Perception of Ultrasonic Haptic Feedback on the Hand: Localisation and Apparent Motion

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ABSTRACT

Ultrasonic haptic feedback is a promising means of providing tactile sensations in mid-air without encumbering the user with an actuator. However, controlled and rigorous HCI research is needed to understand the basic characteristics of perception of this new feedback medium, and so how best to utilise ultrasonic haptics in an interface. This paper describes two experiments conducted into two fundamental aspects of ultrasonic haptic perception: 1) localisation of a static point and 2) the perception of motion. Understanding these would provide insight into 1) the spatial resolution of an ultrasonic interface and 2) what forms of feedback give the most convincing illusion of movement. Results show an average localisation error of 8.5mm, with higher error along the longitudinal axis. Convincing sensations of motion were produced when travelling longer distances, using longer stimulus durations and stimulating multiple points along the trajectory. Guidelines for feedback design are given.

Author Keywords

Ultrasound; haptic feedback; perception; localisation.

ACM Classification Keywords

H.5.2. User Interface – Haptic IO.

INTRODUCTION

Ultrasonic haptic feedback involves the creation of focused air pressure waves from an array of ultrasound transducers. These are reflected off the skin to create tactile sensations without being in direct contact with an actuator [15, 22, 25]. It is potentially useful for gestural interfaces, such as those that utilise body position [27], hand movements [10] or finger gestures [7, 17] for input, as these interfaces suffer from a lack of tactile feedback [7, 8, 10, 17]. The technique is relatively new compared to other forms of tactile feedback, such as vibration motors or pin-arrays. Consequently, there has been less controlled and rigorous research into the perception of ultrasonic haptic feedback, which is vital if it is to be used in HCI. We help to address this by identifying the factors that influence the perception of two fundamental aspects of tactile feedback: localisation and motion across the hand. Research on ultrasonic haptics has tested the detection or differentiation of one [13, 22] or multiple points of feedback [1, 2], the two-point visual-tactile threshold [28] and presented interaction prototypes with limited user studies [9, 11]. Research is needed on what spatial or temporal parameters influence localisation and perception of motion. This paper presents two lab experiments. The first tested localisation of static feedback on the hand to determine spatial resolution for ultrasonic haptics. The second tested the perception of motion across two axes on the hand, to identify which characteristics of feedback (distance, duration, number of stimulated positions and movement direction) elicit convincing sensations of motion.

A limitation of existing ultrasonic haptic devices is that they are relatively large and fixed in place, so feedback can only be presented from one global location and in one orientation (directly facing the array). This limits the usable interaction space for gestural interfaces that could otherwise track users throughout open space and in a variety of orientations. Smaller arrays could be embedded in a range of devices, such as mobile phones/tablets, laptops, desktop phones or kiosks. They could also be carried by a user, who would be freed from the restrictive space above a static array. A wearable ultrasound array mounted on the wrist, facing the palm, would give feedback regardless of hand position or orientation. This could be especially useful in gestural interfaces as the hands and fingers are free to move, form gestures or hold objects, and feedback can be generated dynamically and aimed precisely on the hands.

While there are many advantages, there would be challenges in designing such a wearable device. Firstly, the device would need to be small, reducing the number of transducers that can be used to produce feedback. This will result in lower feedback intensity and limit the system to produce only a single point of stimulation at a time. Secondly, in some previous research on perception of ultrasound feedback, the users have been free to move their hands over the array to actively investigate the feedback [11, 13]. A wrist-mounted array could provide feedback to specific points but the hand would be static relative to this feedback. Therefore, perception of feedback may be reduced.

To examine the efficacy of a small mobile or embedded array for feedback, our experiments utilised an 8 x 8 array

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of transducers held in place a small distance from the hand. The paper begins by discussing the research related to ultrasonic haptic feedback and the perception of localisation and motion using physical stimuli. The two experiments are then described and the results are discussed in relation to guidelines for use in HCI.

BACKGROUND RESEARCH

Ultrasonic haptic feedback is based on the principle of acoustic radiation pressure, where a phased array of ultrasonic transducers creates a beam focused at a point in 3D space. The narrow focus of the beam is determined by the wavelength of the ultrasound (e.g., 8.6mm at 40kHz) and the ultrasound is modulated with a lower frequency, such as 200Hz, so as to be perceivable by mechanoreceptors in the skin [16]. When a focal point is reflected off the skin, the force produced creates a localised tactile sensation akin to "air", "breeze" or "wind" [13, 22]. Focal points can be produced at high spatial resolution and moved rapidly in the space above the array. The applications of this novel form of haptic feedback in HCI have been steadily increasing. It has the advantage of providing tactile feedback in mid-air, without the user holding a device or having one attached.

Traditionally, ultrasound arrays are placed on a flat surface such as a desk [15, 25], or suspended above a surface on a mount [9, 14], at a set orientation facing one direction. Feedback can be used to generate objects or surfaces that the user can feel and investigate by moving his/her hand through the space. Ultrasonic haptics has been investigated as a means of transmitting handwriting [12] and, in conjunction with projection, touchable virtual objects [14]. Hoshi [11] combined a Kinect sensor with two arrays, facing out towards the user and placed either side of a display to produce a touchable gestural interaction surface in mid-air. Alternative configurations include attaching an array to the back of a mobile device to provide media-relevant feedback for TV [1] and using acoustically transparent displays to provide feedback above interactive surfaces [2].

