Perception of Direction for Applied Tangential Skin Displacement: Effects of Speed, Displacement, and Repetition

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Abstract—A variety of tasks could benefit from the availability of direction cues that do not rely on vision or sound. The application of tangential skin displacement at the fingertip has been found to be a reliable means of communicating direction and has potential to be rendered by a compact device. Our lab has conducted experiments exploring the use of this type of tactile stimulus to communicate direction. Each subject pressed his/her right index fingertip against a 7 mm rounded rubber cylinder that moved at constant speed, applying shear force to deform the skin of the fingerpad. A range of displacements (0.05-1 mm) and speeds (0.5-4 mm/s) were tested. Subjects were asked to respond with the direction of the skin stretch, choosing from four directions, each separated by 90 degrees. Direction detection accuracy was found to depend upon both the speed and total displacement of the stimulus, with higher speeds and larger displacements resulting in greater accuracy. Accuracy rates greater than 95 percent were observed with as little as 0.2 mm of tangential displacement and at speeds as slow as 1 mm/s. Results were analyzed for direction dependence and temporal trends. Subjects responded most accurately to stimuli in the proximal and distal directions, and least accurately to stimuli in the ulnar direction. Subject performance decreased slightly with prolonged testing but there was no statistically significant learning trend. A second experiment was conducted to evaluate priming effects and the benefit of repeated stimuli. It was found that repeated stimuli do not improve direction communication, but subject responses were found to have a priming effect on future performance. This preliminary information will inform the design and use of a tactile display suitable for use in hand-held electronics.

Index Terms—Human information processing, haptic I/O, tactile feedback, lateral skin stretch, tangential skin displacement and deformation, response priming.

1 Introduction

Traditionally, haptic devices have been used to approximate real-world sensations for use in virtual reality and teleoperation. In this paper, we explore the use of tactile stimulation to convey other nonsensory information. We have developed a test device to characterize the communication of direction information via applied tangential skin displacement at the fingertip (Fig. 1). A tactor in contact with the skin moves in the plane of the fingerpad, imparting a directional shear force that displaces, deforms, and stretches the skin and also results in microslip around the edges of the tactor. A portable version of such a device, currently under development, could be used for a variety of applications, the most obvious being navigation. Such a device would be useful in guiding a user without the need for distracting cues presented visually (a map) or auditorily (spoken instructions), benefiting drivers, first responders in navigating a building, or soldiers in an urban setting. Integration of such a directional feedback device into a computer interface could guide a user through ordered sets of data, cue attention to important on-screen information (e.g., for an air traffic controller), or turn a standard laptop TrackPoint from a simple cursor input device into an input/output device for a variety of applications. Medical research has also suggested that directional skin stretch at the fingertip could be used to aid in balance and posture control for disabled patients (Jeka and Lackner [1], Wasling et al. [2]) or be used as a tool to evaluate the health of the peripheral and central nervous systems (Olausson and Norsell [3]). In this paper, we identify stimuli that accurately communicate direction and could be easily rendered by a small portable device. We also evaluate several aspects of subject response to these stimuli to help optimize their use in future applications. In the remainder of this paper, we present background on various means of haptic direction communication, describe our bench-top shear feedback device and its performance, describe our two experiments, and discuss their results. A concept for a miniature shear display is presented in brief along with plans for other future work.

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2 Background

2.1 Related Work: Haptic Communication

While the majority of haptic research has focused on rendering realistic interactions for simulation or telepresence, a few researchers have investigated the use of haptic cues to convey arbitrary, abstract information.

Perhaps, the most relevant to our current work is research done by Eves and Novak, where electrocutaneous stimulation of the fingerpad was used to communicate

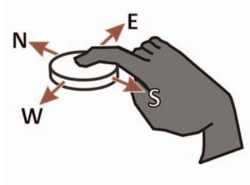

Fig. 1. Communication of direction via tangential skin displacement.

vector information, encoding both magnitude and direction [4]. Vibrating motors have also been used to provide directional haptic information. Tan et al. used vibrotactors imbedded in a chair [5], while Van Erp placed the tactors on a belt worn by the user [6]. Lylykangas et al. were able to successfully communicate three orthogonal directions in a 2D plane using tactile input from a single leadscrew [7]. Bark et al. used skin stretch not to convey direction but as a substitute for proprioceptive information [8]. For a broad view of haptic cues used to represent symbolic information, see the work of Enriquez and MacLean [9].

2.2 Related Work: Tactile Perception of Direction

A significant body of work examines human sensitivity to various types of direction cues. This work varies widely from haptics researchers looking for device design parameters to neuroscientists attempting to diagnose neuropathy.

A few studies have sought to characterize the discrimination of directional skin displacement at the fingertip, although these studies do not agree in all of their findings. Using a variety of stimulator designs, the following researchers applied a shear force to produce in-plane skin displacements. Drewing et al. observed angular resolution thresholds of 14-34 degrees, depending on the subject [10]. Vitello et al. measured thresholds of 30-40 degrees [11]. Keyson and Houtsma found angular thresholds around 14 degrees. Interestingly, the above studies observed different thresholds in different directions, e.g., that the finger is more sensitive to stimuli in the distal direction than in the proximal direction. Placencia et al. [12] also observed direction-dependent sensitivity. However, these studies do not agree on which directions are the most sensitive. We suspect that this disagreement is due to the different stimulators used, as we discuss in greater depth in Section 5.3.4. Despite the disagreement in angular resolution, all of the above papers found thresholds low enough to allow for easy differentiation of the four directions required for simple navigation.

In other related work, Olausson and Norrsell investigated the detection of skin stretch using a two-direction paradigm and determined that the accuracy of direction identification increased with stimulus distance and normal force [3]. Salada et al. studied subjects' ability to discern the direction of an object slipping over the skin and found angular resolution thresholds from 3.6 to 11.7 degrees [13].

Neurologists have studied humans' ability to sense the direction of spatiotemporal stimuli. Spatiotemporal stimulation refers to the application of a moving normal force without applying tangential forces, stimulating a series of spatially separated mechanoreceptors over time. Spatiotemporal stimulation is often accomplished with an air jet, water jet, pin array, or a brush.

Spatiotemporal direction detection thresholds were measured on various parts of the body by De Cillis and found to be the smallest at the fingertip [14]. Also, Loomis and Collins found the fingertip to be highly sensitive to spatiotemporal direction cues, with 75 percent discrimination thresholds for motions in the range 0.1-0.2 mm in a two-direction test [15]. A broad investigation of spatiotemporal stimulus parameters, including stimulus speed, length, position, and orientation, was conducted by Essick and Whitsel [16]. Detection thresholds for saltating spatiotemporal stimuli were investigated by Gardner and Sklar [17]. In work by Whitsel et al., the relationship between stimulus speed and the perceived distance traversed on the skin was explored and it was found that faster stimuli felt shorter, for most speeds [18]. Evidence of spatial summation was found by Olausson, concluding that a larger interface produced lower detection thresholds for spatiotemporal stimulation [19].

