Animated tactile sensations in sensory substitution systems

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ABSTRACT

We have designed and made a computer controlled, electrocutaneously stimulated, tactile display to assist in the interpretation of complex graphical data. This paper covers the initial experiments with the tactile display, complementing the standard VDU. An animated vector was generated and the absolute tactile directional acuity of the observers was measured. Consideration is given as to how the use of animated tactile data would enhance graphical user interfaces for the visually impaired.

Keywords: tactile graphics, directional acuity, blind, multisensory displays

1. INTRODUCTION

This research was conducted to produce a multisensory display system for use in the visualisation of scientific information. The use of visual displays for scientific visualisation is, of course, implicit. Sound display, or sonification, of scientific data has also been researched but is still very much in its infancy. There has been very little research carried out on the use of tactile sensations to complement the visualisation of scientific data, except in the realm of virtual reality where the sense of touch is used primarily for force feedback.

Initially, we considered which aspects of the sense of touch could be of use in the field of scientific visualisation. In the field of scientific visualisation it may also be said that there are many aspects that present problems when using vision only. Thus the definition of the 'problem', as well as the solution, is conveniently loose. This has allowed us to analyze the sense of touch without constraint and then choose an aspect of it that has a potentially high information capacity. It was decided that the best means of maximising the quantity and resolution of data to be displayed tactually would be to have an animated tactile display. The field of scientific visualisation was then explored and a suitable problem chosen. This approach has produced two potential uses for touch in sensory substitution systems, primarily in graphical user interfaces for the blind, and graphical/scientific data displays for the blind.

The tactile display, designed and made by the authors, stimulates the non-dominant hand. In the current configuration, information relating to the region defined by the mouse pointer is displayed on the hand. This information may be the visible data, reemphasised tactually, or it may be another 'dimension' of the information, unseen but tactually correlated with the visual data. The limitations of a purely visual display methodology for scientific visualisation is clear when one compares the multidimensional nature of scientific data with the two dimensions available on a standard VDU. The problems this creates forms the justification for our research and one of these problems is elaborated in the following discussion.

If the screen is initially restricted to black and white only (no shades of grey) then all that can be displayed, without loss of information (except by virtue of pixel resolution) or potentially confusing the observer, is a simple, 1 dimensional, x-y line graph, i.e. 1 dependent variable against 1 independent variable. When the above restriction is removed and colour or grey shading is allowed then a 2 dimensional scalar data set can be displayed. The two independent variables are the horizontal and vertical axes and the dependent variable is mapped onto colour hue or grey shade intensity. Although this method of displaying in three dimensions is loss-less, a degree of error is introduced due to the way the eye and brain interpret visual information (Coren, 1978). There are other methods of displaying three dimensions on a two dimensional screen, each with their own advantages and disadvantages (Walton, 1993). The amount of data displayable at any one time becomes dramatically reduced when vector information needs to be displayed, even when considering only a two dimensional vector on a two dimensional 'field'. Vector data needs encoding; one, often used, method is to use spatially separated arrows. The magnitude is encoded by the colour of the arrow, or size, or length, or doubly encoded using two of these attributes (Collins, 1993). Now, many, and probably a variable number of pixels, are required to display just one point in the data set. The data also requires at least as much interpretation by the observer as in the previous case because

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the user also has to mentally interpolate a vector. A further complexity arises when one, or more, scalar or vector variables are required to be visualised in two or three dimensions. In addition to the above problems, a lot of the data cannot be seen as it is obscured by the data in front of it.

This study explores the animated display of vector information by the sense of touch. A perceived advantage of the resulting multisensory display system can be illustrated as follows. On a surface, it may be useful to display both scalar and vector information. The spatial resolution of the vector data is considerably lower than that of the scalar data. Visually displaying the vector information also masks some of the scalar information. It should be possible to send higher resolution vector information to the tactile display, leaving the VDU clear to display the scalar information.

The structure of this paper is as follows: section 2 covers the choice of stimulation method and the perception of directional information. Section 3 describes the implementation of the computer controlled tactile display. Section 4 discusses the design of the directional acuity experiment and section 5 covers the interpretation of the results. Section 6 explores how these results, along with a previous experiment by the authors, can be used. Some aspects of further work is also outlined.