Researchers have begun to study the perception of ultrasonic haptics. During a controlled study, Yoshino *et al.* [28] presented a visible dot and a focal point to the hand of the user. They estimated the two-point visual-tactile threshold (VTT: minimum distance required for perceptual co-location) as ~10mm, by asking if the two stimuli were in the same location. From informal experiments, Hoshi [13] suggested that users could accurately identify the direction of longitudinal movement of a focal point on the hand, could orient the hand to the location of a focal point and judge the pattern of focal point movement. Alexander *et al.* [1] found that users could identify the number of present focal points (between 0 and 4) with 87.3% accuracy during active investigation. Hasegawa *et al.* [9] tested identification of four discrete stimulation patterns presented to a static hand and found accuracy of ~55-90%. Carter *et al.* [2] presented users with two focal points and examined the effects of physical distance and modulation frequency on the perceptual distinction of the two points. Two points of the same frequency only became reliably distinct at 5cm separation, while using different frequencies decreased the distance to 3cm, although performance improved over time.

There are important limitations to consider. There has been little systematic research on identifying the underlying characteristics that influence the perception of, for example, location or movement of ultrasound feedback. Some initial informal testing has been done on the perception of one-dimensional movement and position of focal points [13][28] or the number of present focal points [1]. Yoshino *et al.* [28] only estimated the VTT as they did not measure where the focal point was perceived to be, nor how far away it was from the visible dot. Therefore, their results do not inform on the accuracy of absolute localisation. Carter *et al.* [2] identified the influences of physical separation and modulation frequency on the perception of focal points. Nothing is known about what influences the perception of direction, movement or position of feedback and so research is needed to understand the components of perception to enable the design of effective and useable tactile sensations for the user interface.

Tactile Perception on the Hand

As we are interested in testing the perception of location and motion of ultrasonic feedback across the hand, it is necessary to understand how the hand perceives tactile signals and what features of physical stimulation influence localisation and motion perception. Pacinian corpuscles (PC), the rapidly adapting mechanoreceptors that are sensitive to vibration and ultrasonic haptic stimulation [22], are most densely populated in the fingertips and less dense in the fingers and palm [16]. Due to the lower force of the small ultrasound array, the more superficial, rapidly adapting mechanoreceptor (RA I; Meissner) may also be stimulated. These have greater population density than PC at the fingertip and are more densely populated in the fingers than the palm [16]. The density of mechanoreceptors is likely responsible for higher tactile acuity, measured by the two-point threshold, in the fingertips followed by the fingers and the palm [16]. Therefore, perception of feedback may differ between the fingers and the palm, which is highly relevant for the design of effective ultrasound feedback.

Research on the localisation of a single point of stimulation on the fingers has found that participants only reached 50-60% accuracy in identifying the specific point of stimulation [23], even after several days of training. This study stimulated one of 42 points on the fingers using a Von Frey hair (0.1g force), with 3 points equally spaced horizontally along each phalanx. Of the incorrect localisations (mislocalisations), 19.5% were localised within the same phalanx, 16.9% were within the same finger but 63.6% were mislocalised to another finger entirely (mostly an adjacent digit). Therefore, stimulation may be difficult to localise even within the same finger. Research looking at localisation on the palm found that participants regularly mislocalised points towards the thumb and the wrist (i.e., they often felt closer to the thumb or wrist than they were), possibly due to “anchoring” landmarks in an ambiguous space [3].

Apparent Motion

Research has shown that stimulating a small number of physically distal positions on the skin can produce the illusory sensation of motion between those points (called “apparent motion” (AM)). The most famous example is that of the “cutaneous rabbit” [5], where 5 ‘taps’ from a stimulator at each of 3 positions spaced 10cm apart on the forearm felt like taps equally spaced along the whole forearm. Therefore, it is possible that sensations of motion could be created using individual ultrasonic focal points that are activated in specific patterns. Kirman [18, 19] looked at the quality of AM across the fingers using two 0.63mm bronze rods. He was interested in isolating the stimulation characteristics that result in “good movement”, defined as “impressive and continuous movement from one stimulating point to the other”. The characteristics included distance (between the points of stimulation), the duration each point was presented for and the interstimulus onset interval (ISOI): the time between the first and second point being presented. Within the range of 5 to 50mm, physical separation of the two stimuli had no effect on good movement and neither did the location of stimulation (finger vs. forearm) [18].

Overall, the quality of movement improved as stimulus point duration increased from 1 to 200ms, with particularly good movement coming from only 100ms and 200ms durations [18]. However, point duration and ISOI interact in the production of good movement. The optimal ISOI (for good movement) increases as the stimulus duration increases and the range of ISOI that can produce good movement also increases. Therefore, as longer stimuli are used, a wider range of activation timings can produce the illusion of movement. For example, for 100ms stimuli, ISOI of 70-110ms are suitable and, for 200ms stimuli, ISOI of 110-200ms are suitable. Kirman [19] also found that increasing the number of stimulating points from two to eight greatly increased the quality of movement, particularly for durations of 100ms.

In summary, 1) shorter stimulus durations lead to poor movement, 2) sequential stimuli of greater than 50ms should produce good movement and 3) increasing the number of stimulating points improves movement, so it appears that it is the number of stimulated points that is more influential than the space between them. Although ultrasound arrays are capable of “continuous” motion, due to high spatial resolution, we would argue that continuous movement is a perceptual factor and not a technical one, as AM studies show that continuous movement/stimulation along the skin is not necessary. This is important for the design of ultrasound feedback, as a single focal point is sufficient for creating convincing motion. Also, AM is desirable due to the reduced computation and power requirements, particularly for a wearable device scenario. Pre-computing fewer focal points and refreshing the output at a slower speed mean the system can be built with cheaper, smaller, less power-consuming hardware. Identifying the minimum activity that produces continuous sensation helps to build the most efficient system. Using AM also makes it easier to move very quickly across larger distances.

