Tactons: Structured Tactile Messages for Non-Visual Information Display

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Abstract

Tactile displays are now becoming available in a form that can be easily used in a user interface. This paper describes a new form of tactile output. *Tactons*, or tactile icons, are structured, abstract messages that can be used to communicate messages non-visually. A range of different parameters can be used for Tacton construction including: frequency, amplitude and duration of a tactile pulse, plus other parameters such as rhythm and location. Tactons have the potential to improve interaction in a range of different areas, particularly where the visual display is overloaded, limited in size or not available, such as interfaces for blind people or in mobile and wearable devices. This paper describes Tactons, the parameters used to construct them and some possible ways to design them. Examples of where Tactons might prove useful in user interfaces are given.

Keywords: Tactons, tactile displays, multimodal interaction, non-visual cues.

1 Introduction

The area of haptic (touch-based) human computer interaction (HCI) has grown rapidly over the last few years. A range of new applications has become possible now that touch can be used as an interaction technique (Wall et al., 2002). However, most current haptic devices have scant provision for tactile stimulation, being primarily programmable, constrained motion force-feedback devices for kinaesthetic display. The cutaneous (skin-based) component is ignored even though it is a key part of our experience of touch (van Erp, 2002). It is, for example, important for recognising texture, and detecting slip, compliance and direction of edges. As Tan (1997) says "In the general area of human-computer interfaces … the tactual sense is still underutilised compared with vision and audition". One reason for this is that, until recently, the technology for tactile displays was limited.

Tactile displays are not new but they have not received much attention from HCI researchers as they are often engineering prototypes or designed for very specific applications (Kaczmarek et al., 1991). They have been used in areas such as tele-operation or displays for blind people to provide sensory substitution – where one sense is used to receive information normally received by another (Kaczmarek et al.). Most of the development of these devices has taken place in robotics or engineering labs and has focused on the challenges inherent in building low cost, high-resolution devices with realistic size, power and safety performance. Little research has gone into how they might actually be used at the user interface. Devices are now available that allow the use of tactile displays so the time is right to think about how they might be used to improve interaction.

In this paper the concept of *Tactons,* or tactile icons, is introduced as a new communication method to complement graphical and auditory feedback at the user interface. Tactons are structured, abstract messages that can be used to communicate messages non-visually. Conveying structured messages through touch will be very useful in areas such as wearable computing where screens are limited. The paper gives some background to the perception and use of tactile stimuli and then describes the design of Tactons. It finishes with examples of potential uses for Tactons.

2 Background and previous work

The skin is the largest organ in the body, about 2 m^2 in the average male (Montagu, 1971). Little direct use is made of it for displaying information in human-computer interfaces (Tan and Pentland, 1997, van Erp, 2002), yet a touch on the hand or other parts of the body is a very rich experience. The skin can therefore potentially be used as a medium to communicate information. As a receiving instrument the skin combines important aspects of the eye and the ear, with high acuity in both space and time (Gunther, 2001) giving it good potential as a communication medium.

The human sense of touch can be roughly split in to two parts: kinaesthetic and cutaneous. "Kinaesthetic" is often used as catch-all term to describe the information arising from forces and positions sensed by the muscles and joints. Force-feedback haptic devices (such as the PHANToM from SensAble) are used to present information to the kinaesthetic sense. Cutaneous perception refers to the mechanoreceptors contained within the skin, and includes the sensations of vibration, temperature, pain and indentation. Tactile devices are used to present feedback to the cutaneous sense.

Current haptic devices use force-feedback to present kinaesthetic stimuli. This works well for some aspects of touch (e.g. identifying the geometric properties of objects) but is poor for features such as texture (normally perceived cutaneously). Oakley *et al.* (2000) found that trying to use texture in a user interface with a force-feedback device actually reduced user performance. One reason for this is that the textures had to be made large so that they could be perceived kinaesthetically, but they then perturbed users' movements. The use of a tactile haptic device to present texture would not have this problem as small indentations in the fingertip would not affect hand movements. At present, however, there are no haptic devices that do a good job of presenting both tactile and force-feedback cues to users.