2. OVERVIEW OF THE TACTILE DISPLAY

2.1 Stimulation Method

There are two main ways currently used to elicit the sensation of touch which are suitable for computer control: electrocutaneous (or electrotactile), and vibrotactile stimulation. Both are widely used in sensory substitution systems for physically handicapped (Kaczmarek, 1991; Szeto & Saunders, 1982). For example, Geake (1994) discussed the use of an array of electrotactile stimulators for giving positional feedback to the user of a motorised upper limb prosthesis. Vibrotactile stimulation is frequently used in displays for the blind.

When compared, each method has advantages and disadvantages depending on the choice of criteria. However, two overriding criteria were the speed at which a system could be implemented and the restriction on cost. This made electrocutaneous stimulation the most attractive alternative for this project.

Electrocutaneous stimulation is the localised stimulation of cutaneous receptors and fibres of the afferent nervous system by means of a small electric charge applied to the skin. The sense of touch can be divided into different modalities i.e. pain, pressure, and temperature. There are several types of cutaneous receptors and nerve endings, including free nerve endings, meissner's, and pacinian corpuscules. Unfortunately, there is no simple relationship between sensation modality and receptor type. For example, in the cornea of the eye there are only free nerve endings, yet it is sensitive to pain, pressure, and temperature (Schiffman, 1995). Electrocutaneous stimulation affects any receptor or fibre which happens to be within range. Thus the quality of the sensation can vary, depending on several parameters, including electrode configuration, skin hydration, and body site. The quality of the sensation can also change with stimulation strength, not surprisingly, if strong enough it will feel painful.

2.2 Perception of Directional Information

From a physiological perspective, tactile directional acuity is governed by two different processes. First, cutaneous stretch receptors are stimulated by the relative frictional motion of an object in contact with the skin. The second is spatial data which changes with time (Norrsell & Olausson, 1994). Our display only exploits the second of these processes.

Gardner & Sklar (1994) have explored directional acuity using a linear vibrotactile array. Such a display does not exploit skin stretch. The object of one of their experiments was to determine the relative importance of density and path length parameters. They concluded that discrimination accuracy depends on the number/density of stimulations, rather than path length. They only studied whether the observer could determine if the stimulus was moving along the finger towards the tip or towards the palm, i.e. a two alternative, forced choice.

There is a sensation known as apparent motion which corresponds fairly closely to visual animation. This sensation appears between two speeds of tactile animation. In an experiment carried out by Sparks (1979), a linear array of electrocutaneous stimulators was used and animated motion was generated by sequentially switching on and off stimulators, very similar to that above. As the speed of this animation was varied, the observers reported two transition points, or thresholds. Below the lower threshold, the sensations were felt as discrete, successive steps. Above this threshold, the animation was felt as a smooth, continuous motion, up to a higher threshold. Beyond this, the sensation was sharp, with no sensation of motion, though the direction could still be determined for a little longer.

By controlling the relative intensities of adjacent stimulators, one can allow the user to mentally reinterpret the two separate simultaneous stimulations as one stimulation located at a point intermediate between the two stimulators. Thus, if one decreases the intensity of one stimulation, whilst simultaneously increasing the stimulation at a different point, one can interpret this as a sensation moving gradually from one point to the other. Alles (1970) explored this 'phantom' sensation using vibrotactile stimulators.

Keyson & Houtsma (1995) studied direction discrimination using a motorised trackerball arrangement. This test makes use of frictional contact with the skin of the fingertip. Tests were made at eight equally spaced directions. At each of these positions a threshold test was carried out by presenting a reference stimulus followed by a variable test stimulus, and asking the observer to tell the difference. Whilst this test examined one's directional acuity at a number of directions, it did not test one's ability to absolutely determine the direction of stimulation. It was considered that a measurement of absolute directional acuity would be desirable.

