TACTILE SKIN STRETCH FOR DIRECTION COMMUNICATION

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

The study of haptic interfaces focuses on the use of the sense of touch in human-machine interaction. This document presents a detailed investigation of lateral skin stretch at the fingertip as a means of direction communication. Such tactile communication has applications in a variety of situations where traditional audio and visual channels are inconvenient, unsafe, or already saturated. Examples include handheld consumer electronics, where tactile communication would allow a user to control a device without having to look at it, or in-car navigation systems, where the audio and visual directions provided by existing GPS devices can distract the driver's attention away from the road.

Lateral skin stretch, the displacement of the skin of the fingerpad in a plane tangent to the fingerpad, is a highly effective means of communicating directional information. Users are able to correctly identify the direction of skin stretch stimuli with skin displacements as small as 0.1 mm at rates as slow as 2 mm/s. Such stimuli can be rendered by a small, portable device suitable for integration into handheld devices. The design of the device-finger interface affects the ability of the user to perceive the stimuli accurately. A properly designed conical aperture effectively constrains the motion of the finger and provides an interface that is practical for use in handheld devices. When a handheld device renders directional tactile cues on the fingerpad, the user must often mentally rotate those cues from the reference frame of the finger to the world-centered

reference frame where those cues are to be applied. Such mental rotation incurs a cognitive cost, requiring additional time to mentally process the stimuli. The magnitude of these cognitive costs is a function of the angle of rotation, and of the specific orientations of the arm, wrist and finger. Even with the difficulties imposed by required mental rotations, lateral skin stretch is a promising means of communicating information using the sense of touch with potential to substantially improve certain types of human-machine interaction.

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CHAPTER 1

INTRODUCTION

Electronic devices have become an important and ubiquitous source of information, but current information communication technology can significantly limit the utility of these devices. Products such as smart phones, in-car computers, and gaming consoles are used frequently in daily life, while advanced systems like cockpit displays and advanced navigation systems provide critical information in specialized applications. Typically, all of these devices communicate with the user through audio and visual displays such as images, text, spoken words and audible alerts. With the growing quantity of available information has come growing demands on our visual and audio resources, sometimes to the detriment of usability, convenience, or safety. For example, the visual and audio directions from an in-car navigation system can distract a driver from the road [1]. Current smart phone interfaces and touch screens cannot be operated without constant visual attention. In information-rich environments, such as cockpit displays and gaming systems, visual and audio channels are often saturated to the point that users can no longer absorb any additional information [2]. In these and other situations, the total reliance on graphical and auditory interfaces adversely affects the user experience, impacting convenience, function and safety.

In order to alleviate the problems associated with visual- and audio-only interfaces, haptics researchers endeavor to use the sense of touch to supplement or replace traditional methods of human-machine interaction. In situations where traditional interfaces are inconvenient, tactile interfaces provide an alternative means of interaction. For example, a smart phone with a tactile interface could be controlled without requiring visual attention, or without even being taken out of one's pocket. In other cases where one's eyes and ears are needed to maintain safety-critical situation awareness, such as while driving a car or working in a dangerous environment, important information could be communicated by a tactile device.

The research presented in this dissertation addresses one particular type of tactile communication with potential for use in a variety of devices: lateral skin stretch. Lateral skin stretch is the displacement, stretch, and deformation of the skin of the fingerpad in a direction tangent to the surface of the skin. Skin stretch can provide directional information with a simple, easy to interpret, tactile cue. Such a tactile stimulus has potential applications in a range of tasks, such as navigation, interaction with lists and menus, and entertainment. This document presents the results of several studies addressing problems of perception and rendering using lateral skin stretch. Chapter 2 establishes lateral skin stretch as an effective means of direction communication, characterizing the effects of stretch speed and magnitude on perceptual acuity. Experimental results also describe the effectiveness of repeated stimuli, the effects of practice, and direction confusion. Chapter 3 describes the design of a portable device capable of rendering skin stretch, along with experiments characterizing and validating the device, and measurements of the stiffness of *in vivo* skin. Chapter 4 presents refinements of the device interface that are necessary for practical use in a portable device. Experiments evaluate a range of finger restraint designs and compare perceptual acuity between the index finger and thumb. Chapter 5 address a complication inherent in the use of directional tactile cues in a handheld device: the problem of mapping directional information from the reference frame of the fingertip to other, nonaligned reference frames. Experiments explore how users mentally rotate direction cues and how various joint rotations affect the difficulty of interpreting the direction cues. In total, the above experiments provide the necessary background for future work integrating tactile cues into portable devices.