Current force-feedback devices use a *point interaction* model; the user is represented by a single point of contact corresponding to the tip of a stylus. This is analogous to exploring the world by remote contact through a stick thus depriving the user of the rich, spatially varying cutaneous cues that arise on the finger pad when contacting a real object (Wall and Harwin, 2001). Users must integrate temporally varying cues as they traverse the structure of virtual objects with the single point of contact, which places considerable demands on short-term memory (Jansson and Larsson, 2002). Even when exploring simple geometric primitives, performance is greatly reduced compared to natural touch. Lederman and Klatzky (1999) have shown that such removal of cutaneous input to the fingertip impedes perception of edge direction, which is an essential component of understanding haptic objects. It can therefore be seen that tactile feedback and cutaneous perception are key parts of touch that must be incorporated into haptic displays if they are to be effective and usable.

2.1 Vibrotactile actuators

There are two basic types of vibrotactile display device. These evoke tactile sensations using mechanical vibration of the skin (usually in the range 10-500Hz) (Kaczmarek et al., 1991). This is commonly done by vibrating a small plate pressed against the skin or via a pin or array of pins on the fingertip. These are very easy to control from standard PC hardware. Other types of actuator technology are available, including pneumatic and electrotactile (Stone, 2000), but these tend to be bulkier and harder to control so are less useful in many situations.

Figure 1: The pins arrays on the VirTouch tactile mouse (www.virtouch.com).

The first type of vibrotactile display uses a pin or array of small pins (e.g. the VirTouch mouse in Figure 1 or those produced by Summers *et al.* (2001)) to stimulate the fingertip. Such devices can present very fine cues for surface texture, edges, lines, etc. The second type uses larger point-contact stimulators (e.g. Figure 2 or alternatively small loudspeaker cones playing tones, or other simple vibrating actuators placed against the skin as used by Tan (1997) and in devices such as the CyberTouch glove – www.immersion.com). The cues here are much lower resolution but can exert more force; they can also be distributed over the body to allow multiple simultaneous cues (often mounted in a vest on the user's back or in a belt around the waist). These devices are both easy to control and use. For a full review see Kaczmarek *et al.* (1991).

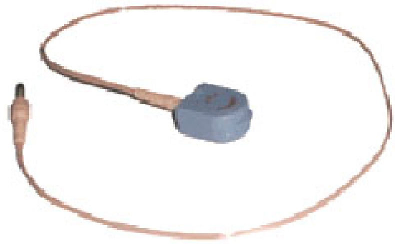

Figure 2: Audiological Engineering Corp. VBW32 transducers (www.tactaid.com).

2.2 Previous work on tactile display

One common form of tactile output is Braille, and dynamic Braille cells are available. A display is made up of a line of 'soft' 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). The focus of the work reported here is not on Braille as it tends to be used mainly for representing text (although other notations are used, e.g. music) and the cells are very low resolution (8 pins maximum). These displays are also very expensive with an 80 cell display costing around £4000. There have been many other tactile devices for blind people, such as the Optacon (TeleSensory Inc.), which used an array of 144 pins to display the input from a camera to the fingertip, but again these are mainly used for reading text. Pin arrays produce Braille but can do much more, especially the higher resolution displays such as shown in Figure 1.

Our research also builds on the work that has been done on tactile graphics for blind people (this mainly takes the form of raised lines and dots on special 'swell' paper). Kurze (1997, 1998) and Challis (2001) have developed guidelines which allow images and objects to be presented that are understandable through touch by blind users.

Two other examples show that the cutaneous sense is very effective for communication. Firstly, *Tadoma* is a tactile language used by deaf/blind people. The transmitter speaks normally and the receiver puts a hand on the face of the speaker, covering the mouth and neck (Tan and Pentland, 2001). Tadoma users can listen at very high speeds (normal speaking speed for experts) and pick up subtleties of the speech such as accent. In the second example, Geldard (1957) taught participants a simple tactile language of 45 symbols, using three intensities, three durations and five locations on the chest. Participants were able to learn the alphabet quickly and could recognise up to 38 words per minute in some cases. Other sensory substitution systems convert sound into vibration for hearing-impaired people (e.g. the TactAid system from Audiological Engineering). Again this shows that cutaneous perception is very powerful and if we can make use of it at the user interfaces we will have a rich new way to present information to users.