USE CASE: GESTURAL INTERFACES

Providing tactile feedback in vision-based gestural interfaces is a challenge, as the user may not be wearing or touching anything. The use of external cameras leaves the user unencumbered by sensors but limited in interaction space due to the field of view of the camera. Cameras worn on the body result in a less practical and more complex setup but provide an interaction space on the move. Actuators worn on the body may be limited to locations physically separated from the point of interaction, such as actuators on the arm [20]. Instrumented gloves can provide richer tactile feedback but may be limited in the number of available actuators, can be complex and costly to setup [4] and may get in the way of the hands. Like ultrasonic haptics, AIREAL [24] can provide tactile feedback in mid-air using air vortices without user instrumentation. Feedback could be directed quickly and accurately within 1m distance to an 8.5cm diameter target. This is precise enough to target a whole hand, but finer details are not possible with this device. Ultrasonic haptic feedback can produce focal points only ~1cm wide, allowing for much finer details as well as the creation of two-dimensional shapes/patterns. They could also be made small enough to be worn on the body.

A wrist-mounted array could provide feedback directly across the whole hand, targeted to specific parts depending on the interaction and gesture performed. Projected displays on the hand [8] could be made physical by stimulating both the projected hand and the pointing finger. The spatial boundaries and content of “imaginary interfaces” [7] in mid-air could be provided to aid in precise gesture orienting and pointing. And, because the device is worn on the person, interaction can occur anywhere in space. A benefit of placing a gestural interaction device on the wrist is that it leaves the hands free to perform input movements. Digits [17] can create gestural interfaces anywhere and at any orientation. The input method moves with the hands and, by adding a wrist-mounted ultrasound array, tactile feedback could also move with them. There are potential issues with the use of a wrist-mounted array, however. Having an attached device could affect fatigue and interfere in interactions with objects or devices. Array size/weight could be minimised by using smaller, more efficient components. The array would be positioned ~10cm from the palm, so objects can still be held and the fingers are free to gesture.

Due to the lack of controlled perceptual research into ultrasonic haptics and the challenges in producing feedback from a small array, the focus of the research in this paper was to use a small array to establish the perceptual characteristics of two fundamental features of tactile feedback: the localisation of a point of feedback and the perception of movement. The results can be generalised to form the foundation for studies on large arrays, as well as starting to test the feasibility of a wrist-mounted array.

ULTRAHAPTICS SYSTEM

Our Ultrahaptics system is a scaled down version of Carter *et al.*'s [2]. It features an 8 x 8 array of muRata MA40S4S ultrasound transducers, which have a diameter of 10mm. The array was driven by a single Ultrahaptics driver board with two XMOS L1-128 processors providing synchronised output. To create a focal point, each transducer is driven with a specific phase delay and amplitude. These values are computed with the waveform algorithm described in [2]. Even with a small array, achieving a run time fast enough for real time applications requires the computing power of a high-end desktop PC. This does not align with the prospect of a wearable system. We therefore pre-computed the phase delays and amplitudes for a large set of focal points, which were then stored in a lookup table on the driver board. A lightweight UART protocol was then used to communicate with the system and move it into a pre-defined state.

Due to the nature of phased array focusing, focal points closer to the centre of the array will exert a greater force. For our array, a focal point produced 20mm to the right of the centre, 100mm above the array, was 91.5% the force of one produced 100mm above the centre. A focal point offset from the centre by 20mm along both X- and Y-axes was 83.7% the force. During our evaluations, no focal point was produced closer to the edge of the array.

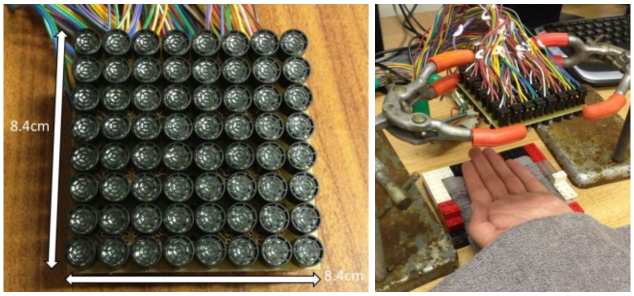

Figure 1: 8 x 8 ultrasound array (left). Experimental setup (right) with participant hand in position under the array.

EXPERIMENTAL SETUP

This paper describes two experiments carried out to test 1) the localisation of ultrasonic haptic feedback and 2) the perception of movement across the hand, in order to identify the factors that influence perception. This section describes the shared aspects of the experimental setup.

Both experiments took place at a desk in a usability lab. The ultrasound array was held face down towards the desk, as seen in Figure 1. The focal points were generated at a distance of 10cm, so the height of the array was set to 10cm from the palm surface. The participant sat at the desk with the non-dominant hand placed directly underneath the array, with the palm facing up. The hand rested on a cloth for comfort. Research suggests there is no significant difference in tactile sensitivity between the dominant and non-dominant hand [26], so the dominant hand was used to control the mouse for making responses. The configuration was very similar to that used by Yoshino *et al.* [28] and was chosen to ensure the hand remained stationary relative to the array. It was imperative that the hand remained in the same fixed position for each condition, as the feedback was presented in fixed positions relative to the array, rather than relative to the hand. Three rigid walls were stuck to the desk surrounding the north, east and west sides of the area beneath the array to keep the hand in place.

The hand was placed under the array so that the join between the proximal phalanx of the middle and ring fingers was directly under the centre of the array. An adhesive ring (paper ring reinforcer) was put on the cloth in this position to indicate where to place the hand and the experimenter ensured the positions matched. This location was considered a central position on the hand, and the position would allow for comparison of sensitivity of the fingers vs. the palm [16]. The drop in focal point force away from the centre would affect both areas equally. The participant was instructed to maintain the hand in a flat position with the fingers together, as in Figure 1. The experimenter monitored the hand position and shape throughout the experiment to ensure they remained correct. Because of the size of the array, low-intensity side lobes (secondary focal points) could be produced within close proximity to the array and, depending on participant hand size, could be felt at the base of the palm. To mask these potentially confusing distractor signals, a folded cloth was placed over the base of the palm and wrist. The software controlling the ultrasound array and the experiment were run on a desktop PC, connected to a monitor and mouse to provide output and input. Headphones were worn, and white noise was played, to mask any sound from the ultrasound array and remove any extraneous aids as to the presence or form of feedback.