3. IMPLEMENTATION OF TACTILE DISPLAY

Our tactile display is controlled by a C program running on a '486 based personal computer (PC) under MS-DOS. Our original intention was for the PC to pass brief, high level instructions to a slave microprocessor which would then control the tactile display. This approach was desirable because scientific visualisation is a computationally intensive task and sharing the PC between the animation of the tactile display and graphical rendition would have meant a loss of real time control. However, financial restrictions forced the abandoning of the idea of a slave processor. Experimental work so far has not involved complex visualisation.

The display consists of 9 electrodes in an approximately square, 3x3 grid, thus there is one electrode on each of the proximal, middle, and distal phalanges of the index, middle, and ring fingers of the non-dominant hand. The non- dominant hand is used for ease of implementation and also Wilker et. al. (1991) found no significant difference in observer performance between mounting a vibrotactile display on the non dominant hand, with the dominant hand controlling a mouse, and mounting the vibrotactile display on the mouse, thus displaying to the dominant hand. Each electrode is of concentric design, with a central electrode 2mm in diameter and an outer ground-referenced ring of 9mm diameter. The electrodes are mounted on a clay hand 'jig'. The hand rests on the electrodes. Thus lateral movement of the hand and fingers is restricted, improving placement accuracy and repeatability, whilst allowing easy and quick hand removal, should this prove desirable. A momentary thumb switch, mounted on the jig, has to be pressed and held to allow electrocutaneous stimulation to occur.

One stimulation is, in fact, a brief burst of six 'biphasic' current pulses. The time delay between these pulses is controlled. A biphasic pulse consists of a short positive-going phase, rapidly followed by an equally short negative-going phase of equal amplitude. The phase widths, and inter phase interval are also software controlled. To vary the intensity of the stimulation, the software adjusts the electrode current amplitude, whilst the timing parameters are held constant.

The software to control the device has to give the appearance of doing two things at the same time and in as close an approximation to real time control as possible. The tactile display is initialised and the timing parameters are used to produce a look-up table that is downloaded to the display interface and is stored in RAM there. When a stimulation is initiated by the computer, the RAM addresses are counted through by the hardware and the biphasic pulse burst is generated. Just before the stimulation is required, nine digital to analogue converters (DACs) are given the desired individual amplitudes for the nine electrodes. By having successive pulse bursts and adjusting the relative intensities of the electrodes it is possible to animate the tactile display, so an apparently moving stimulation can be displayed. The vector is encoded as a moving, broad wave. The relative position, at a moment in time, of an electrode to this wavefront is calculated so that arbitrary vector directions can be animated. This is done by having another look-up table, this time residing in the computer. This holds the shape of the wave, which will be used to adjust the amplitudes of the individual electrodes. A wave travels in a direction perpendicular to the line of its wavefront and a wavefront is defined as a contour of equal phase. The perpendicular distance of an electrode to the desired wavefront is calculated and determines an initial offset (phase) into the look-up table for that electrode. The look-up table values are, after various scaling processes, passed to the DACs and the first frame of the animation is initiated. The time between frames is kept constant. This is so that the perceived speed of the complete computer system is not dependent on the speed of the wave stimulation. To control the speed of the wave the size of the increment, added equally to each of the offsets in the look-up table, is controlled. The smaller the increment, the slower the wave.

There are very many parameters which affect the perception of the stimulus and it would be impossible to optimise each of them in any quantitative way. Several pilot studies were conducted to qualitatively optimise these. Consider, for example, the sensation of apparent motion mentioned above. Speeds below the lower threshold cause the wave to be perceived in successive steps, and that was found to be confusing and resulted in difficulties with direction discrimination. Speeds above the upper threshold were felt as a single pulse over the fingers, with no discernable direction.

To maximise the probability of determining the absolute direction of a stimulation wave, the speed should be at the useable minimum. It was considered that the lower threshold of apparent motion could be reduced by using the method of phantom sensation. The required magnitude of the phantom sensation, as it moves from one electrode to the next, affects the shape of the wave. If the sensation is designed to be half way between two electrodes, the magnitudes of the stimulations on each of the electrodes are equal, but each is less than 50% of the stimulation magnitude of a wave, were it located directly under an electrode. Yet another parameter which affects apparent motion is the delay between successive waves. If too short, this can clash with the requirements of wave shape and, therefore, phantom stimulation perception, causing an inability to tell whether the stimulation is travelling forward or backward.