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CHAPTER 2

PERCEPTION OF DIRECTION FOR APPLIED TANGENTIAL SKIN DISPLACEMENT: EFFECTS OF SPEED, DISPLACEMENT AND REPETITION

B. T. Gleeson, S. K. Horschel, and W. R. Provancher, "Perception of Direction for Applied Tangential Skin Displacement: Effects of Speed, Displacement and Repetition," *IEEE Transactions on Haptics,* vol. 3(3), pp. 177-188, 2010.

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 mm-1 mm) and speeds (0.5 mm/s-4 mm/s) were tested. Subjects were asked to respond with the direction of the skin stretch, choosing from 4 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% 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.

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1 INTRODUCTION

TRADITIONALY, 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, non-sensory, 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 micro-slip 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 & Lackner [1], Wasling, et al. [2]) or be used as a tool to evaluate the health of the peripheral and central nervous systems (Olausson & 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.

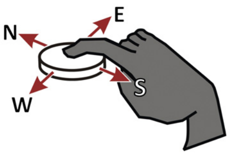

Fig. 1. Communication of direction via tangential skin displacement.

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 & Novak, where electrocutaneous stimulation of the fingerpad was used to communicate vector information, encoding both magnitude and direction [4].

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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 & 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 & 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 4 directions required for simple navigation.

In other related work, Olausson & Norrsell investigated the detection of skin stretch using a 2-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 & Collins found the fingertip to be highly sensitive to spatiotemporal direction cues, with 75% discrimination thresholds for motions in the range 0.1-0.2 mm in a 2-direction test [15]. A broad investigation of spatiotemporal stimulus parameters, including stimulus speed, length, position and orientation, was conducted by Essick & Whitsel [16]. Detection thresholds for saltating spatiotemporal stimuli were investigated by Gardner & 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 highest sensitivity (Johansson & Flanagan [20], 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 its numbing and occasionally uncomfortable after-effects.

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 then 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 & Olausson [23], used an air jet to generate stimuli. A water jet was used by Loomis & Collins [15], a rolling cylinder by Olausson [19], and Gardner & 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 comparing skin stretch and spatiotemporal stimulation, such as those by Norrsell & 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 & 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 4 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 and encoded directional information [28]. This is supported by early work by Vallbo & 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 that 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 & 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 & 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 1250 ticks/revolution, providing position resolution of approximately 0.4 μm. 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 +/-

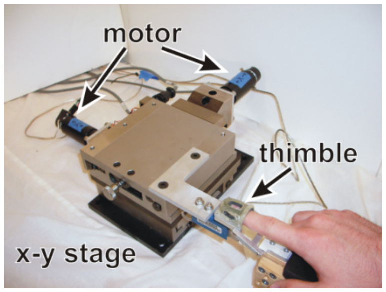


Fig. 2. The test device, a two-axis stage for rendering skin displacement stimuli. The finger is restrained in an open-bottomed thimble.

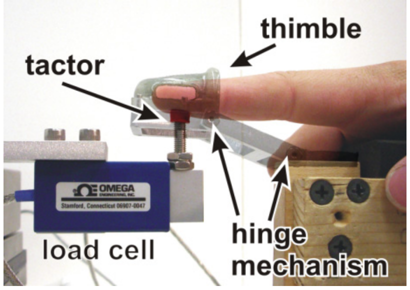


Fig. 3. The tactor in contact with the finger. The thimble and thimble mount are shown translucent so that the finger and tactor can be seen. The thimble is free to move up and down, but constrained in the plane of tactor motion.

0.03%. Off-axis forces affected the readings, however, introducing 4% 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 non-linear 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 all cases, this linear region comprises at least 70% 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 μm and 100 μm. Backlash distances on the x-axis (radial-ulnar axis) and y-axis (proximal-distal axis) were less than 2.7 μm and 4.8 μm, respectively. The motor gearbox and the stage's lead screw nut are the primary sources of backlash. In post-hoc 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 affect on subject performance (for all stimuli, $t<1.35$, $p>0.20$).