Research and existing applications have shown that the cutaneous sense is a very powerful method of receiving information. Other work has shown that it can be used in user interfaces and wearable computers (Gemperle et al., 1998). Tan has begun to investigate the use of tactile displays on wearable computers (Tan and Pentland, 1997). She used a 3x3 grid of stimulators on a user's back to provide navigation information. Informal results suggested it was useful but no formal evaluation has taken place. Other relevant work has taken place in aircraft cockpits to provide pilots with navigation information (van Veen and van Erp, 2001, Rupert, 2000). In these examples only simple tactile cues for direction have been provided. For example, an actuator maybe vibrated on one side of the body to indicate the direction to turn. More sophisticated cues could be used to provide much more information to users without them needing to use their eyes.

Gunther *et al.* have used tactile cues to present 'musical' compositions to users (Gunther, 2001, Gunther et al., 2002). They say: "The approach taken … views haptic technologies – in particular the vibrotactile stimulator – as independent output devices to be used in conjunction with the composition and perception of music. Vibrotactile stimuli are viewed not as signals carrying information *per se*, but as aesthetic artifacts themselves". He used an array of 13 transducers across the body of a 'listener' so that he/she could experience the combined sonic/tactile presentation. Gunther created a series of compositions played to listeners who appeared to enjoy them. This work was artistic in nature so no formal usability assessments were made but the listeners all liked the experience.

In order to create a tactile composition (the same is true for the Tactons described below) a good understanding of the experience of touch is needed. However, as Gunther *et al.* suggest: "It is indeed premature to hammer out the details of a language for tactile composition. It seems more productive at this point in time to identify the *underpinnings* of such a language, specifically those dimensions of tactile stimuli that can be manipulated to form the basic vocabulary elements of a compositional language". Research is needed to gain a more systematic understanding of cutaneous perception for use in the presentation of such messages.

Enriquez and MacLean (2003) recently proposed 'haptic icons', which they define as "brief programmed forces applied to a user through a haptic interface, with the role of communicating a simple idea in a manner similar to visual or auditory icons". The problem they are trying to address is different to that of Tactons, as they say "With the introduction of "active" haptic interfaces, a single handle – e.g. a knob or a joystick – can control several different and perhaps unrelated functions. These multi-function controllers can no longer be differentiated from one another by position, shape or texture… Active haptic icons, or "hapticons", may be able to solve this problem by rendering haptically distinct and meaningful sensations for the different functions". These use one degree-of-freedom force-feedback devices, rather than tactile displays, so encode information very differently to Tactons. They report the construction of a tool to allow a user to create and edit haptic icons. This is early work and they do not report results from the use of hapticons in any interfaces. Their results, however, will be directly relevant to Tactons.

3 Tactons

Given that the cutaneous sense is rich and a powerful communication medium currently little utilised in HCI, how can we make effective use of it? One approach is to use it to render objects from the real world more realistically in virtual environments, for example in improving the presentation of texture in haptic devices. It could also be used to improve targeting in desktop interactions along the lines suggested by Oakley *et al.* (2000). In this paper it is suggested that it can additionally be used to present structured informational messages to users.

Tactons are structured, abstract messages that can be used to communicate complex concepts to users non-visually. Shneiderman (1998) defines an icon as "an image, picture or symbol representing a concept". Tactons can represent complex interface concepts, objects and actions very concisely. Visual icons and their auditory equivalent earcons (Blattner et al., 1989, Brewster et al., 1994) are very powerful ways of displaying information but there is currently 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. Tactons fill this gap. Icons/Earcons/Tactons form a simple, efficient language to represent concepts at the user interface.

Tactons are similar to Braille in the same way that visual icons are similar to text, or earcons are similar to synthetic speech. For example, visual icons can convey complex information in a very small amount of screen space, much smaller than for a textual description. Earcons convey 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. Research will also show which form of iconic display is most suitable for which type of information. Visual icons are good for spatial information, earcons for temporal. One property of Tactons is that they operate both spatially and temporally so they can complement both icons and earcons. Further research is needed to understand how these different types of feedback work together.