Summation of electrocutaneous stimulation occurs along a finger, but does not occur across fingers. When a wave is travelling perpendicular to the proximal - distal direction all three electrodes on a finger are energised at the same time and the intensity of the sensation is considerably higher than the sum of their individual sensations: a similar effect as the phantom sensation correction required above. To remove this problem another parameter had to be introduced. This attenuated the stimulation by an amount dependant on the direction of the vector wave.

4. EXPERIMENTAL SETUP

To evaluate its potential usefulness, an experiment has been conducted to evaluate users' directional acuity with this device. Quantitative parameters associated with maximising the dynamic range of sensation for an individual electrode were found to be in agreement with work done by Kaczmarek (1990) to optimise them. Qualitative parameters determined in our pilot studies are:

Wave shape: Shifted Cosine

Duty cycle: 0.3

Wave speed: 80mm/sec

Direction-dependent attenuation factor: 0.4

The pilot studies also showed that the length of time for an observer to make a judgement of the direction of stimulation was longer than expected. Psychological loss of attention and irritation are major problems in tedious psychophysical experiments. It was therefore decided that the experiment would be broken down into 5 tests, one per day. Each test consisted of 90 trials. A trial was one judgement of the direction of the stimulation. It was also decided that the experiment would be carried out over only 180 degrees to reduce the volume of data required. The experiment was designed so that it could be considered reasonable to extrapolate the results over 360 degrees.

The decision of the observer was entered graphically on the computer screen. A circle was displayed with an outer arc

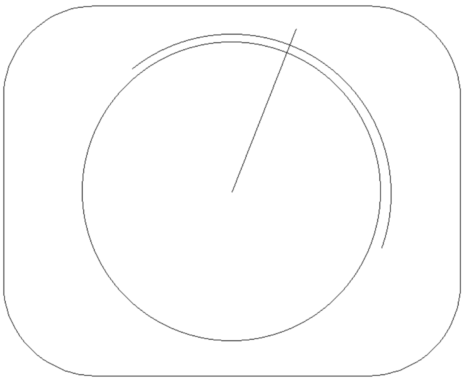

Figure 1. *Experiment input screen showing region of directions and radial arm.*

showing the region of directions to be displayed. This region was chosen arbitrarily from 140 degrees, moving clockwise to 310 degrees. For ease of data analysis, 12 o'clock position was identified with 180 degrees. The direction input was displayed with a radial arm (Figure 1). The direction of the arm was controlled with the mouse, clicking the left button to register the decision. The tactile trial vector was displayed until a decision was made.