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% of the outbound speed to reduce confusion between the outbound

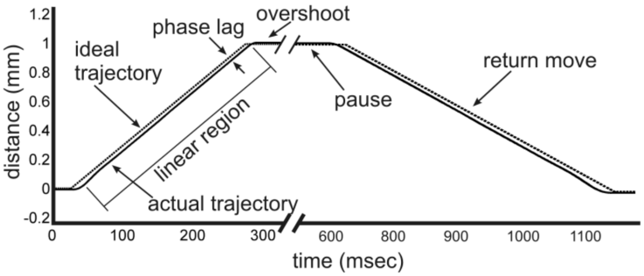


Fig. 4. Sample tactor trajectory. Each stimulus includes an outbound move, a pause (partially omitted in figure), and a slower return move. The device follows a linear trajectory with some phase lag but successfully maintains constant speed and high position accuracy. The linear region used for speed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

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.

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 micro-scale 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.

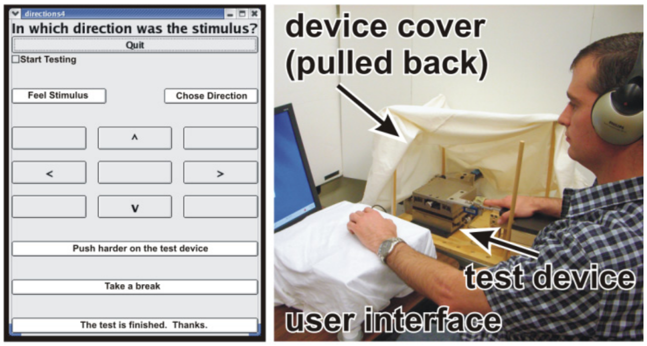


Fig. 5. The test setup. The user sits with his/her right index finger in a thimble with the tactor contacting the fingerpad. The device cover is shown pulled back for documentation purposes only. The graphical user interface used for prompting and recording user responses is shown on the left.

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 displacements * 4 speeds * 4 directions = 80 unique stimuli). Pilot testing showed little variation in 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 because 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 5 subjects, 3 male, 2 female, ranging in age from 26 to 28 years. Of these 5 subjects, 4 were right-hand dominant and 2 were authors involved in the development of the experiment. The short test was completed by 11 subjects, 9 male, 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 that trajectory shape did not significantly affect 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.

User comments confirmed that the three-part move (outbound, pause, 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 J. 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 8 directions, spaced 45 degrees apart. Discrimination of all 8 directions was found to be somewhat difficult and dependent on the position and orientation of the subject's hand. Further tests were limited to 4 directions, as most potential applications for our device would only require the communication of 4 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 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 1-axis load cell. Contact force, averaged over all stimuli and all subjects, was 0.71 N with standard deviation 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% 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 & 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% 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 2 possible directions, where random responses would result in 50% accuracy. In our 4-direction experiment, random responses would

	Speed (mm/sec)			
Displacement (mm)	**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, speeds on the horizontal. Identification accuracy rates and corresponding 95% confidence intervals are shown in the grid squares. The shading of the squares corresponds to accuracy, with lighter color indicating higher accuracy.

result in 25% accuracy.

Other research has sought to indentify 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 & 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%) accuracy was desired, a stimulus of 0.2 mm 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% 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.

5.3.2 *Influence of Speed and Displacement*

Looking again at 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. 8 (top). Each curve in Fig. 8 (top) was independently subjected to an omnibus ANOVA test and Tukey's Honest Significant Difference, performed with $\alpha = 0.05$. The improvement in accuracy is statistically significant (for all velocities: $F(4, 64) > 18$, $p < 0.001$). 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 ($\alpha = 0.05$).

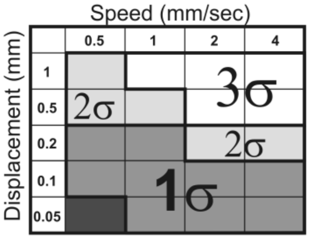
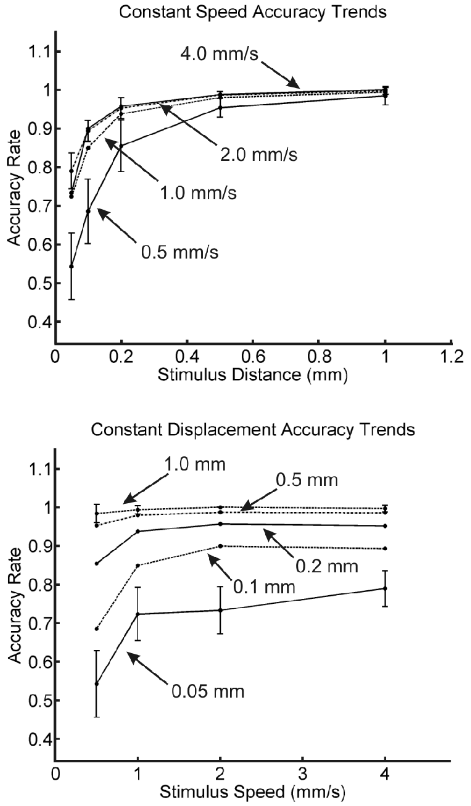