Using speech as an example from the auditory domain: presenting information in speech is slow because of its serial nature; to assimilate information the user must hear a spoken message from beginning to end and many words may have to be comprehended before the message can be understood. With earcons the messages are shorter and therefore more rapidly heard, speeding up interactions. The same is true of Tactons when compared to Braille. Speech suffers from many of the same problems as graphical text in text-based computer systems, as this is also a serial medium. Barker & Manji (1989) claim that an important limitation of text is its lack of expressive capability: It may take many words to describe a fairly simple concept. Graphical iconic displays were introduced that speeded up interactions as users could see a picture of the thing they wanted instead of having to read its name from a list (Barker and Manji, 1989). In the same way, an encoded tactile message may be able to communicate its information in fewer symbols. The user feels the Tacton then recalls its meaning rather than having the meaning described in Braille (or speech or text). The icon is also (in principle) universal: it means the same thing in different languages and the Tacton would have similar universality.

4 Designing with Tactons

Tactons are created by encoding information using the parameters of cutaneous perception. The encoding is similar to that of earcons in sound (Blattner et al., 1989, Brewster et al., 1994) where each of the musical parameters (e.g. timbre, frequency, amplitude) is varied to encode information. Similar parameters can be used for Tactons (although their relative importance is different). As suggested by Blattner, short motifs could be used to represent simple objects or actions and these can then be combined in different ways to represent more complex messages and concepts. As Tactons are abstract the mapping between the Tacton and what it represents must be learned, but work on earcons has shown that learning can take place quickly (Brewster, 1998b).

The properties that can be manipulated for Tactons are similar to those used in the creation of earcons. The parameters for manipulation also vary depending on the type of transducer used; not all transducers allow all types of parameters. The general basic parameters are:

Frequency: A range of frequencies can be used to differentiate Tactons. The range of 20 – 1000 Hz is perceivable but maximum sensitivity occurs around 250 Hz (Gunther et al., 2002). The number of discrete values that can be differentiated is not well understood, but Gill (2003) suggests that a maximum of nine different levels can be used. As in audition, a change in amplitude leads to a change in the perception of frequency so this has an impact on the use of frequency as a cue. The number of levels of frequency that can be discriminated also depends on whether the cues are presented in a relative or absolute way. Making relative comparisons between stimuli is much easier than absolute identification, which will lead to much fewer discriminable values, as shown in the work on earcon design (Brewster et al., 1994).

Amplitude: Intensity of stimulation can be used to encode values to present information to the user. Gunther (2002) reports that the intensity range extends to 55 dB above the threshold of detection; above this pain occurs. Craig and Sherrick (1982) indicate that perception deteriorates above 28 dB so this would seem to be a useful maximum. Gunther (2001) reports that various values, ranging from 0.4dB to 3.2dB, have been reported for the just noticeable difference (JND) value for intensity. Gill states that that no more than four different intensities should be used (Gill, 2003). Again the number of useful discriminable values will depend on absolute or relative presentation of stimuli. Due to the interactions between this and frequency several researchers have suggested that they be combined into a single parameter to simplify design

Waveform: The perception of wave shape is much more limited than with the perception of timbre in sound. Users can differentiate sine waves and square waves but more subtle differences are more difficult (Gunther, 2001). This limits the number of different values that can be encoded and makes this a much less important variable than it is in earcon design (where it is one of the key variables).

Duration: Pulses of different durations can encode information. Gunther (2001) investigated a range of subjective responses to pulses of different durations. He found that stimuli lasting less than 0.1 seconds were perceived as taps or jabs whereas stimuli of longer duration, when combined with gradual attacks and decays, may be perceived as smoothly flowing tactile phrases. He suggests combining duration with alterations in the envelope of a vibration, e.g. an abrupt attack feels like a tap against the skin, a gradual attack feels like something rising up out of the skin.

Rhythm: Building on from duration, groups of pulses of different durations can be composed into rhythmic units. This is a very powerful cue in both sound and touch. Gunther (2001) suggests that differences in duration can be used to group events when multiple events occur on the same area of skin.

Specific transducer types allow other parameters to be used:

Body location: Spatially distributed transducers can encode information in the position of stimulation across the body. The choice of body location for vibrotactile display is important, as different locations have different levels of sensitivity and spatial acuity. A display may make use of several body locations, so that the location can be used as another parameter, or can be used to group tactile stimuli.