Participants

Fourteen participants took part (8 male, 6 female), aged from 18 to 39 (mean = 25.5, std = 6.27) and were paid £6 for participation in both experiments (localisation and movement). All were right-handed by chance. Participants completed the two experiments in a counterbalanced order, which took approximately 60 minutes in total.

EXPERIMENT 1: POINT LOCALISATION

This study tested how precisely participants could localise a single, brief focal point presented to the hand when both the array and hand are static, and so give an indication of the spatial resolution useful for feedback. No research has yet conducted this type of study on ultrasonic haptic feedback, as research on localisation [13] or identifying the number/presence of focal points [1, 2] have allowed for active movement of the hand in front of the array. As mentioned, although we use a similar design to Yoshino *et al.* [28], their research did not measure or report on localisation accuracy, only whether the visual and tactile stimuli were perceived as co-located. Our experiment stimulated 25 *positions* in an equally spaced 5 x 5cm grid centred on the centre of the array (see Figure 2). Each position was spaced 1cm from the vertically and horizontally adjacent positions. Two stimulus *durations* were compared (100 and 1000ms), to judge if duration impacted perception.

The experimental design is a variation on research studying tactile localisation on the hand using physical stimuli such as Von Frey hairs [3, 23]. In these studies, individual stimuli are applied to specific locations on the hand and the participants report a) if they felt a stimulus and, if they did, b) where it was felt. To record where stimuli were felt, other research has used generic outlines of the hand printed on paper [23] or have marked on the participant's own hand [3]. This method was not suitable for our study, as the position of feedback is relative to the array, not to fixed positions on the hand (e.g. a fingertip) and hand size varies. Instead, a digital photograph was taken of the participant's hand and was presented on the monitor. Participants used the mouse to click the location on the hand image where the stimulus was felt. An adjustable arm held a camera facing down towards the desk. The participant rested the non-dominant hand on a cloth underneath the camera. This gave a view directly downwards showing the whole hand.

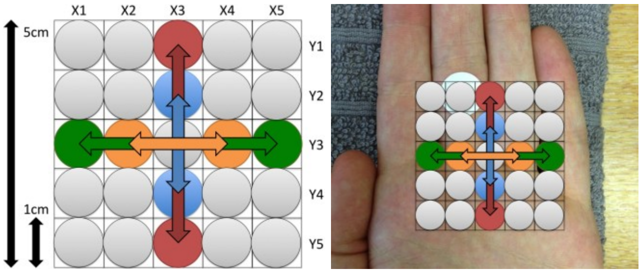

Figure 2: 5 x 5 focal point grid, also showing apparent motion start and end points (left); overlaid on hand at scale (right).

The centre point in the array was known to be at the join between the proximal phalanx of the middle and ring finger, and the position clicked on the hand was known from the image, but because of differences in hand size, the relative scale was not known. Therefore, another adhesive ring was stuck to the pad on the proximal phalanx of the middle finger before the image was taken. The diameter of the ring was 1.4cm and so provided a scale for each image/hand. Dividing the number of pixels in the ring's diameter by 1.4 gave the number of pixels per centimetre. The intended position (in mm) of each focal point in the grid could therefore be calculated from the centre point at the join between the middle and ring finger. The position of each perceived (clicked) location on the hand image was converted to mm and its distance to the intended position gave the localisation accuracy measure. Only the adhesive ring was shown in the image, with no guides as to feedback positions.

Procedure & Variables

The experiment was divided into two halves by *duration* and participants completed them both in a counterbalanced order. This was also fully balanced across the experimental ordering (localisation and movement). After the experiment had been explained to the participant, the adhesive ring was placed on the middle finger and the image was taken of the hand. The image was then transferred to the experimental software while the participant removed the ring from the finger. The headphones were put on before the hand was positioned beneath the centre of the array and the cover cloth was put in place to mask any side lobes.

During each *duration* condition, a focal point was produced at each of the 25 stimulus *positions* from the 5 x 5 grid twice in a random order. After an initial gap of ten seconds at the start of the condition, a random focal point was presented for the set *duration* before stopping. Immediately, a dialogue box appeared on the monitor asking if the stimulus had been felt. Clicking "Yes" would bring up the hand image for the participant to indicate where it was felt. A black circle, centred on the clicked position, was drawn on screen to show the perceived position and the participant could correct the position, moving the circle, by clicking elsewhere. Clicking "Submit" recorded the responses. Clicking "No" required no further input. The responses were logged and another stimulus was presented after a gap of three seconds. This repeated until all 50 stimuli had been presented.

The Independent Variables for the study were: *Duration* (100ms & 1000ms), *X-position* (5 columns in the 5cm x 5cm grid, from left-to-right) and *Y-position* (5 rows in the grid, from top-to-bottom). The Dependent Variables were: *Detection* (if the stimulus was detected) and *Localisation* (where it was felt: distance, in mm, from actual location).

Results

Stimulus Detection

Overall there was a mean stimulus detection rate of 98.9%. A 2 x 5 x 5 (*duration* x *x-position* x *y-position*) repeated measures ANOVA was carried out on the percentage of detected stimuli. A significant effect of *x-position* was found ($F_{(4,108)} = 3.809$, $p < 0.01$), however, no *post hoc* Bonferroni pairwise comparisons reached statistical significance. Mean detection rates for each *x-position* were 97.9%, 97.9%, 100%, 100% and 98.9% for columns 1 to 5, respectively. There was no main effect of *duration*, with mean detection rates of 98.4% for 100ms and 99.4% for 1000ms, nor for *y-position*, with means of 97.9%, 99.6%, 99.3%, 98.9% and 98.9% for rows 1 to 5, respectively.