2.3 Stimulus Choice

There are several possible means of communicating direction with tactile stimuli; various types of stimuli could be used and these stimuli could be delivered to a variety of locations on the body. We have chosen to interface with the fingertip as it is the most natural way to interact with a portable device and because it is also the region of the highest sensitivity (Johansson and Flanagan [20] and De Cillis [14]).

Of the methods of tactile direction communication previously discussed, many were rejected due to mechanical design constraints or limitations in human perception. Vibrating actuators were not a desirable option due to space constraints. Previous researchers have used several widely spaced actuators to communicate direction (e.g., [6]), but fitting multiple actuators in the space of the fingertip and integrating them into a portable device would be a significant engineering challenge. Electrocutaneous stimulation was not chosen by the authors due to its numbing and occasionally uncomfortable aftereffects.

Rendering direction using the sensation of slip was eliminated for both mechanical and perceptual reasons. An interface capable producing the long displacements required to achieve slip on the fingerpad (>6 mm, Srinivasan et al. [21]) would be too large to fit in a portable device. In addition, humans are less sensitive to slip than to skin displacement. Srinivasan et al. performed experiments using a device that first rendered skin displacement and slip and observed that slip provided very little improvement in direction identification compared to the shorter skin displacement stimuli [21]. The same conclusion can be drawn from the work of Salada et al. [22].

Spatiotemporal stimulation, that is, the application of a laterally moving normal force, was also rejected for both mechanical and perceptual reasons. Many investigations of spatiotemporal perception, including those by De Cillis [14] and Norrsell and Olausson [23], used an air jet to generate stimuli. A water jet was used by Loomis and Collins [15], a rolling cylinder by Olausson [19], and Gardner and Sklar used a pin array [17]. We feel that these mechanisms are ill-suited for implementation in a small portable device due to their mechanical complexity. Additionally, studies directly

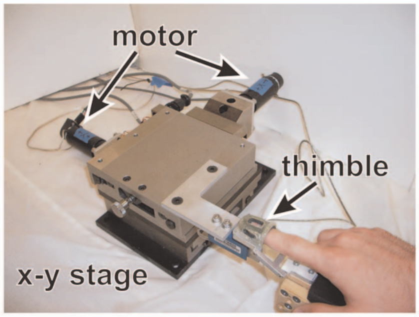

Fig. 2. The test device, a two-axis stage for rendering skin displacement stimuli. The finger is restrained in an open-bottomed thimble.

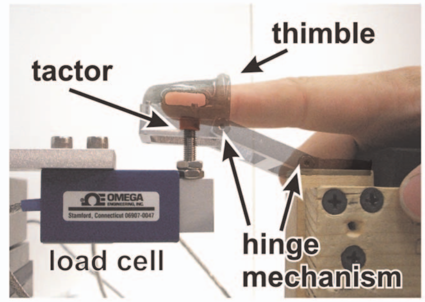

Fig. 3. The tactor in contact with the finger. The thimble and thimble mount are shown translucent so that the finger and tactor can be seen. The thimble is free to move up and down, but constrained in the plane of tactor motion.

comparing skin stretch and spatiotemporal stimulation, such as those by Norrsell and Olausson [24] and Gould et al. [25], have found direction detection thresholds to be lower for skin stretch than for spatiotemporal stimuli. These results are supported by research published by Biggs and Srinivasan, which found the fingertip to be generally more sensitive to tangential forces than normal forces [26].

Tangential skin displacement was chosen by the authors as the best method for direction communication at the fingertip. Humans are highly sensitive to skin stretch, previous studies suggest that differentiation of four directions should be achievable, and skin displacements can be rendered by a small, portable device, as we discuss in a related paper [27].

2.4 Physiology of Tangential Skin Displacement

Shear force and tangential skin displacement are encoded by a range of mechanoreceptors. Birznieks et al. applied directional forces to the fingerpad and found that SA-I, SA-II, and FA-I afferents all responded to and encoded directional information [28]. This is supported by early work by Vallbo and Johansson who identified SA-II as the primary receptor for skin stretch but argued that other receptor types were involved as well [29]. Work by Srinivasan also identifies SA-II as the primary means of encoding tangential skin displacement [21]. Olausson et al. also concluded that lateral skin stretch is encoded primarily by SA-II afferents but SA-I afferents were more sensitive to spatiotemporal stimuli [30].

The role of spatial recruitment in the detection of skin stretch was analyzed in papers by Norrsell and Olausson [24] and Olausson et al. [31], who found that lateral skin stretch activates sensors over a large area of skin ranging more than 15 mm from the point of contact.

Wang and Hayward [32] and Maeno et al. [33] have sought to understand tangential skin deformation through measuring and modeling the properties of the human fingerpad.

3 Device Description

Stimuli were rendered using a Parker Two-Axis Linear Stage driven by Maxon RE36 DC motors with a gear ratio of 4.8:1 (Fig. 2). Position was measured by US Digital E2 encoders with 1,250 ticks/revolution, providing position resolution of approximately $0.4\ \mu m$. The user's finger was constrained with an open-bottomed thimble, as described by Provancher et al. [34]. Thimbles of different sizes were made to accommodate a range of finger sizes. A hinge mechanism prevented the thimble from moving in the proximal/distal and lateral directions but allowed the thimble to move up and down (Fig. 3). The user was thus able to regulate the force applied to the device but was constrained from moving in the plane of the stimuli. The device contacted the fingerpad through a sandpaper-like IBM ThinkPad TrackPoint tactor, measuring approximately 7 mm in diameter.

The contact force between the user's finger and the device was measured with an Omega LCEB-5 single-axis load cell, accurate to $\pm\ 0.03$ percent. Off-axis forces affected the readings, however, introducing 4 percent error (empirically determined) into our readings.

The device was driven by a PC running RTAI 3.1 on Red Hat 9 Linux. Position and velocity were controlled by a 5 kHz servo rate PD controller with several nonlinear modifications implemented to address our experiment's specific performance requirements. The device rendered stimulus position and velocity with high fidelity over a range of 0.05-1 mm and 0.5-4 mm/s, as shown in Table 1.

Note that all speeds presented in this paper are calculated from data collected during the linear (constant speed) region of the stimulus trajectory, omitting data recorded while the device accelerated at the start and end of the movement. See the sample tactor trajectory in Fig. 4. In

TABLE 1
Stimulus Rendering Fidelity

Displacement (μm)	Mean Error (μm)	σ (μm)
100-1000	< 2	< 2
50	<1.2	< 0.5

Speed (mm/s)	Mean Error (mm/s)	σ (mm/s)
1.0-4.0	< 0.072	< 0.072
0.5	< 0.01	< 0.009

Stimulus rendering fidelity, based on encoder readings of all stimuli rendered during experiments. Mean error is the mean of all errors recorded for a given stimulus. σ is the standard deviation in the error. Errors in displacement and speed are smaller at shorter, slower stimuli. The upper limit on error is reported separately for short/slow stimuli and for the remaining stimuli.