The fingers are often used for vibrotactile displays because of their high sensitivity to small amplitudes and their high spatial acuity (Craig and Sherrick, 1982). However, the fingers are often required for other tasks, so other body locations may be more suitable. Craig and Sherrick suggest the back, thigh and abdomen as other 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.

Certain body locations are particularly suitable, or particularly unsuitable, for certain types of vibrotactile displays. 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). An example of a suitable body location is in Gunther's Skinscape display, where he positions low frequency transducers on the torso as this is where low frequencies are felt when loud music is heard.

The method of attaching the transducers to a user's body is also important. The pressure of the transducer against the body has a significant effect on the user's perception of the vibrations. Transducers should rest lightly on the skin, allowing the user to feel the vibration against the skin, and to isolate the location of the vibration with ease. Exerting too much pressure with the transducer against the user's body will cause the vibrations to be felt in the bone structure, making them less isolated due to skeletal conduction. In addition, tightening the straps holding the transducer to achieve this level of pressure may impede circulation (Gunther, 2001).

Rupert (2000) suggests using the full torso for displaying 3D information, with 128 transducers distributed over the body. His system displays information to pilots about the location of objects around them in 3D space, by stimulating the transducers at the part of their body corresponding to the location of the object in 3D space around them. This could be used to indicate horizons, borders, targets, or other aircraft.

Spatiotemporal patterns: Related to position and rhythm, spatial patterns can also be "drawn" on the user's body. For example, if a user has a 3x3 array of stimulators located on his/her back, lines and geometric shapes can be "drawn" on the back, by stimulating, in turn, the stimulators that make up that shape. In Figure 3, an 'L' shaped gesture can be drawn by activating the stimulators: 1-4-7-8-9 in turn. Patterns can move about the body, varying in time and location to encode information. Cholewiak (1996) and Sherrick (1985) have also looked at low-level perception of distributed tactile cues.

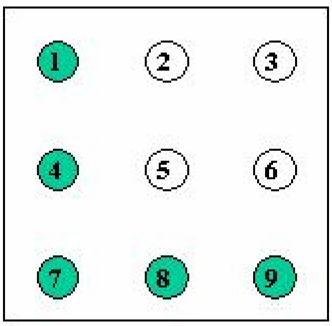

Figure 3: "Drawing" an L-shaped gesture.

Now that the basic parameters for Tactons have been described, we will give some examples of how they might be designed to convey information. The fundamental design of Tactons is similar to that of earcons.

4.1 Compound Tactons

A simple set of Tactons could be created as in Figure 4. A high-frequency pulse that increases in intensity could represent 'Create', a lower frequency pulse that decreases in intensity could represent 'Delete'. A two note falling Tacton could represent a file and a two rising notes a folder. The mapping is abstract; there is no intuitive link between what the user feels and what it represents.

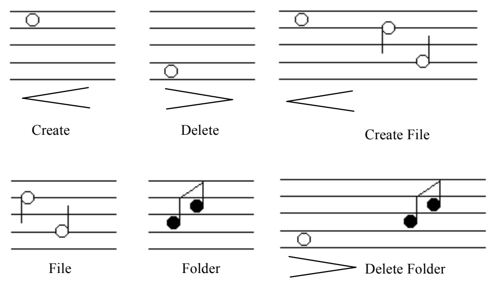

Figure 4: Compound Tactons (after Blattner et al., 1989).

These Tactons can then be combined to create compound messages. For example, 'create file' or 'delete folder'. The set of basic elements could be extended and a simple language of tactile elements created to provide feedback in a user interface.

4.2 Hierarchical Tactons

Tactons could also be combined in a hierarchical way, as shown in Figure 5. Each Tacton is a node in a tree and inherits properties from the levels above it. Figure 5 shows a hierarchy of Tactons representing a hypothetical family of errors. The top of the tree is a family Tacton which has a basic rhythm played using a sinewave (a different family of errors would use a different rhythm so that they are not confused). The rhythmic structure of Level 2 inherits the Tacton from Level 1 and adds to it. In this case a second, higher frequency Tacton played with a squarewave. At Level 3 the tempo of the two Tactons is changed. In this way a hierarchical structure can be presented. The other parameters discussed above could be used to add further levels.