There was a significant *duration* * *x-position* interaction ($F_{(4,108)} = 3.566$, $p < 0.01$). At 1000ms, *x-position* 1 had 97.1% detection rate while all other positions had 100%. In contrast, at 100ms, *x-positions* 1, 2 and 5 had <100% accuracy. There was also a significant *x-position* * *y-position* interaction ($F_{(16, 432)} = 2.801$, $p < 0.001$). In general, top-left grid positions had lower detection rates more often.

Localisation

The data were analysed in terms of absolute localisation error (distance from intended location along x- and y- axes) and the distributions of perceived points relative to the intended locations. To analyse absolute error, the x- and y-axis distance of each perceived location (in mm) from the intended x- and y- position was calculated and a 2 x 5 x 5 x 2 (*duration* x *x-position* x *y-position* x *axis*) repeated measures ANOVA was carried out. The average localisation error was 8.5mm (std = 6.84mm). There was a significant effect of *duration* ($F_{(1,24)} = 19.798$, $p < 0.001$), with the short duration having a larger mean localisation error of 9.2mm, compared to 7.9mm for 1000ms. There was also a significant effect of *x-position* ($F_{(4,96)} = 5.086$, $p < 0.01$): Bonferroni-adjusted comparisons showed that column 1 (mean = 10mm) had higher error than columns 2 and 3 (both 7.8mm). The mean error for columns 4 and 5 were 8.4mm and 8.5mm, respectively. There was no effect of *y-position*, with mean error of 8.6mm, 8.6mm, 7.7mm, 9.0mm and 8.7mm for rows 1 to 5, respectively. Several interaction effects were also found (see Table 1).

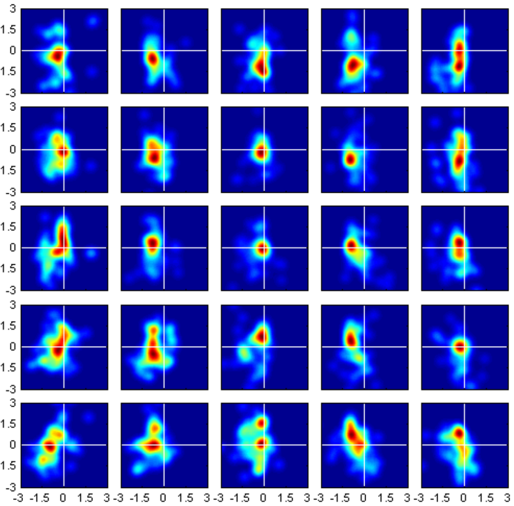

Figure 3: Heat map of perceived stimulus locations relative to intended locations (crosshairs) in the 5 x 5 grid, averaged across both durations. Density increases from blue to red.

Figure 3 shows the distributions of perceived stimulus locations around the intended locations in the 5 x 5 grid. Each plot has a scale of -3 to 3 cm along both axes. As targets were spaced only 1cm apart, overlapping of points into adjacent distributions would occur and so the plots for each target are separated for clarity. What is clear from the distributions is the significant difference in localisation error (see Table 1, "Axis") along the y-axis (10mm) compared to the x-axis (7mm), illustrated in the elongated heat patterns.

EXPERIMENT 2: APPARENT MOTION

This study followed a similar design to research on apparent motion using pin arrays [5, 18, 19] and sequentially activated vibration motors [21]. The focus of previous research has been to identify the influence of various stimulus characteristics, such as distance, ISOI or the number of stimulators on the "quality" of apparent motion. In these studies, no continuous motion is present but the illusion of motion can be triggered by the activation of spatially distributed stimulators across the skin. Some studies used pin arrays, which are capable of presenting multiple pins simultaneously. Because of the size of our ultrasound array, only one focal point of sufficient force can be produced at one time, so it was necessary to adjust the experimental design.

As only a single focal point can be presented, we could not vary ISOI as widely as previous research, which often involved overlapping pin presentations when the ISOI was shorter than the duration of a single point. Therefore, ISOI was ignored as a variable in this study, and set equal to the duration of each focal point, resulting in sequential presentation of focal points. Previous research suggests that sequential presentation of pins results in good apparent motion at the 100ms and 200ms durations used here [18]. As in previous research, each stimulus consisted of at least a start and an end point, located a given distance apart [18, 19] (see Figure 2). Four stimulus characteristics were varied in the study: *distance* (the gap between the inside edges of the start/end points), *direction* (the relative direction the focal points moved across the hand), *number of points* (the number of focal points presented between the start/end points) and point *duration* (the time each focal point was presented for). It is unclear whether physical distance influences perception of motion [18, 19] and so it was included. As hand size varies, two distances were compared which would be small enough to fit within a small hand: 1cm and 3cm.

Although full two-dimensional movement is possible with the array, we limited this initial study to perception of the four cardinal directions: up, down, left and right. Figure 2 shows the start and end points along each dimension and direction, with the short arrows indicating 1cm movement, and the long arrows 3cm movement. Perception of *direction* depends partly on the number of stimulators used and the rapidity of stimulus presentation [21]. Research has also shown that these factors influence the perception and quality judgments of apparent motion [18, 19]. Only a single focal point could be produced from the array and so the number of stimulators here relates to the *number of points* in space the focal point is positioned at between the end points. We used *two points* (only the two start/end points) or *every point* (each point in the grid between the start/end points). Finally, four *durations* were used to compare to previous research [18]: 50, 100, 200 and 300ms. Therefore, a *two-point* stimulus consisted of: 1) a focal point is presented at the start position for the duration (e.g., 100ms), 2) the focal point is stopped, 3) immediately the second focal point is presented at the end point for the set duration.