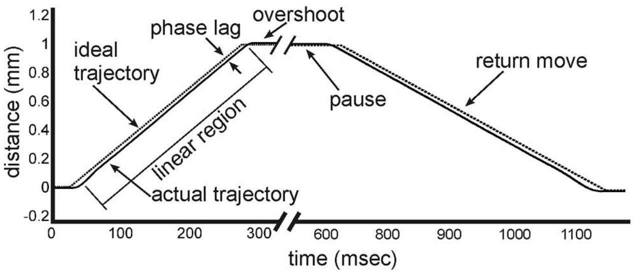

Fig. 4. Sample tactor trajectory. Each stimulus includes an outbound move, a pause (partially omitted in figure), and a slower return move. The device follows a linear trajectory with some phase lag but successfully maintains constant speed and high position accuracy. The linear region used for speed calculations is shown.

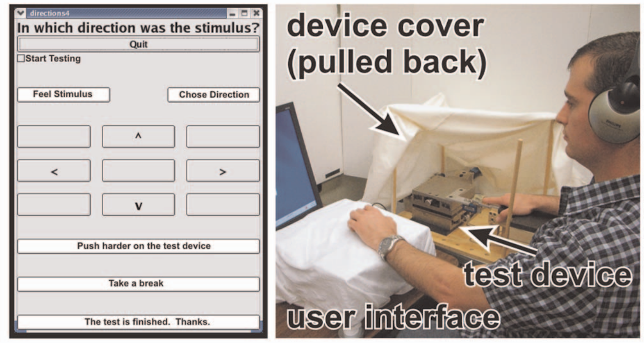

Fig. 5. The test setup. The user sits with his/her right index finger in a thimble with the tactor contacting the fingerpad. The device cover is shown pulled back for documentation purposes only. The graphical user interface used for prompting and recording user responses is shown on the left.

all cases, this linear region comprises at least 70 percent of the move, by distance.

Mechanical backlash was measured on both axes with the x-y stage moving at 4 mm/sec and with two different displacements: 50 and $100\ \mu\mathrm{m}$. Backlash distances on the x-axis (radial-ulnar axis) and y-axis (proximal-distal axis) were less than 2.7 and $4.8\ \mu\mathrm{m}$, respectively. The motor gearbox and the stage's leadscrew nut are the primary sources of backlash. In posthoc analysis, stimuli affected by backlash (but unaffected by direction repetition, see Section 5.3.6) were identified and analyzed to see if backlash affected subjects' responses. Backlash was not found to have a statistically significant effect on subject performance (for all stimuli, $\mathrm{t} < 1.35$, $\mathrm{p} > 0.20$).

4 General Experimental Methods

In this research, we endeavored to use tangential skin displacement at the fingertip to communicate direction. Experiments were conducted to determine what factors influence direction identification and to improve our device design by finding optimal values for important factors. Two experiments were conducted: one exploring the effects of stimulus speed and distance and a second investigating stimulus repetition. This section contains general methods common to both experiments. Informal pilot tests were conducted to guide our experiment design. These tests determined the kind of stimuli rendered, finger restraint methods, and what variables would be tested.

A stimulus was designed to convey direction as effectively as possible. Each stimulus consisted of three portions: an outbound move, a pause, and a return move, as shown in Fig. 4. During the outbound move, the tactor moved in a straight line in the given direction, at a constant speed, for a given displacement. Upon reaching the end of its travel, the tactor would pause for 300 msec. After the pause, the return move brought the tactor back to the original position, along a straight line, at a constant speed. The return speed was set at 66 percent of the outbound speed to reduce confusion between the outbound and inbound stimuli. These stimulus parameters were determined through pilot testing.

During testing, subjects sat with their right index finger in the thimble (Fig. 5) and brought their fingerpad into contact with the tactor. A padded arm rest was provided for the subject's right forearm, which was held parallel to the subject's sagittal plane. A cloth covered the device and the user's hand. Headphones played white noise to mask any sound from the device. The headphones also played an audio cue which preceded each stimulus by 500 msec. After each stimulus, a graphical user interface (Fig. 5) prompted the user to respond with the direction of the stimulus by clicking on buttons marked with arrows using a computer mouse. The interface software also monitored the contact force between the user's finger and the device. Below 0.25 N, the user was visually prompted to press harder on the device.

The 0.25 N threshold was empirically determined to ensure that slip did not occur between the finger and the tactor. The test device was temporarily instrumented with a six-axis JR3 force sensor (model no. 67M25A-U562) and shear forces were monitored for a range of device movements. These data were also used to estimate the coefficient of static friction between the tactor and finger (it was directionally dependent, but >1.6 for all directions). For all experimental stimuli, the friction safety factor to ensure that no slip occurred (friction force/required shear force) was greater than 1.4, assuming a contact force of 0.25 N. Some localized microscale slip could occur, particularly around the edges of the tactor, but this is unavoidable without gluing the tactor to the skin, a useful method for some research (e.g., Olausson et al. [31]), but impractical for a user interface.

All tests were completed under Institutional Review Board approved human subjects protocol.

5 Experiment 1: Speed and Displacement

In this experiment, we investigated the effects of stimulus speed and displacement when communicating direction using tangential skin displacement at the fingertip. In addition to speed and displacement, a series of pilot tests examined a number of other factors.

5.1 Method

Subjects were presented with directional stimuli with varying direction, total tactor displacement, and speed, and then asked to indicate the direction of the stimulus. Speeds and displacements were chosen to provide stimuli with a range of perceptual difficulty. The displacements chosen were 0.05, 0.1, 0.2, 0.5, and 1 mm and stimulus speeds were 0.5, 1, 2, and 4 mm/s. Communication was attempted in four directions, separated by 90 degrees: distal, proximal, ulnar, and radial motions on the fingertip. These directions will be referred to as North (N), South (S), East (E), and West (W), respectively.

Two tests were constructed: a long test and a short test. The long test consisted of all combinations of the above parameters ($5 \text{ displacements} \times 4 \text{ speeds} \times 4 \text{ directions} = 80$ unique stimuli). Pilot testing showed little variation in the performance on 1 mm stimuli, making it unnecessary to test a large number of subjects at this displacement. A shorter test was designed that omitted all 1 mm stimuli, leaving 64 unique stimuli.