4.3 Transformational Tactons

A third type of Tacton is the Transformational Tacton. These have several properties, each represented by a different tactile parameter. For example, if Transformational Tactons were used to represent files in a computer interface, the file type could be represented by rhythm, size by frequency, and creation date by body location. Each file type would be mapped to a unique rhythm. Therefore, two files of the same type, and same size, but different creation date would share the same rhythm and frequency, but would be presented to a different body location. If two files were of different types but the same size they would be represented by different rhythms with the same frequency.

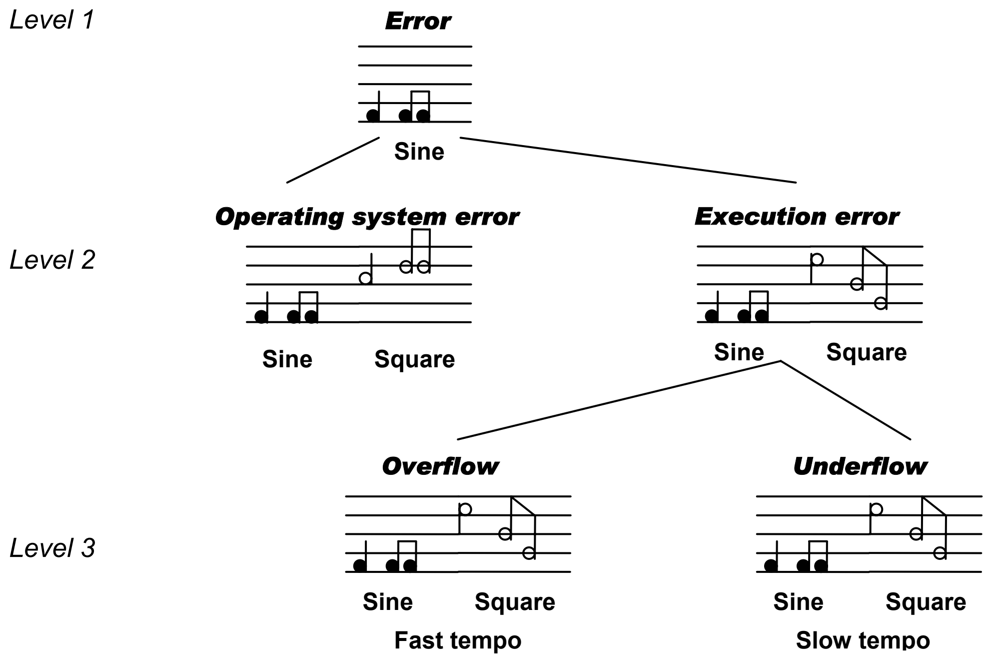

Figure 5: Hierarchical Tacton composition.

5 Uses for Tactons

We are interested in three areas of use for Tactons, although there are many others where they have potential to improve usability.

5.1 Enhancements of desktop interfaces

The first, and simplest, area of interest is in the addition of Tactons to desktop graphical interfaces. The addition of earcons to desktops has shown many advantages in terms of reduced errors, reduced times to complete tasks and lowered workload (Brewster, 1998a). One problem with audio is that users believe that it may be annoying to use (although no research has actually shown this to be the case) and it has the potential to annoy others nearby (for a discussion see (Brewster, 2002)). The addition of Tactons to widgets has the same potential to indicate usability problems but without the potential to annoy.

One reason for enhancing standard desktop interfaces is that users can become overloaded with visual information on large, high-resolution displays. In highly complex graphical displays users must concentrate on one part of the display to perceive the visual feedback, so that feedback from another part may be missed. This becomes very important in situations where users must notice and deal with large amounts of dynamic data or output from multiple applications or tasks. If information about secondary tasks was presented through touch then users could concentrate their visual attention on the primary one but feel information about the others.