Participants were instructed that the focus of the study was on sensations of "continuous movement" [18, 19]. If they perceived that the sensation met this criterion then they were asked to rate the movement as one of three categories, labelled "A", "B" and "C". "A" was defined as "movement was impressive and continuous"; "B" was "movement was present but unimpressive"; and "C" was "movement was very partial or ambiguous", from Kirman [18, 19].

Procedure & Variables

As in the Localisation experiment, participants first put headphones on to mask any noise before positioning their hand under the centre of the array. The experiment was divided into two blocks of the same stimuli and all participants took part in both blocks. In each block there were 2 *distances*, 4 *directions*, 2 *numbers of points* and 4 *durations* giving a total of 64 stimuli per block: each stimulus was presented once in a random order. For each stimulus, the same pattern was presented twice, to aid perception, with a gap of 1.5 seconds between repetitions. A gap of five seconds separated stimulus presentations. Once the stimulus has been given, a dialogue box appeared on screen asking "Did you feel movement?". Clicking "Yes" presented a second dialogue box with two sets of radio buttons to indicate the perceived *direction* and *quality* of movement. The first contained four labelled *direction* buttons along with an arrow illustrating the direction. The second contained three buttons, labelled with the categories of movement quality: A, B and C (including the relevant descriptions). Clicking "No" was recorded as a lack of continuous movement.

The Independent Variables were: *Distance* (1cm and 3cm), *Direction* (up, down, left and right), *Number of Points* (2 and all) and *Duration* (50, 100, 200 and 300ms). The Dependent Variables were: *Movement Perception* (whether continuous movement was perceived), *Perceived Direction* (up, down, left, right) and *Movement Quality* (A, B or C). Analysis of the apparent motion data was only done on trials where continuous movement was perceived, and included the perceived quality and direction of movement.

Results

Movement Perception

The overall percentage of trials that resulted in "continuous movement" was 62.9%. The data were analysed using a 2 x 4 x 2 x 4 (*distance* x *direction* x *number of points* x *duration*) repeated measures ANOVA. The details of the ANOVA can be seen in Table 1. There were main effects of *distance*, *number of points* (*"num points"*) and *duration*, as well as several interaction effects. The short *distance* of 1cm produced significantly fewer reports of movement (mean = 57.8%) than 3cm (mean = 68.0%). Using only two *points* produced significantly fewer reports (49.6%) than using all intervening *points* (76.2%). Finally, the number of movement reports increased as the *duration* of each *point* increased: 50ms was significantly lower (mean = 27.2%) than 100ms (61.8%), 200ms (79.2%) and 300ms (83.3%). 100ms was also significantly lower than 200ms and 300ms. There was no effect of *direction* (means of 58.9%, 65.4%, 64.3% and 62.9% for up, down, left and right, respectively).

Movement Quality

As 62.9% of trials resulted in perceived continuous movement, the same number had a movement quality value, leading to an uneven number of trials for each condition. Therefore, the data were normalised into the percentage of all trials in each condition that produced ratings of "A", "B" and "C". For analysis, the three ratings were converted into percentage scores of movement quality, so that *A =100%*, *B = 67%* and *C = 33%*, in a similar manner to Kirman [18, 19]. Due to a low number of data points for some stimuli (e.g., 1cm + down + 2 points + 50ms) data were collapsed and variables were analysed separately using non-parametric analyses: Friedman's for comparing more than two levels and Wilcoxon for pairwise comparisons (using Bonferroni adjusted p-values for *post hoc* tests).

Point Localisation					Movement Perception			
Effect/ Interaction	*df*	*MS*	*F-value*		**Effect/ Interaction**	*df*	*MS*	*F-value*
Duration (A)	1, 24	10.80	19.80 ‡		Distance (E)	1, 27	4.62	18.52 ‡
xPos (B)	4, 96	6.41	5.09 †		Direction (F)	3, 81	0.36	1.32
yPos (C)	4, 96	1.68	1.74		Num Points (G)	1, 27	31.88	113.11 ‡
Axis (D)	1, 24	54.64	39.00 ‡		Duration (H)	3, 81	48.01	99.04 ‡
AxB	4, 96	2.21	5.22 †		ExF	3, 81	0.97	7.22 ‡
AxC	4, 96	1.32	2.19		ExG	1, 27	9.58	85.25 ‡
AxD	1, 24	0.93	3.15		ExH	3, 81	2.40	18.80 ‡
BxC	16, 384	1.65	2.19 *		FxG	3, 81	0.30	1.87
BxD	4, 96	3.97	4.81 †		FxH	9, 243	0.39	3.27 †
CxD	4, 96	2.21	2.40		GxH	3, 81	1.07	7.57 ‡
AxBxC	16, 384	0.41	1.21		ExFxG	3, 81	0.11	0.98
AxBxD	4, 96	1.81	4.42 †		ExFxH	9, 243	0.39	2.30 *
AxCxD	4, 96	0.88	2.80 *		ExGxH	9, 243	0.07	0.57
BxCxD	16, 384	0.36	0.62		FxGxH	3, 81	1.04	9.43 ‡
AxBxCxD	16, 384	0.30	1.20		ExFxGxH	9, 243	0.17	1.51

Table 1: ANOVA results for point localisation (left) & movement perception (right), including main effects (A-F) and interactions (e.g., AxB). Significance indicated by: *, † and ‡ (≤ 0.05, ≤ 0.01 and ≤ 0.001, respectively).