To ensure that all stimuli would be equally affected by any temporal trends, the different stimuli were distributed evenly throughout the test. Both the short and long tests were organized into blocks, with each block containing one instance of each stimulus, in random order. Each subject was presented with 16 identical test blocks. This experiment design was used so that temporal trends could be analyzed without the confounding factor of changing stimulus order. Because the blocks were long and there was no signal marking the beginning or end of the blocks, we were not concerned about subjects memorizing the stimulus order or recognizing a pattern.

Average test durations were about 1 hour 20 minutes for the long test and 1 hour for the short test. The test was divided into 15 minute sections, with a rest period between each section.

The long test was completed by five subjects, three male, two female, ranging in age from 26 to 28 years. Of these five subjects, four were right-hand dominant and two were authors involved in the development of the experiment. The short test was completed by 11 subjects, 9 male and 2 female, aged between 21 and 36 years. All but one subject were right-hand dominant and one subject was hearing impaired.

5.2 Pilot Testing

Several different means of restraining the finger were explored. The open-bottom thimble design was chosen as the best combination of finger constraint, user comfort, and applicability to other applications. The thimble design has proved effective in other experiments, e.g., Provancher et al. [34], and has been incorporated into our portable tactile display [27]. Another attempted restraint method was a cylindrical splint covering the entire dorsal side of the finger as well as the intermediate and proximal phalanges on the palmar side. While the splint restrained the finger well, was comfortable, and performed well in pilot testing, it was deemed inappropriate for a general application; restraining all finger joints is impractical for a haptic interface and incompatible with our portable device design.

The tactor trajectory, i.e., the shape of the tactor position-versus-time curve, was also explored. Tested trajectories included linear (constant speed), exponential (speed increase with time), decaying exponential (speed decreases with time), and various combinations of these trajectories. Through these tests, it was found that stimulus speed was significant but trajectory shape did not significantly affect the performance. The linear trajectory (constant speed) was chosen because it is easy to characterize and had a feel that was preferred by users. See a sample trajectory in Fig. 4.

Displacement (mm) \ Speed (mm/sec)	0.5	1	2	4
1	0.98 ±0.024	0.99 ±0.011	1.00 ±0.000	1.00 ±0.009
0.5	0.95 ±0.024	0.98 ±0.013	0.99 ±0.010	0.99 ±0.009
0.2	0.85 ±0.067	0.94 ±0.050	0.96 ±0.025	0.95 ±0.027
0.1	0.69 ±0.083	0.85 ±0.061	0.90 ±0.027	0.89 ±0.027
0.05	0.54 ±0.086	0.72 ±0.069	0.73 ±0.061	0.79 ±0.046

Fig. 6. Experimental results, combining data from all stimulus directions. Subjects attempted to identify the direction of skin displacement stimuli at a range of stimulus speeds and displacements. Stimulus displacements are shown on the vertical axis, and speeds on the horizontal. Identification accuracy rates and corresponding 95 percent confidence intervals are shown in the grid squares. The shading of the squares corresponds to accuracy, with lighter color indicating higher accuracy.

User comments confirmed that the three-part move (outbound, pause, and return) reinforced directional information without causing confusion. The fast outbound move was the most salient, due to its high speed. The return move reinforced the direction cue and its slower speed helped the user to differentiate it from the outbound move. The 300 msec pause between the two moves allowed the user to sense the two distinct signals; omitting the pause caused users to experience one muddled signal that was hard to interpret. This observation is in agreement with previous vibrotactile stimulus masking experiments by Craig, in which subjects were unable to differentiate between two stimuli if the time between the onset of the two stimuli (stimulus onset asynchrony) was too brief [35]. Craig's work suggests that 300 msec is a sufficient pause to prevent any stimulus masking in our experiments.

Initial tests attempted to communicate eight directions, spaced 45 degrees apart. Discrimination of all eight directions was found to be somewhat difficult and dependent on the position and orientation of the subject's hand. Further tests were limited to four directions, as most potential applications for our device would only require the communication of four directions.

5.3 Experimental Results and Discussion

5.3.1 *Direction Discrimination*

Pilot tests revealed displacement and speed to be the important features of the tactile stimulus. Subjects were, therefore, asked to identify the direction of stimuli applied to the fingertip over a range of speeds and displacements. Results were pooled from all subjects. Pooled results and confidence intervals are shown in Fig. 6. In general, direction was communicated with greater accuracy when larger displacements and higher speeds were applied. Confidence intervals are typically larger for the more difficult stimuli; subjects performed uniformly well on the easier stimuli, but performance on the difficult stimuli

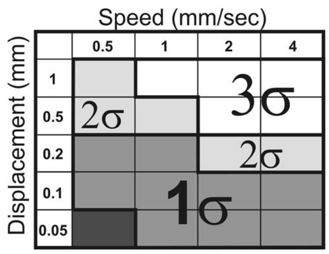

Fig. 7. Experimental results from Fig. 6, broken into regions corresponding to the 1-, 2- and 3-σ points (approximately 68, 95, and 99 percent accuracy, respectively). Given some design criterion, e.g., 95 percent accuracy in direction communication, this plot makes clear the range of stimuli from which one could choose when designing a device.

varied widely. Confidence intervals on the 1 mm stimuli are somewhat large due to the small number of subjects (5) tested at that displacement.

Contact force was recorded during all tests with a one-axis load cell. Contact force, averaged over all stimuli and all subjects, was 0.71 N with standard deviation of 0.35 N. Force data show that users consistently maintained sufficient contact pressure to prevent any gross slip during stimuli.

We have found no data in the literature suitable for direct comparison with our observations, but we can draw meaningful implications from a few relevant studies. A study of skin stretch on the forearm by Olausson et al. found 66 percent accuracy in direction discrimination with 0.13 mm stimuli, although the stimuli used in this earlier study were all faster than those used in our experiments [31]. On the fingertip, we observed higher accuracy at speeds slower than those used by Olausson et al. This confirms that the fingertip is more sensitive to skin stretch than the forearm, as expected. In another study of skin stretch on the forearm by Olausson and Norrsell, direction discrimination accuracy was found to increase with stimulus distance and speed, which agrees with our observations [3]. In a study of direction discrimination of spatiotemporal stimulation, Loomis and Collins rendered stimuli with a water jet at the fingertip and found displacements of 0.1-0.2 mm, rendered at speeds around 5 mm/s, to result in 75 percent accuracy [15]. Our observation of higher accuracy in the same range of displacements confirms our assumption that people are more sensitive to directional tangential skin displacement than to directional spatiotemporal stimulation. It should be noted that all of the above studies involved discrimination between two possible directions, where random responses would result in 50 percent accuracy. In our four-direction experiment, random responses would result in 25 percent accuracy.

Other research has sought to identify angle discrimination thresholds for directional skin displacement at the fingertip, as discussed previously. These studies typically used stimuli of 1 mm or longer and reported thresholds between 14 and 40 degrees, depending on the methods and metrics used (Drewing et al. [10], Vitello et al. [11], and Keyson and Houtsma [36]). These thresholds predict that subjects should easily be able to discriminate between four-direction stimuli with 1 mm of displacement, which is in agreement with our results.