As a simple example, the display of a progress bar widget could be presented tactually. Two sets of tactile pulses could be used to indicate the current and end points of a download. The time between the two pulses would indicate the amount of time remaining, the closer the two pulses the nearer the download is to finishing. The two pulses could use different waveforms to ensure they were not confused. Different rhythms for each pulse could be used to indicate different types of downloads. If a more sophisticated set of transducers on a belt around the waist was available then the position of a pulse moving around the body in a clockwise direction (starting from the front) would give information about progress: when the pulse was at the right side of the body the download would be 25% of the way through, when it was on the left hand side 75%, and when it got back around to the front it would be finished. There would be no need for any visual presentation of the progress bar, allowing users to focus their visual attention on the main task they are involved with.

Tactons could also be used to enhance interactions with buttons, scrollbars, menus, etc. to indicate when users are on targets and when certain types of errors occur. Others have shown that basic tactile feedback can improve pointing and steering type interactions (Akamatsu et al., 1995, Campbell et al., 1999). There are some commercial systems that give simple tactile feedback in desktop user interfaces, e.g. the software that comes with the Logitech iFeel mouse (www.logitech.com). This provides basic targeting: a brief pulse is played, for example, when a user moves over a target. We believe there is much more that can be presented with tactile feedback.

5.2 Visually impaired users

Tactons will be able to work alongside Braille in tactile displays for blind and visually impaired users, in the same way as earcons work alongside synthetic speech. They will allow information to be delivered more efficiently. In addition, hierarchical Tactons could help users navigate around Braille media by providing navigation information (Brewster, 1998b).

One of our main interests is in using Tactons to improve access to graphical information non-visually. Text can be rendered in a relatively straightforward manner by speech or Braille, but graphics are more problematic. One area that we and others have focused on is visualisation for blind people. Understanding and manipulating information using visualisations such as graphs, tables, bar charts and 3D plots is very common for sighted people. The skills needed are learned early in school and then used throughout life, for example, in analysing information or managing home finances. The basic skills needed for creating and manipulating graphs are necessary for all parts of education and employment. Blind people have very restricted access to information presented in these visual ways (Edwards, 1995). As Wise *et al.* (2001) say "Inaccessibility of instructional materials, media, and technologies used in science, engineering, and mathematics education severely restricts the ability of students with little or no sight to excel in these disciplines". To allow blind people to gain the skills needed for the workplace new technologies are necessary to make visualisations usable. Tactons provide another route through which information can be presented.

Research has shown that using haptic devices is an effective way of presenting graphical information non-visually (Yu and Brewster, 2003, Wies et al., 2001, Van Scoy et al., 2000). The most common approach has been to use haptic devices to present graphs, tables or 3D plots that users can feel kinaesthetically by tracing a line or shape with a finger using a device like the PHANToM (www.sensable.com). Lederman and Klatzky (1999) have shown that removal of cutaneous input to the fingertip impedes perception of edge direction, which is an essential component of tracing a haptic line graph. This lack of cutaneous stimulation leads to problems with navigation (exploring using a single point of contact means it is difficult to locate items as there is no context, which can be given in a tactile display), exploring small scale features (these would be perceived cutaneously on the finger pad in real life), and information overload (all haptic information is perceived kinaesthetically rather than being shared with cutaneous perception). Incorporating a tactile display into a force-feedback device will alleviate many of these problems and potentially increase user efficiency and comprehension of visualisations.

Tactons could be presented as the user moves the force-feedback device over the visualisation. Dimensions of the data can be encoded into a Tacton to give information about the current point, using the parameters described in Section 4. This would allow more data to be presented more efficiently. For example, with multidimensional data one dimension might be mapped to the frequency of a pulse in a Tacton, another might map to rhythm and another to body locatoin. As the user moves about the data he/she would feel the different parameters. In addition to the finger pad, we can also include tactile displays to other parts of the body (e.g. to the back) using spatially distributed transducers to provide even more display area. As long as this is done in a comprehensible manner users will be able to gain access to their data in a much more effective way than with current force-feedback only visualisation tools.