Fig. 7. Experimental results from Fig. 6, broken into regions corresponding to the 1-, 2- and 3-σ points (approximately 68%, 95%, and 99% accuracy, respectively). Given some design criterion, e.g. 95% accuracy in direction communication, this plot makes clear the range of stimuli from which one could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


Constant Speed Accuracy Trends

Constant Displacement Accuracy Trends

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

When the skin was displaced 1 mm at any of the tested speeds, the user identified the direction correctly almost 100% of the time. At 1 mm of displacement, there were occasional incorrect responses at speeds of 0.5 mm/s 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. 8 (bottom)). For stimuli with displacements of 0.05 mm through 0.5 mm, there is a statistically significant improvement in accuracy as speed increases ($F(3, 60) > 5.0$, $p < 0.01$). 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 towards certain directions, there is no evidence of confusion between the different direction cues.

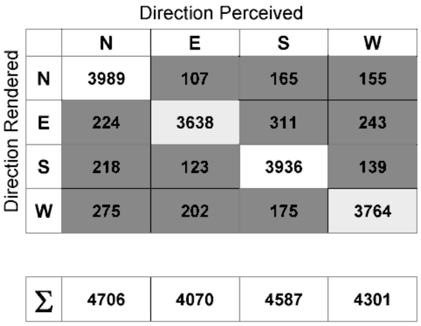
When considering the use of haptic cues for navigation, it is important to know how easily cues will be misinterpreted. It would be problematic if directions were easily confused. A confusion matrix was assembled from all pooled data to compare rendered directions and perceived directions (Fig. 9). Each 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 discussed in the following section.

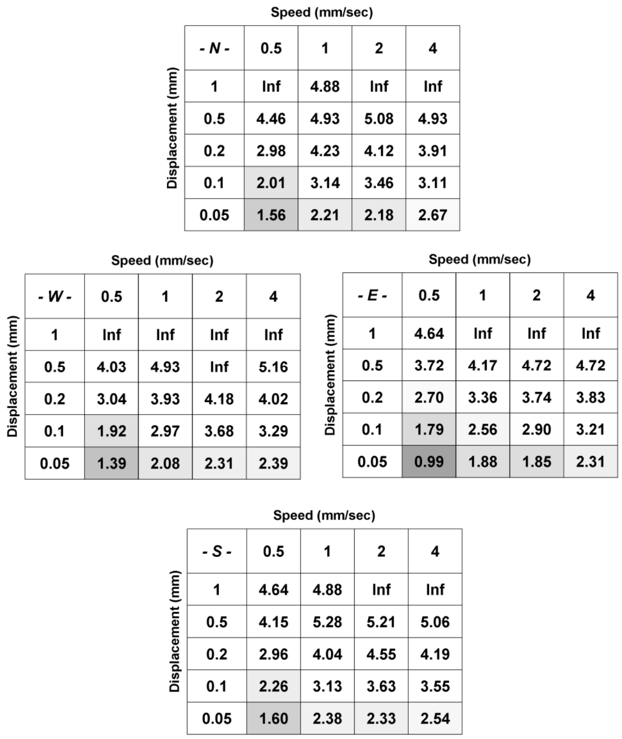
5.3.4 Influence of Direction

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 towards 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 & 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.



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 (4416 stimuli were rendered in each direction). There is no evidence of stimulus confusion, however, there appears to a response bias towards North and, to a lesser extent, South.



Speed (mm/sec)

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

Speed (mm/sec)

Displacement (mm) - 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

Speed (mm/sec)

Displacement (mm) - 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

Speed (mm/sec)

Displacement (mm) - 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.