One goal of our research was to identify design parameters for an interface that could be small and portable. The size, weight, and power consumption of such a device could all be minimized by keeping stimulus speed and displacement requirements low. It is, therefore, important to identify easily rendered stimuli which could be used to convey direction with a high accuracy rate. The choice of a target accuracy rate is somewhat arbitrary. One possibility is to consider accuracy rates in terms of sigma levels, as shown in Fig. 7. For example, if two-sigma (roughly 95 percent) accuracy was desired, a stimulus of 0.2 and 2 mm/s could be chosen. Such a stimulus could be rendered by a compact device, and the confidence interval for that stimulus is such that we can reasonably assume that communication accuracy rates would be near 95 percent for an average user.

It should be noted, however, that communication accuracy might change in a real-world environment. The high cognitive load of some primary task (e.g., driving a car) could distract a user's attention from the haptic cues or the cues could become more difficult to understand if the hand were allowed to move freely. These factors will be the subject of future work.

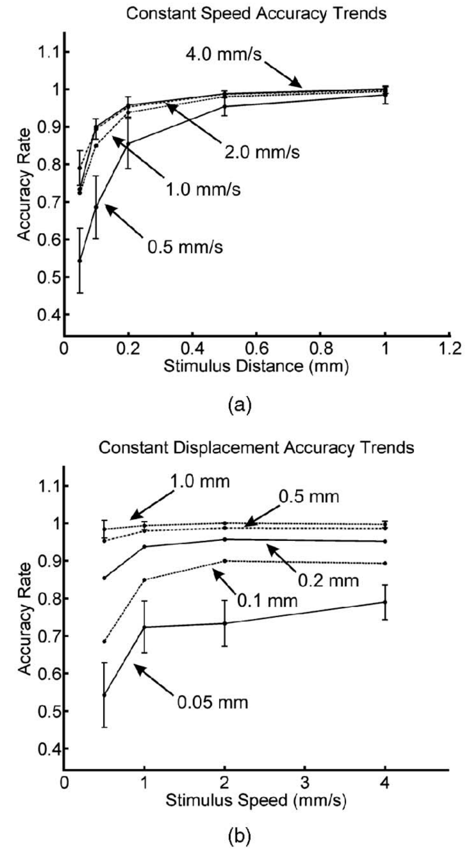

Fig. 8. Accuracy trends plotted for stimuli of (a) constant speed and (b) constant distance, combining data from all stimulus directions. Error bars, shown on only two curves for greater clarity, indicate 95 percent confidence intervals. Accuracy increased at higher speeds and larger distances.

5.3.2 Influence of Speed and Displacement

Looking again in Fig. 6, interesting trends can be seen as stimulus speed and displacement are altered. For any group of stimuli with equal speed, there is a clear trend of accuracy increasing as displacement increases. This can be seen more clearly in Fig. 8a. Each curve in Fig. 8a was independently subjected to an omnibus ANOVA test and

Direction Rendered \ Direction Perceived	N	E	S	W
N	3989	107	165	155
E	224	3638	311	243
S	218	123	3936	139
W	275	202	175	3764
Σ	4706	4070	4587	4301

Fig. 9. Stimulus confusion matrix. Each row shows instances of rendered stimuli and each column shows instances of perceived stimuli. The fifth row shows the total number of stimuli perceived in each direction (4,416 stimuli were rendered in each direction). There is no evidence of stimulus confusion, however, there appears to a response bias toward North and, to a lesser extent, South.

Tukey's Honest Significant Difference, performed with $\alpha = 0.05$. The improvement in accuracy is statistically significant (for all velocities: $\mathrm{F}(4, 64) > 18,\ \mathrm{p} < 0.001$). Tukey's test shows a statistically significant improvement between 0.05 mm stimuli and 0.1 mm stimuli at all velocities, and between 0.1 mm stimuli and 0.2 mm stimuli for most velocities. Beyond 0.2 mm, there was no significant improvement ($\alpha = 0.05$).

When the skin was displaced 1 mm at any of the tested speeds, the user identified the direction correctly almost 100 percent of the time. At 1 mm of displacement, there were occasional incorrect responses at speeds of 0.5 and 1 mm/s, but these errors could be explained by subject distraction during the long stimulation. Some subjects reported such distraction.

When looking at stimuli with equal displacement, the effect of speed is not as simple (Fig. 8b). For stimuli with displacements of 0.05-0.5 mm, there is a statistically significant improvement in accuracy as speed increases ($\mathrm{F}(3, 60) > 5.0, \mathrm{p} < 0.01$). For stimuli in this range of displacements, Tukey's test generally shows an improvement in accuracy between 0.5 mm/s stimuli and 1.0 mm/s stimuli, but no significant improvement at higher speeds ($\alpha = 0.05$). For stimuli with displacement $= 1.0$ mm, high accuracy rates resulted in a ceiling effect and no trends could be established.

The implication of the above analysis is that communication accuracy can be improved with faster stimuli, but increasing speeds beyond 1 mm/s does not result in significant improvement. Similarly, accuracy increases as the stimulus displacement gets longer, but no significant improvement is to be seen when stimuli become longer than 0.2 mm.

5.3.3 *Stimulus Confusion*

Part of understanding subjects' perception of direction cues is an analysis of incorrect responses. While subject responses seem to be biased toward certain directions, there is no evidence of confusion between the different direction cues.

When considering the use of haptic cues for navigation, it is important to know how easily cues will be misinterpreted. It would be problematic if directions were easily confused. A confusion matrix was assembled from all pooled data to

Speed (mm/sec); rows: Displacement (mm)

- N -	0.5	1	2	4
1	Inf	4.88	Inf	Inf
0.5	4.46	4.93	5.08	4.93
0.2	2.98	4.23	4.12	3.91
0.1	2.01	3.14	3.46	3.11
0.05	1.56	2.21	2.18	2.67

- W -	0.5	1	2	4
1	Inf	Inf	Inf	Inf
0.5	4.03	4.93	Inf	5.16
0.2	3.04	3.93	4.18	4.02
0.1	1.92	2.97	3.68	3.29
0.05	1.39	2.08	2.31	2.39

- E -	0.5	1	2	4
1	4.64	Inf	Inf	Inf
0.5	3.72	4.17	4.72	4.72
0.2	2.70	3.36	3.74	3.83
0.1	1.79	2.56	2.90	3.21
0.05	0.99	1.88	1.85	2.31

- S -	0.5	1	2	4
1	4.64	4.88	Inf	Inf
0.5	4.15	5.28	5.21	5.06
0.2	2.96	4.04	4.55	4.19
0.1	2.26	3.13	3.63	3.55
0.05	1.60	2.38	2.33	2.54

Fig. 10. Results separated by stimulus direction, using d' as a measure of accuracy. Higher values correspond to greater accuracy. When a bias-free measure of accuracy is used, there is little difference in accuracy between the four directions.

compare rendered directions and perceived directions (Fig. 9). Each row of the matrix shows instances of rendered stimuli and each column shows instances of perceived stimuli. A fifth row has been added showing the total number of stimuli perceived in each direction.