5.3 Mobile and wearable devices

Our other main application area is mobile and wearable device displays (for both sighted and blind people). Mobile telephones and handheld computers are currently one of the fastest growth areas of computing and this growth will extend into more sophisticated, fully wearable computers in the future. One problem with these devices is their limited output capabilities. Their small displays easily become cluttered with information and widgets and this makes interface design difficult. In addition, users are not always looking at the display of a device as they must walk or navigate through their environment which requires visual attention. One way to solve this problem is to use other display modalities and so reduce demands on visual display, or replace it if not available. Work has gone into using speech and non-speech sounds to overcome the display bottleneck. Tactile displays have great potential here too but are much less well investigated.

Sound has many advantages but it can be problematic; in loud environments it can be impossible to hear auditory output from a device, in quiet places the audio may be disturbing to others nearby. Blind people often do not like to wear headphones when outdoors as they mask important environmental sounds. Tactile displays do not suffer from these problems (although there may be other problems for example, perceiving tactile stimuli whilst running due to the difficulties of keeping the transducers in contact with the skin). Mobile telephones commonly have a very simple point-contact tactile stimulator built-in that can alert the user to a call. These are often only able to produce pulses of different durations. A pin array would be possible on such a device as the user will be holding it in a hand when in use. Such a sophisticated tactile display could do much more, e.g. it could give information on the caller, replace or enhance items on the display (like icons, progress indicators, games) or aid in the navigation of the devices' menus so that the user does not need to look at the screen.

In a wearable device users could have body mounted transducers so that information can be displayed over their body. In the simplest case this could be used to give directional information by vibrating one side of the body or other to indicate which way to turn (Tan and Pentland, 1997). A belt of transducers around the waist could give a compass-like display of direction; a pulse could be played continuously at north so the user can maintain orientation after turning (useful when navigating in the dark) or at the position around the waist corresponding to the direction in which to head. A more sophisticated display might give information about the user's context. For example, presenting Tactons describing information such as the type of building (shop, bank, office-block, house), the type of shop (clothes, phones, food, furniture) the price-bracket of a shop (budget, mid-range, expensive), or information more related to the concerns of visually impaired people, such as the number of stairs leading up to the entrance (for firefighters, whose vision is impaired due to smoke and flames, a tactile display could also provide information on the location of rooms and exits in a burning building). A tactile display could also present information on stock market data (building on from the work on tactile visualisation in the section above) so that users could keep track of trades whilst away from the office. Such tactile displays could also work alongside auditory or visual ones.

6 Future work and conclusions

This paper has laid out some of the foundations of information display through Tactons. There is still much work to be done to fully understand how they should be designed and used. There are many lower level perceptual questions to be addressed before higher level design issues can be investigated. Many of the parameters of touch described in Section 4 are not fully understood and the full usable ranges of the parameters are not known. Studies need to be undertaken to explore the parameter space so that the relative importance of the different parameters can be discovered.

Once the range of parameters is understood then the construction of Tactons can be examined. Basic studies are needed to understand how the parameters can be combined to construct Tactons. Parameters which work well alone may not work well when combined with others into a Tacton. For example, one parameter may mask another. When the basic design of Tactons is understood the composition of simple Tactons into more complex messages, encoding hierarchical information into Tactons, and their learnability and memorability can be investigated. The concurrent presentation of multiple Tactons must also be studied. These studies will answer some of the main questions regarding the usability of Tactons and a good understanding of their design and usability will have been achieved.

Another important task is to investigate the strong relationships between hearing and touch by examining cross-modal uses of audio and tactile multimodal displays (Spence and Driver, 1997), e.g. combined audio and tactile cues, redundant tactile and audio cues, and moving from an audio to a tactile presentation of the same information (and *vice versa*). This is important in a mobile/wearable context because at different times different display techniques might be appropriate. For example, audio might be inappropriate in a very noisy environment, or tactile cues might be masked when the user is running. One important issue is to identify the types of information best presented in sound and those best presented tactually. For example, the range of the vibrotactile frequency response is roughly 20 times less than that of the auditory system. Such discrepancies must be accounted for when performing cross-modal mappings from hearing to touch.

In conclusion, this paper has proposed a new form of tactile output called Tactons. These are structured tactile messages that can be used to communicate information. Tactile output is underused in current interfaces and Tactons provide a way of addressing this problem. The basic parameters have been described and design issues discussed. A technique is now available to allow tactile display to form a significant part of the set of interaction and display techniques that can be used to communicate with users at the interface.

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