The overall mean quality rating was 73.15%, between "B" and "A". There was a significant main effect of *distance* (Wilcoxon Z = 5.346, $p < 0.001$), as 1cm movements had lower quality (mean = 68.3%) than 3cm movements (78.7%). Using two *points* resulted in significantly lower quality movement (65.4%) than using all *points* (79.4%; Z = 7.06, $p < 0.001$). Movement quality was also significantly affected by *duration* (χ^2 (3) = 34.429, $p < 0.001$): *post hoc* Wilcoxon tests showed 50ms (mean = 63.2%) producing lower quality than 100ms (66.2%), 200ms (77.7%) and 300ms (79.9%) and 100ms producing lower quality movement than 200ms and 300ms. There was no effect of *direction*, with mean quality values of 72.8%, 71.8%, 74.9% and 76.7% for up, down, left and right.

Direction Identification

Direction identification was measured in terms of the percentage of correct responses. Like the movement quality data, only those trials where movement was perceived had an associated *direction*. Data were normalised, collapsed and analysed in the same manner as movement quality. The percentage values relate to the proportion of trials in that condition that produced continuous movement. A Wilcoxon test showed a significant effect of *distance* on direction accuracy (Z = 5.620, $p < 0.001$), with the 1cm *distance* resulting in lower accuracy (mean = 82.0%) than 3cm (93.6%). A Friedman test found a significant effect of *direction* (χ^2 (3) = 23.389, $p < 0.001$). *Post hoc* Wilcoxon tests showed that the up *direction* was identified significantly less well (mean = 79.9%) than all other directions:

92.0%, 91.3% and 89.0% for down, right and left, respectively. There was no effect of *num points*, with means of 87.3% and 89.6% for two *points* and all *points*, respectively. There was also no effect of *duration* (87.7%, 87.7%, 86.9% and 90.2% for 50ms, 100ms, 200ms and 300ms).

DISCUSSION AND DESIGN GUIDELINES

Point Localisation

Detection: 98.9% of all stimuli were detected and there was no main effect of stimulus duration, so even rapid low-force ultrasound feedback is reliably detectable on the hand. However, *where* the feedback was presented had an impact on detection rates. The x-position had a significant effect, but no comparisons between positions reached significance, so it is difficult to draw strong conclusions. In general, positions towards both the left and right extremes had lower detection rates, but the real world differences were very small (98-99%, instead of 100%). While duration had no effect by itself, the slightly lower detection rate at the extremes was slightly increased when using only the short stimuli. There was no effect of y-position but x- and y-position interacted, as it appears that positions towards the top-left of the 5 x 5 grid were more likely to have <100% detection. Of the six positions that had <100% detection, five were along the extreme sides of the grid. A technical limitation of ultrasound arrays is that focal points around the extreme edges have lower force than those near the centre (see above). While this appears to have had a small influence on detection rates, the uneven patterns of lower detection rates around the edges suggests differences in tactile sensitivity are also present.

Localisation: The average localisation error was 8.5mm (std = 6.8mm). This is comparable to the figure Hoshi [13] found (mean of 8.9mm, std of 7.4mm) when using active investigation (users could move their hands), suggesting that active investigation may not influence localisation. It is slightly lower than the estimated 10-13mm two-point visual-tactile threshold [28] during passive feedback reception. While duration had no effect on detection, it had a significant effect on localisation, with 1000ms stimuli being localised 1.3mm more accurately than the shorter stimuli, on average. Therefore, longer stimuli appear to be easier to localise. The slightly higher sensitivity for central regions mentioned for detection is also highlighted in the localisation error, with duration and position also interacting strongly. X-position again had a significant effect, as localisation of points at the extreme left (column 1) were significantly less accurate than points in columns 2 and 3, with the effect stronger at 1000ms, compared to 100ms. The force output of the array drops equally regardless of direction, so the uniquely poorer localisation along the far left again indicates that there are other influences at work, such as lower tactile sensitivity. X-position and y-position interacted: positions in the top-left and bottom-left corners suffered higher localisation error. However, there was no significant effect of y-position, which might suggest that the fingers and palm were comparably sensitive.

Localisation for a given point was significantly worse along the y-axis than the x-axis by as much as 3mm (43%), on average. Therefore, localisation of static ultrasound on the hand along the longitudinal axis (long axis of body) is considerably worse than along the transverse axis (across the body). Previous research on tactile acuity has found that judgements along the longitudinal axis have a smaller Weber function than judgements along the transverse axis (suggesting poorer acuity), but not significantly so [6]. The error axis interacted with both x-position and y-position individually, but in different ways. In general, as x-position increases (moves from left to right on the grid) x-axis error increases and y-axis error stays flat. As y-position increases (moves from top to bottom on the grid) y-axis error increases and x-axis error stays fairly flat.

An exception to these trends is higher error along both axes, but particularly along the y-axis, in the far left column (x-position 1). The bottom-left corner is more error-prone than other areas. Y-axis error increases the further down the hand, and the bottom-left corner is the closest area to the thumb, as all participants were right-handed (left hand was stimulated). Research has shown that static stimuli are often mislocalised towards the thumb, particularly those closer to it [3]. The distributions in Figure 3 also appear to show this bias towards the thumb (towards the left).

Apparent Motion

Movement Perception: 62.9% of all stimuli were reported as producing a sensation of “continuous movement”, although this number ranged from 12.5% up to 91.5%, depending on the combination of variables. Increasing the distance between the start and end points increased the sensation of continuous movement, which is in contrast to the results from previous research [18], possibly due to the larger and less defined focal point we used compared to the small diameter rods used in other research. Carter *et al.* [2] found that focal points of the same modulated frequency needed to be 5cm apart to be perceptually distinct, so when the points are too close, they may feel like one entity. In accordance with other research [5, 18, 19, 21], the number of stimulating points had a large effect on movement perception. 76.2% of trials stimulating all points resulted in continuous sensations, compared to only 49.6% when using only the two start and end points. The negative impact of using only two points was exacerbated when travelling the longer distance or using shorter durations, as movement reports decreased from 1cm to 3cm and from 300ms to 50ms. These results support the assertion that the number of stimulators (or intervening points) is more important for the illusion of movement than the distance between them.