For all rendered directions, incorrect responses are distributed fairly evenly over the possible incorrect choices, indicating the absence of direction confusion. This corresponds with anecdotal evidence from subjects, who reported a clear dichotomy between stimuli they understood and those to which they responded randomly. From an application perspective, the lack of direction confusion is encouraging.

The confusion matrix also speaks to subject response bias. Equal numbers of stimuli were rendered in all directions, but the matrix shows that subjects perceived stimuli to be in the North direction more than any other, followed by South, West, then East. North and South have the most correctly identified instances as well as the most incorrect responses. That is, when misidentifying a stimulus, subjects are most likely to respond to the North or South, regardless of the actual direction of the stimulus. The reason for this bias is not fully understood, but a few possible explanations are discussed in the following section.

5.3.4 *Influence of Direction*

It was observed that subjects' accuracy varied with stimulus direction. In general, subjects appeared to perform better in the North and South directions. However, the confusion matrix (Fig. 9) reveals a bias toward the North and South, suggesting that the apparent direction-dependent accuracy could be an effect of direction bias. The data were, therefore, reanalyzed using d', a bias-free measure of detection accuracy (see Macmillan and Creelamn for a discussion d' [37]). The results of this analysis are shown in Fig. 10. When the effects of bias are removed, it is seen that subjects did, in fact, respond more accurately to North and South stimuli. Of the four directions, stimuli to the East were the most difficult for subjects to identify. These results coincide with what is seen in the confusion matrix; both the response biases and the bias-free accuracies follow the same trend.

Possible explanations for this direction dependence include anisotropy in innate sensitivity of the fingertip and effects of our test hardware. For example, the thimble used to restrain the finger in our experiments was not radially symmetric, and therefore, could have direction-dependent effects. The thimble may have provided better restraint to the finger in the North-South direction, or it is possible that the geometry of the thimble impeded the detection of East-West stimuli by squeezing the sides of the finger and limiting spatial summation or by asymmetrically compressing the nail bed. Olausson found that constraining the skin around the point of contact decreased a subject's sensitivity to skin stretch by limiting afferent spatial summation [19]. Birznieks et al. have discussed the importance of receptors along nail bed in sensing direction forces [38]. Our thimble contacts the sides of the finger and the nail bed in a way that could cause an asymmetry in sensitivity and a directional bias. Ongoing work with different finger restraints will provide us with additional information on hardware-induced effects.

Alternately, the direction dependence could be the result of physiological factors. Other research indicates that the fingertip is more sensitive to tangential skin displacements in some directions than others. Such anisotropy in sensitivity was observed by Salada et al. [13] who utilized a stimulus incorporating both slip and stretch, and found the fingertip to be more sensitive along the proximal-distal (North-South) axis, particularly at low speeds. Researchers studying the angular resolution of skin displacement at the fingertip have also observed direction-dependant sensitivity. Drewing et al. found the finger to be most sensitive in the North direction [10], with all other directions approximately equal. Placencia et al. observed the greatest sensitivity in the North direction and the worst sensitivity to the West, with South and East approximately equal [12]. Vitello et al., however, observed greater sensitivity to the East than the North [11]. Using a powered trackball-type display, Keyson and Houtsma concluded that sensitivity is greatest toward the South, with North ranking second in sensitivity [36]. Clearly, there is no agreement in the literature about which directions are most sensitive to skin displacement, but the majority of studies point toward heightened sensitivity in the proximal-distal (North-South) direction. This is in agreement with the North and South accuracies observed in our research.

The lack of agreement in the above studies could be due to slight differences in stimulation method, with some studies using a tactor glued to the finger, some relying on friction, and others using a rounded, rolling stimulator. It is reasonable to assume that different stimulator types induce slightly different responses from the various mechanoreceptors in the fingertip, depending on the amount of microslip, edge sharpness, etc. Birznieks et al. studied afferent stimulation at the fingertip and found different mechanoreceptor types to have different direction-dependent sensitivity [28]. They found that SA-I afferents are biased toward the North, SA-II toward the South, and FA-I toward the South and East. If different simulators activate different receptor groups, and different receptors have different direction biases, then it is not surprising that all of the above studies observed different direction-dependent sensitivities. From this, we can only conclude that some direction-dependent sensitivity is present in our experiment, but that this may be specific to our tactor and our test hardware.

Alternately, other findings have suggested a relationship between orientation of the fingerprint ridges and directional sensitivity (Paré et al. [39], Maeno et al. [33], and Scheibert et al. [40]). Thus, variable direction dependence could be the result of variations in the subjects' fingerprints. How direction-dependent sensitivity, whatever the cause, might affect the use of our device in a navigation application is unclear, but its presence argues for the use of stimuli well above threshold, where the subtle effects of directional bias and sensitivity differences would be less significant.

5.3.5 Temporal Trends

In order to better understand our data, the test results were analyzed for temporal trends. When considering the use of tactile cues for the communication of information, it will be important to know how quickly users learn to interpret those cues and if their performance declines with prolonged use. No significant learning trends were observed. Subjects did show a decrease in performance over time, but recovered after a rest break. Changes in performance over time could be caused by a range of factors, including changing subject attention levels, saturation or overstimulation of mechanoreceptors, and increasing familiarity with the experiment.

Analysis of temporal trends was simplified by the experiment design. The experiment consisted of 16 identical blocks, allowing for the direct comparison of the performance between blocks. To remove any effects arising from the differences between subjects, difference scores were computed for each test block as the performance minus the subject's mean performance. The difference scores were pooled and analyzed using Spearman's Rank Correlation for trends over two different domains: over the entire test and over each individual test section (period between rest breaks, approximately 15 minutes). Data from the short (60 min.) and long (80 min.) tests were treated separately.

Within each section, a significant decline in accuracy was detected, averaging -4.95 and -1.45 percent over the 15 minute section for the long and short tests, respectively. This trend was statistically significant (short tests: $\mathrm{r_s} = -0.460$, $\mathrm{p} < 0.0001$; long tests: $\mathrm{r_s} = -0.239$, $\mathrm{p} = 0.039$). After taking a rest break, the subjects recovered and performance returned to previous levels. Over the duration of the entire test, subjects displayed no learning trend. For the short test, there was no significant correlation between time and performance over this domain ($\mathrm{r_s} = 0.0009$, $\mathrm{p} = 0.981$). Data from the long test showed a slight decrease in the performance (2.4 percent over the entire test) which was significant ($\mathrm{r_s} = -0.238$, $\mathrm{p} < 0.0001$), although most of this decline occurred during the last 20 minutes of the test. Pooled results for all subjects participating in the short experiment are shown in Fig. 11. These pooled data were not used for analysis but are presented to illustrate general trends.