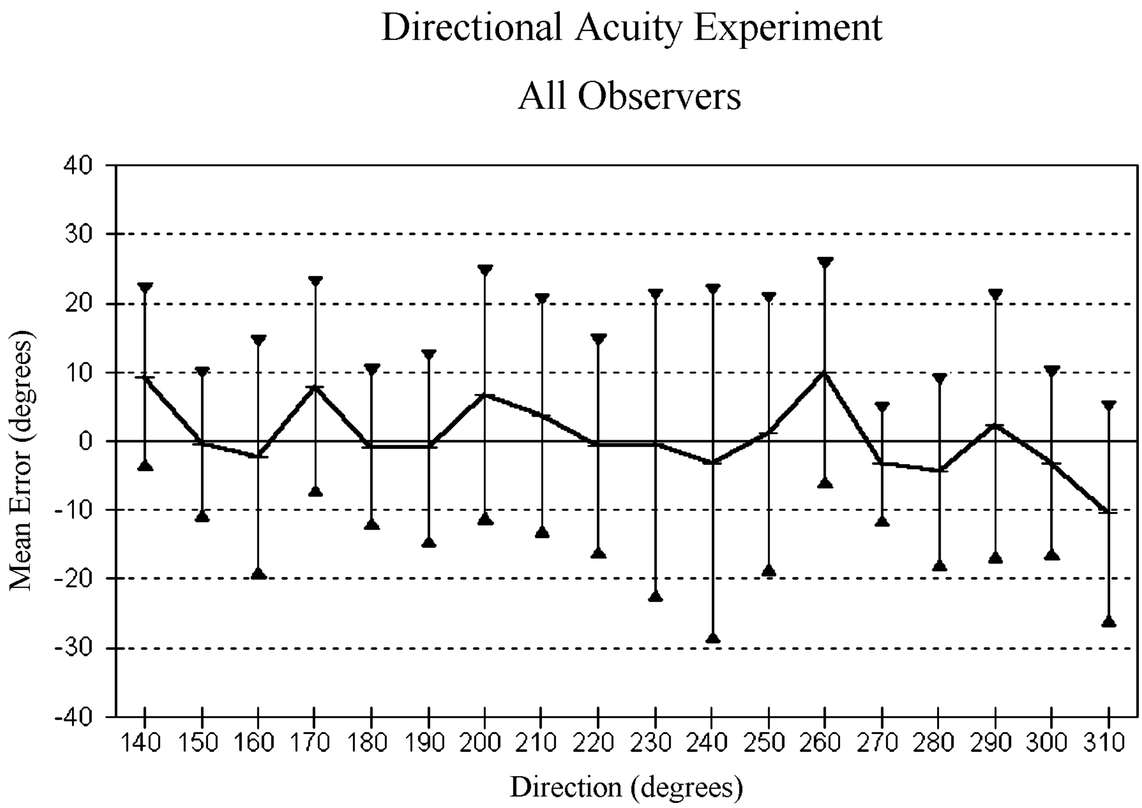

Figure 2. *Mean error for all observers combined (1350 trials). Error bars +/- 1 S.D.*

Unknown to all but one of the observers were the details of the experiment. The region of directions was broken down into 18 discrete directions at 10 degree increments. The trials were block-randomizes and each direction was presented 5 times. The observers were not even told that there were 90 trials to a test.

Feedback was, however, given after each trial. A radial arm pointing in the correct direction was briefly displayed together with the observers judgement so that any error could be visually assessed. A percentage score was also displayed, zero percent denoting an error of 180 degrees. When asked, none of the observers 'guessed' any of the details of the experiment.

The nine electrodes need to be individually calibrated for both zero (just on the threshold of sensation) and span (comfortably below the threshold of pain). The spans on each electrode needed to be adjusted so that their sensations were all about the same. In the calibration procedure each electrode was energised sequentially. Calibration was found to be difficult and was iterated with a 'learn' facility. Before each test the calibration was checked and adjusted as necessary, and learning allowed. The learn facility was visually the same as the test except that the observer controlled the direction of the stimulation via the mouse controlled radial arm.

5. DISCUSSION OF RESULTS

Three observers, including the principal author were used in this experiment. There was no significant difference in their performances, despite one of them knowing the details of the experiment. Within each observer's set of 5 tests there were no significant differences between individual tests. This shows that there was no learning (or otherwise) effect. These two results allowed all the data to be combined, making a total of 1350 trials, 75 at each direction. The mean error between the trial direction and the observers judgement was determined, as was the standard deviation. Figure 2 shows the mean error at each trial direction, the error bars are +/- 1 standard deviation. The mean decision time was approximately 9 seconds, or 12 complete wave cycles. This is a long time but is probably due to the experimental methodology. It is considered that in a 'real' situation judgements would be differential and the interactive nature of the interface would allow much faster assessment of direction.

Two observations can be made about the results from this graph. First, the results at the ends of the range may be affected by 'end effects'. There are fewer 'choices' of direction for a stimulation which is considered to be at, or near, an end. Not only that, but the choices are lop-sided. This manifests itself as a positive mean error at the 140 degree end and negative at the 310 degree end. Whilst this characteristic appeared on each observer's results, it was not found to be significant.

The second observation is that there appears to be no trend, or function, to the results. In vision, there is an oblique effect, whereby one's angular acuity is much better at the horizontal and vertical orientations. If there were a similar tactile effect, the mean error and standard deviation would be much smaller around 180 and 270 degrees. The absence of an oblique effect for this frictionless method of stimulation is in agreement with others, for example Norrsell & Olausson (1974). A tactile oblique effect has been noted when skin stretch has been utilised (Keyson & Houtsma, 1995).

