactile feedback. When different combinations of audio, tactile and visual feedback were added to drag-and-drop, there was little benefit to the tactile feedback over a standard visual display, except when it was in combination with audio (Jacko et al., 2003). A second study showed that AMD had a major effect on the drag-and-drop task, with AMD sufferers performing significantly worse than fully-sighted people of the same age. Again tactile showed little effect on its own, improving performance by a small amount. However, when it was combined with audio it had a much greater effect. AMD sufferers got more benefit from the addition of extra feedback than the fully sighted (Jacko et al., 2004).

Results from this work appear to conflict with those of Cockburn and Brewster as they showed audio and tactile feedback were more beneficial on their own. It is difficult to compare the two studies as they used different users, devices and stimuli. These results do show that the use of tactile displays is an active research area with many questions still to be answered. Designers must be careful to test their applications with the devices they will actually use to ensure that usability is improved.

Brewster and Brown (2004) have investigated an alternative encoded form of tactile presentation: the Tacton, or tactile icon. Tactons are structured, abstract messages that can be used to communicate messages non-visually. Visual icons and their auditory equivalent Earcons (Blattner et al., 1989) are very powerful ways of displaying information but there is no tactile equivalent. In the visual domain there is text and its counterpart the icon, the same is true in sound with synthetic speech and the Earcon. In the tactile domain there is Braille but it has no 'iconic' counterpart. Visual icons can convey complex information in a very small amount of screen space, much smaller than for a textual description. Earcons transmit information in a small amount of time as compared to synthetic speech. Tactons can convey information in a smaller amount of space and time than Braille. The shared temporal property between audio and tactile means that certain audio characteristics such as rhythm, tempo and duration could be transformed into tactile stimuli (and *vice versa*). Therefore, the same information may be presented interchangeably via the two different modalities. This is a bi-directional form of sensory substitution where the information could be presented to one sense or other depending on the user's particular disabilities or current situation.

Tactons are created by manipulating the parameters of cutaneous perception (detailed previously) to encode information. For example, Brown *et al.* (2005) encoded two pieces of information into a Tacton to create messages for mobile telephones. The type of a call or message (voice call, text message, or multimedia message) was encoded in the rhythm, while the priority (low, medium or high) of a call or message was encoded in the roughness (via amplitude modulation). Using this mapping, the same rhythm would represent a high and low priority voice call but they would each be presented using a different waveform, whereas a high priority voice call and a high priority text message would share the same waveform, but have different rhythms. An initial study (Brown et al., 2005) on these nine Tactons showed that participants could identify them with over 70% accuracy, with rhythms being identified correctly 93% of the time. These results show that Tactons can be a powerful, non-visual way of communicating information, and useful to users who cannot see.

Conclusions

This chapter has reviewed the contribution of tactile displays for sensory substitution and supplementation for sensory impaired users. Tactile feedback offers an alternative channel through which information can be communicated when other channels are impaired or overloaded. This might be in addition to graphical or audio displays, or as an alternative depending on the user’s preferences and any disabilities.

The human sense of touch is very powerful, but abilities change with age. There is some detailed research into the effects of these changes at the physiological level, but this has not yet fed into much of the applied research on tactile displays for sensory substitution. There is much to be done on looking at what changes might need to be made to ensure tactile displays are useful to users with a wide range of abilities. Basic things like being able to control the amplitude of stimulation are important. Devices such as the Optacon allowed this so that the user could set a comfortable, perceivable level. This is not possible with many other available devices, which may make them hard for someone with less sensitivity to use, or painful for someone with heightened sensitivity.

Other important issues for designers were raised in the review of perception. The interaction between frequency and amplitude means that care must be taken if one parameter is varied as it may change the way the other is experienced. The duration of stimulation is important too. If it is too short then stimuli may go unnoticed, too long and information transfer will be too slow. Rhythm has also been shown to be a good parameter for information display, mapping well to auditory stimuli if crossmodal presentation is required. Finally, location on the body must be considered. The fingertip is very sensitive but may not be usable if a user needs to type or hold a mouse. Other body locations are possible but sensitivity will be lower and the effects of age may affect different sites in different ways. When multiple stimulation sites are required, each actuator should be positioned near an anatomical reference point for accurate localisation. All of these issues are important to tactile HCI and further research will help designers deal with them to avoid problems of cues being missed or misinterpreted.

There are no standard tactile devices; they are evolving at the same time as the applications that use them. This can make it hard to generalise results from one device to another. As the area gets more attention and more studies are undertaken this problem will be resolved. However, at the present time it is important for designers to test out their applications with the specific devices they intend to use to be sure of the usability benefits.

Before the full potential of touch can be realised in computer systems, further technology developments are required. From an interaction perspective there are important requirements for new devices. For vibrotactile devices we need to be able to present a wider range of frequencies to the skin. Presently the frequency range is limited to around 250Hz on most devices. If this could be widened it would allow greater use of the skin's ability to detect vibration. Much of the work on pin arrays presented above used devices with small numbers of widely spaced pins that can only be raised or lowered with no resolution on between. To simulate textures accurately or represent detailed images much higher resolution displays are needed. The two-point difference threshold has been estimated at 0.7mm, which is the necessary spacing of pins to fuse stimuli into a continuous image. To enable height to be used as a filtering mechanism to give information on relative importance of items in a scene, the amplitude of the pins needs to be controllable. Summers' work is going in this direction with arrays of much higher density (Summers and Chanter, 2002).

There are many new application areas that could benefit from tactile displays. The use of mobile devices has grown very rapidly over the last five years. Mobile telephones, handheld computers and handheld computer games are now very common, with new devices and applications appearing all the time. There is a strong research focus in computing science on how better interfaces might be designed for this new type of device, but many are currently difficult or impossible for disabled people to use. Small screens make it hard to display information at a size that people with poor eyesight can see. Tactile displays have an important role to play in making these devices usable by older or visually impaired people. Information could be presented using sophisticated tactile displays that could give people access to the user interface in a form that is suitable for them.

More sophisticated tactile cues could be used to provide much more information to help users navigate without using vision. Vibrations could be presented to the left or right side of the body to indicate changes in direction or assist in more complex obstacle avoidance. In a context-aware mobile device a tactile display could give information about the environment surrounding the user as he/she is mobile, for example encoding information about the type of building the person is next to, where the door is and the number of steps to get inside. This has advantages as information delivered through sound can often be problematic if the environment is noisy or the information is confidential. A tactile display is private to the user and less affected by the environment.

The work reviewed here shows that the sense of touch has great potential as a channel for communication. A range of different applications for disabled people has been developed over the years. It is now becoming possible to use tactile displays creatively in mainstream HCI research to design a new generation of accessible user interfaces.

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