These results support the use of tangential skin displacement cues as a means of direction communication. In an

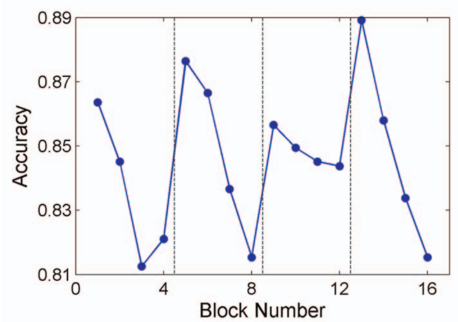

Fig. 11. Temporal trends, pooled across all subjects who participated in the short experiment. Rest break periods are shown by vertical dashed lines. Performance declined with prolonged testing but recovered after a rest break. This trend was statistically significant. No significant learning trends were observed. Note that the pooled performance plotted here is intended only to illustrate the trends; all analysis was conducted on difference scores.

Speed (mm/sec)

Displacement (mm) / Δ	0.5	1	2	4
1	0.02 ±0.046	0.01 ±0.015	0.00 ±0.000	0.01 ±0.014
0.5	0.01 ±0.032	0.01 ±0.019	0.01 ±0.012	-0.00 ±0.017
0.2	0.02 ±0.045	0.03 * ±0.025	0.02 ±0.036	0.01 ±0.025
0.1	0.10 * ±0.103	0.04 ±0.058	0.02 ±0.052	0.05 * ±0.048
0.05	0.17 * ±0.117	0.11 * ±0.071	0.05 ±0.096	0.05 * ±0.047

Fig. 12. Effect of direction repetition. The value in each cell is calculated as accuracy on repeated stimuli minus accuracy on nonrepeated stimuli. Thus, positive numbers indicated an increase in the performance due to repetition. The 95 percent confidence intervals are also shown. The asterisks (*) mark those effects which are statistically significant ($\alpha = 0.05$).

application that did not involve prolonged use, the temporal decline in the performance would not be a factor and users could be expected to perform slightly better than the subjects in these experiments. Additionally, no learning trends were detected, meaning that subjects achieved maximum accuracy without long training. This suggests that the skin displacement stimuli are intuitive and simple to understand. Both of these observations recommend skin displacement as an easy and effective means of communication.

5.3.6 Direction Repetition

Further analysis of the data revealed that direction repetition had an effect on subject performance. Repeated stimuli, i.e., stimuli in the same direction as the prior stimulus, were found to result in higher accuracy for almost all stimulus types and were found to increase accuracy to a statistically significant degree for several stimulus types. The difference between repeated stimuli and nonrepeated stimuli is shown in Fig. 12. This result suggests that direction repetition could result in a priming effect, as discussed in greater detail in the following sections. This indication of priming inspired a further investigation, presented as Experiment 2.

5.4 Summary of Experiment 1

Subjects were asked to identify the direction of various stimuli in order to evaluate skin displacement as a potential means of direction communication. Data were analyzed to determine communication accuracy over the range of speeds and displacements rendered. Accuracy rates increased with greater speed and greater displacement, but high accuracy rates were achieved even at small displacements. It was determined that subjects did not easily confuse the different directions, but they were biased in favor of certain directions. Subject performance was found to decline with prolonged testing, but learning trends were not observed. Our data suggest that direction repetition improves recognition rates, but this requires further investigation.

6 Experiment 2: Priming and Repetition

Results from the previous experiment suggested that repetitive stimuli could be used to increase communication accuracy. It appeared that stimuli had a priming effect and increased sensitivity to future repetitions of the same stimulus. A second experiment was conducted to test this hypothesis.

6.1 Priming Background

In the previous experiment, subjects appeared to be more sensitive to a stimulus when the prior stimulus occurred in the same direction. A similar effect was observed by Gardner and Sklar, who found subjects better able to perceive stimuli from a pin array when those stimuli were repeated [17]. This effect can be explained by stimulus priming, although a thorough explanation of this cognitive effect is beyond the scope of this research.

Cognitive scientists have explored priming effects, where the responses to stimuli are influenced by previous stimuli. Perceptual priming is a well-studied phenomenon, whereby exposure to a stimulus increases future sensitivity to that stimulus (Wiggs and Martin [41]). Interestingly, this effect has been observed by Bar and Biederman, among others, even when the priming stimulus is presented below the perception threshold [42]. While the majority of research in perceptual priming has focused on visual stimuli, there is evidence to suggest that the phenomenon is similar in the haptic modality (Ballesteros and Reales [43] and Easton et al. [44]). In our experiment, perceptual priming may have played a role, heightening the sensitivity to stimuli with direction repetition, regardless of the speed or displacement of the priming stimulus. However, perceptual priming has been shown to have long-term effects by Cave [45] and it is not clear how to interpret the short-term effect we observed in the context of perceptual priming.

Another possible explanation for our observations is response priming. With response priming, a prime stimulus aids a subject in responding to a second congruent stimulus (Kiesel et al. [46]). Like perceptual priming, the response priming effect has been shown by Neumann and Klotz in cases where the prime stimulus is subthreshold [47]. Again, most research into this form of priming has used visual stimuli, but the application of response priming effects to haptic experiments, as well as cross-modal effects between vision and touch have been discussed by Proctor et al. [48]. While studies on response priming use interstimulus intervals applicable to our experiment, they consider effects on reaction time, not perceptual accuracy, making the

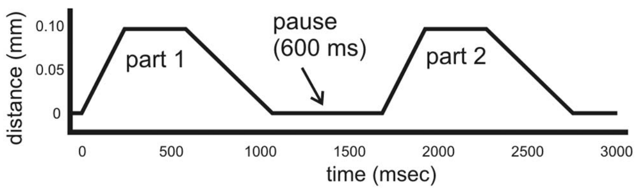

Fig. 13. Sample double-stimulus tactor trajectory. Each double-stimulus includes two out-pause-return moves, separated by a longer 600 msec pause.

conclusions of this research difficult to apply to our experiment.

Our data suggest the presence of priming effects in our experiment, but because of the inapplicability of previous priming research, it is difficult to understand the exact nature of the effect. Still, even without a full understanding of the cognitive factors underlying the observed priming effect, it may be possible to utilize the priming effect to enhance direction communication. With this goal in mind, a second experiment was designed to explore the possible use of priming effects to improve direction identification accuracy.