The effect of duration was also marked. Movement perceptions increased significantly as the duration increased from 50ms to 200ms, with no difference above 200ms. Research using rigid stimuli found similar trends, as longer durations produced good movement more reliably [18]. Only 27.2% of 50ms trials felt continuous, compared to 83.3% of 300ms trials. It seems that there is no extra benefit in increasing the duration beyond 200ms. However, the interaction between distance and duration suggests fast movement (50-100ms) should be across larger distances, and slow movement (200-300ms) should be across shorter distances. There was no effect of direction on movement perception but, as is described below, it strongly interacted with other variables.

Overall, there was a pattern that transverse movement was more often felt as continuous, and that the benefits of duration and number of points had a stronger impact on longitudinal movement. Longitudinal movement was more convincing when using the larger distance, while transverse movement was less affected. This could be because transverse movement crosses multiple fingers, making the change in location more apparent, while longitudinal movement only moves within the same digit. The borderline significant interaction between distance, direction and duration showed that upwards movements suffered the most from the small distance and short duration, but therefore benefited the most by increasing those. It is unclear why this might be. The results also suggest that transverse movement needs shorter distances and durations of 100ms+ for good movement, while longitudinal movement needs longer distances and longer durations (200ms+).

Movement Quality: The overall quality of movement was high, at 73.1%, although this is lower than movement quality using pins/rods [18, 19]. Therefore, ultrasound feedback from a small, static source using only a small number of focal points can reliably produce good sensations of movement. Like movement perception, longer distances, larger number of points and longer durations led to better movement quality, however, there was no extra benefit of increasing duration past 200ms, echoing previous research [18, 19]. In contrast, this previous research suggested physical distance had no effect on movement quality across similar distances to those used in our experiment, so our less defined focal points may require more distance to be distinct [2]. Direction did not significantly affect quality.

Direction Accuracy: Overall, participants were able to identify the direction of movement well, at ~88%. The longer distance led to significantly better accuracy (93.6%, compared to 82.0%), so direction is easier to judge when the start and end points are further from each other. There was no effect of either number of points or duration, suggesting that these factors are more important for producing a convincing sensation of movement, rather than the direction of that movement. Movement upwards was significantly less well identified than all other directions. It is unclear why movement up the fingers from the palm would be worse than movement towards the palm from the fingers. When moving down, perhaps the more sensitive fingers give a clearer starting point and the more vague sensation on the palm is sufficient to determine direction. When moving up, given a more vague starting position, attention may be preoccupied during the clearer sensation on the fingers. Hoshi [13] found that users were able to identify the direction of longitudinal movement at 100% accuracy, but he used a larger array (384 transducers), a larger distance (4cm gap between end points) and it is unclear which parts of the hand were stimulated.

Design Guidelines

Based on our results, we propose guidelines for the design of ultrasonic haptic feedback in HCI. Due to the functional similarities, the guidelines here can also be applied to larger ultrasonic arrays. The influence of each feedback characteristic is explained in relation to localisation and the creation of motion, as are general interaction guidelines: spatial resolution and the feasibility of a wrist-mounted array.

Distance: The use of larger distances improves the sensation and quality of movement. However, if using fewer points of stimulation, it is best to use shorter distances and longer durations to improve movement. If using more points, use longer distances and moderate-to-long durations.

Number of Points: Increasing the number of intervening stimuli improves the sensation and quality of movement.

Duration: Rapid stimuli (100ms) are reliably detectable, but longer durations improve perception and localisation. Longer stimuli also improve the perception and quality of movement. If fast movement (50-100ms per point) is needed it should be across larger distances, while slower movement (200-300ms) should be across shorter distances.

Location/Direction: Sensitivity and localisation are better nearer the centre of the hand (near the metacarpophalangeal joints), and particularly bad towards the thumb. Localisation is worse, and movement is generally less clear, along the longitudinal axis, and longer distances are needed for good movement. Transverse movement benefits from shorter distances and longer durations.

Spatial Resolution: Localisation error was 8.5mm on average, with a standard deviation of 6.8mm. As error along the y-axis was 3mm worse than x-axis, this suggests that focal points can be reliably localised at a spatial resolution of one point (i.e., one pixel) per 1.5 x 2cm. This could give a display of 5 x 7 pixels across a hand area of 7.5 x 14cm.

Virtual object size: A virtual object would need to be at least 2cm^2, otherwise users may not be able to accurately resolve its spatial location or movement, especially if movement is small, potentially leading to inaccurate interaction or a perceptual mismatch, if using visual feedback.

Wrist-Mounted Array: Part of our motivation was to examine the efficacy of a small mobile or embedded array for feedback, particularly during gestural interaction. The results from our experiments indicate that a wrist-mounted ultrasonic haptic array could provide as effective and salient feedback as larger static arrays [13]. 99% of static stimuli were detected and the majority of non-static stimuli produced sensations of continuous movement at a high quality, even when using a small, low force array and passive feedback reception. There are issues to consider, however, such as the influence of array angle relative to the hand on perception of focal points, or the impact of user and array movement, such as when gesturing.

CONCLUSIONS

This paper reported two experiments that identified some of the underlying perceptual characteristics of location and movement of ultrasound feedback on the hand. By using a small array we also investigated the feasibility of a wrist-mounted array for gestural interaction. The results showed that users could localise a static point of ultrasound feedback within 8.5mm across 25cm^2 of the hand. Using only a single focal point, a range of feedback characteristics can provide a convincing sensation of continuous motion, but using larger distances, longer stimulus durations and stimulating more intervening points maximises movement perception. Due to the functional similarities, our results and guidelines can also be used in the design of feedback produced by larger ultrasonic feedback arrays. Passive feedback from a small array can provide as effective feedback as active investigation over large arrays, suggesting a wrist-mounted array for gestural interaction is feasible.

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