Although many trials have been taken, the mean errors are still quite large. This is considered to be due to variations in calibration between tests. An unnoticed error in adjustment could cause the perceived direction to be consistently different from the true direction. The mean of the standard deviations is 15 degrees. When the dynamic range of the stimulation is taken into account, this could be taken as a measure of absolute directional acuity.

6. CONCLUSION

When evaluating the usefulness of these results, one has to bear in mind that this is an 'absolute' test of directional acuity. In other words, each stimulation is psychologically assessed in isolation. It would be desirable to carry out this experiment's visual analog, however no means could be simply devised to do this without introducing cues which would confound the experimental procedure. An earlier, unpublished experiment by the authors considered near-absolute grey scale intensity on a computer VDU, and will serve as a comparison.

In this grey scale intensity experiment a 256 shade grey scale was displayed on one side of the screen (area 100mm high, 50mm wide) and on the other side of the screen was a test shade (area 100mm high, 50mm wide). A thin horizontal line, under mouse control, was used by the observer to match the test shade to the correct point on the grey scale.

In both the tactile experiment and the visual grey scale experiment there were no trends in the standard deviations. There was also a simple linear relationship between the dependant and independent variables so a simple comparison between the two can be considered. Dividing the dynamic range of the sensory modality by the mean of the standard deviations, gives a dimensionless measure of acuity. In the visual test, the dynamic range was from zero to 255, black to white, and the mean of the standard deviations was 12. This gives a value of 21. Taking the mean of the standard deviations from the tactile directional acuity experiment above and a dynamic range of 360 degrees, the measure of acuity is 24. It should be noted that the acuity of an observer greatly depends on the design of the experiment. Generally, experiments which study relative, or differential, acuity produce 'better' results.

So far, only the direction of the stimulation has been considered. Future experiments should address the interaction between the direction and magnitude of the vector. The magnitude of the vector could be encoded in two ways. Either the overall magnitude of the sensation could be modulated in proportion with the magnitude of the vector, or the speed of the animated wave could be varied, or both.

After magnitude effects have been studied, further work proposed will concentrate on cognitive evaluation of the use of the display, rather than the psychophysical experiment presented above. These experiments will evaluate how well the user understands graphical information displayed tactually and not how well the tactile display performs. Though the exact format has yet to be decided, there are two main areas of interest: tactile only and visual/tactile displays.

'Tactile only' experiments would be especially relevant to visually impaired computer users. Many aspects of the graphical user interface could be tactually displayed and vector information used to guide the user to places requiring attention. Experiments could be conducted to determine the ability to locate 'targets' using tactile guidance. Access to graphical data, such as numerical diagrams, photo-realistic images, etc. could be enhanced due to the greater information capacity of an animated tactile display. To explore this, an experiment using a two dimensional vector field could be carried out. The user is given the task of extracting information from the display. This could be done by the user drawing streamlines on the visual display from information portrayed on the tactile display, identifying sinks and sources, vortices, etc. 'Visual/tactile' experiments would explore the ability to assimilate tactile and visual information at the same time.

One of our previous experiments with this tactile display (Eves & Novak[96]) discovered that there is a strong ability to learn animated tactile symbols, or icons. These could be used in an interactive environment in a similar manner to audible icons. They would have a great advantage over audible icons as they would be silent and so not disturb other people. This would also allow much more liberal use. It is considered that the number of animated tactile icons available on the current 9 electrode display is considerably greater than the number humanly discernable. The current display is theoretically capable of displaying 511 static icons, even without stimulation magnitude encoding. It would be useful to determine the rules and size of a dynamic tactile symbolic vocabulary. Given the great number of animated tactile symbols theoretically available, it should be possible to choose ones that are intuitive, or at least, easily learnt.

Combining directional tactile display and animated tactile symbols may provide better, more complete information display for visually impaired computer users. To give visually impaired people access to graphical information using computer technology requires the translation of graphical information into a form that can be input and processed by acoustical or tactile display devices. These devices have to have as large a repertoire as possible to give the translator of graphical information a large choice of display techniques, thereby helping to maximise the accuracy of rendition.

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