6.2 Method

A second experiment was designed to test the effects of stimulus repetition. The same hardware and general methods described in Sections 3 and 4 were again used in Experiment 2. This experiment was conducted in two parts: a test of stimuli without repetition (as in Experiment 1) and a test of double stimuli. The single stimulus consisted of a single out-pause-return movement (Fig. 4). The double stimulus repeated the same movement twice, with a 600 msec pause between repetitions (Fig. 13).

Where Experiment 1 covered a large range of stimulus distance and speeds, Experiment 2 focused on a limited subset of these speeds and distances. Four difficult stimuli were selected so as to avoid ceiling effects: distances 0.05 and 0.10 mm and speeds 0.5 and 4 mm/s. Subjects were presented with 16 repetitions of each stimulus in random order. In both parts of the experiment, the single- and double-stimulus tests consisted of 16 unique stimuli $(2 \text{ speeds} \times 2 \text{ distances} \times 4 \text{ directions})$ for a total of 256 stimuli $(16 \text{ stimuli} \times 16 \text{ repetitions})$. The single- and double-stimulus tests required approximately 20 and 30 minutes to complete, respectively. All subjects completed the single-stimulus test first and the two tests were separated by at least two weeks to minimize learning effects.

This experiment was conducted on 15 volunteer subjects. An effort was made to recruit the same subjects as used in the first experiment, but only 10 were available for retesting. These subjects completed the double-stimulus test but were not required to complete the single-stimulus test, as single-stimulus data were available in Experiment 1. A group of five additional subjects were recruited, and these subjects completed both the single-stimulus test and the double-stimulus test. Posthoc analysis found no statistically significant difference in the performance of the two test groups. In all, 15 subjects were tested, 14 male, 1 female, 14 right-hand dominant, 1 left-hand dominant, ranging in age from 22 to 37 years.

Displacement (mm) \ Speed (mm/sec)	0.5	4
Δ	0.5	4
0.1	0.06 ±0.093	0.03 ±0.032
0.05	0.06 ±0.087	0.03 ±0.045

Fig. 14. Mean effect of double stimuli, with 95 percent confidence intervals. The effect was calculated on a within-subjects basis and is equal to the performance on the double stimulus minus the performance on the single stimulus. None of these effects are statistically significant ($\alpha = 0.05$). While recognition rates did mildly improve, we conclude that doubling the stimulus is not a valuable method of improving direction communication.

Data analysis was conducted on a within-subjects basis, with the effect of the double stimulus calculated as the subject's performance on the double stimulus minus the subject's performance on the corresponding single stimulus. These differences were then pooled from all subjects and analyzed.

6.3 Results and Discussion

This experiment sought to prove the hypothesis that repeated, or doubled, stimuli could be used to increase direction communication accuracy. The results, however, do not support this hypothesis. Average performance on double stimuli was slightly better than on single stimuli, but these differences were not statistically significant.

Data were analyzed on a within-subjects basis to establish a difference between the identification accuracy of double stimuli and single stimuli. The results are shown in Fig. 14. For all tested stimuli, small improvements are seen, but these improvements are not statistically significant. Considering these results as they apply to application design, it does not appear that double stimuli would be a useful method to improve direction communication accuracy.

Additional analysis was conducted on these data, analyzing stimulus confusion and the influences of speed, distance, and direction. The results of these analyses agreed well with those in Experiment 1.

The absence of any significant effect from the double stimulus seems at odds with the results of Experiment 1, which showed that subjects were more likely to correctly identify repeated stimuli. The difference between the two experiments that seems to explain this contradiction is the extra subject response in Experiment 1. In Experiment 1, the subject received a single stimulus, responded by clicking on a direction arrow in the GUI, and then, felt a second stimulus. In Experiment 2, the subject received two fast repetitions of the stimulus, without an intervening response. This leads us to the following question: by clicking a visual arrow after the first stimulus in Experiment 1, was the subject primed to respond in that direction on the second stimulus? There is evidence to suggest such priming.

Proctor et al. discussed visual-haptic response priming effects, as well as the relationship between the stimulus and the response mechanism [48]. Easton et al. observed visual-haptic cross-modal perceptual priming effects and concluded that both haptic and visual information share a common abstract representation in the mind [44]. The data from Experiment 1 were reanalyzed to look for possible

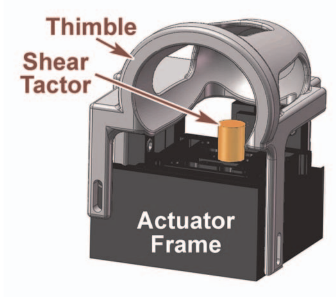

Fig. 15. Miniaturized fingertip shear display concept.

priming effects from the previous subject response. It was found that subjects repeated their previous response on 29.2 percent of trials, which is higher than what would be seen if they were guessing randomly (25 percent) or answering correctly (25.8 percent for the short test and 23.1 percent for the long test). Because this difference is statistically significant ($t(15) = 3.00$, $p = 0.009$), we conclude that subjects were primed by their previous responses.

6.4 Summary of Experiment 2

An experiment was conducted to test the effects of stimulus repetition. It was hypothesized that repeated stimuli would be more effective for direction communication. The results of the experiment hint at some small effect of stimulus repetition, but this effect was not statistically significant and too small to be of any practical value. A reanalysis of data from Experiment 1 suggests that apart from whatever priming was caused by previous stimuli, subjects were primed by their previous responses. This is an interesting observation of priming effects as they apply to general haptic experiments, but it does not have any special implications for the use of our device for direction communication.

7 Future Work

There is great potential for further work on this subject. As we consider using tangential skin displacement in a portable device, we will have to determine how external factors will influence the perception of these haptic cues. One question we will investigate is how direction is perceived when the position and orientation of the user's finger change, similar in spirit to the direction perception work done by Kappers [49]. Additionally, it will be necessary to investigate the cognitive load of interpreting skin displacement cues in applications where the user's attention is divided among multiple tasks and how this might reduce the saliency of the cues. We will also investigate how the skin displacement stimulus can be altered to improve perception accuracy by, for example, removing the tactor from the skin when returning to the center position. Development of a miniaturized skin displacement device will also be necessary for future work and is currently underway. One such design is presented in a separate publication [27] and is depicted in Fig. 15.

8 Conclusion

Tangential skin displacement at the fingertip was found to be well suited to the communication of direction cues. Subjects were able to identify the direction of stimuli as short as 0.2 mm with 95 percent accuracy, without showing evidence of any confusion between directions. This is encouraging, as such small displacements could potentially be rendered by a miniature haptic display capable of integration into mobile electronic devices. Further analysis showed that subjects learn to interpret these direction cues quickly although performance was found to decline slightly after prolonged testing. While some direction-dependent bias exists, unbiased accuracy was found to be approximately equal in all directions. Priming effects were observed, suggesting that earlier stimuli and responses influenced future responses. Contrary to our hypothesis, repeated stimuli were not found to be useful for improving direction communication accuracy.

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