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 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 nailbed. 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 nailbed 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 to the North [11]. Using a powered trackball-type display, Keyson and Houtsma concluded that sensitivity is greatest towards 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 towards 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 micro-slip, 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 towards the North, SA-II towards the South, and FA-I towards the South and East. If different stimulators 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], 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 performance between blocks. To remove any effects arising from the differences between subjects, difference scores were computed for each test block as 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% over the 15 minute section for the long and short tests, respectively. This trend was statistically significant (short tests: $r_s = -0.460$, $p < 0.0001$; long tests: $r_s = -0.239$, $p = 0.039$). After taking a rest break, the subject 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 ($r_s = 0.0009$, $p = 0.981$). Data from the long test showed a slight decrease in performance (2.4% over the entire test) which was significant ($r_s = -0.238$, $p < 0.0001$), 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 results 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 application that did not involve prolonged use, the temporal decline in 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 non-repeated 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 that 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 & 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 & Martin [41]). Interestingly, this effect has been observed by Bar & 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 & Reales [43], 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

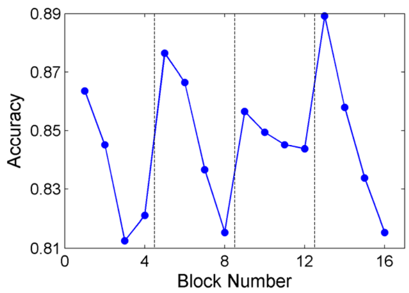
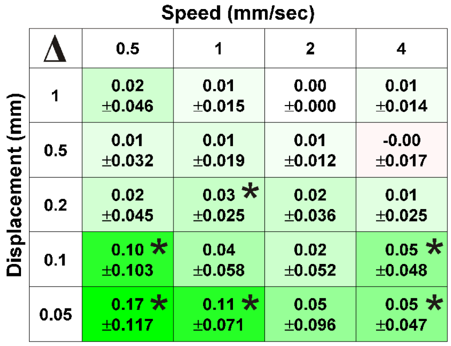


Fig. 11. Temporal trends, pooled across all subjects who participated in the short experiment. Rest break periods are shown by vertical dashed lines. Performance declined with prolonged testing but recovered after a rest break. This trend was statistically significant. No significant learning trends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



Δ	Speed (mm/sec)			
Displacement (mm)	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 non-repeated stimuli. Thus, positive numbers indicated an increase in performance due to repetition. 95% confidence intervals are also shown. The asterisks (*) mark those effects which are statistically significant (α = 0.05).

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 & Klotz in cases where the prime stimulus is sub-threshold [47]. Again, most research into this form of priming has used visual stimuli, but the application of response priming affects 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 inter-stimulus intervals applicable to our experiment, they consider effects on reaction time, not perceptual accuracy, making the 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 mm & 0.10 mm and speeds 0.5 mm/s & 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 speeds x 2 distances x 4 directions) for a total of 256 stimuli (16 stimuli x 16 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 2 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 re-testing. These subjects completed the double-stimulus test but were not required to complete the single-stimulus test, as single-stimulus data were available from Experiment 1. A group of 5 additional subjects were recruited, and these subjects completed both the single-stimulus test and the double-stimulus test. Post-hoc 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.

Data analysis was conducted on a within-subjects basis, with 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.

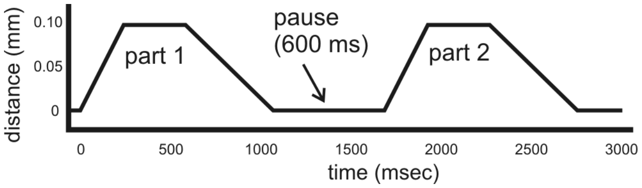


Fig. 13. Sample double-stimulus tactor trajectory. Each double-stimulus includes two out-pause-return moves, separated by a longer, 600 msec pause.

6.3 Results and Discussion

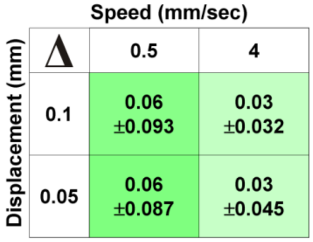
This experiment sought to prove the hypothesis that repeated, or doubled, stimuli could be used to increase direction communication accuracy. The results, however, do not support this hypothesis. Average performance on double stimuli was slightly better than on single stimuli, but these differences were 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 from 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 priming effects from the previous subject response. It was found that subjects repeated their previous response on 29.2% of trials, which is higher than what would be seen if they were guessing randomly (25%) or answering correctly (25.8% for the short test, 23.1% 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.



Displacement (mm)	Speed (mm/sec)	
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% 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 (α = 0.05). While recognition rates did mildly improve, we conclude that doubling the stimulus is not a valuable method of improving direction communication.

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 changes, 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% 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.

ACKNOWLEDGMENT

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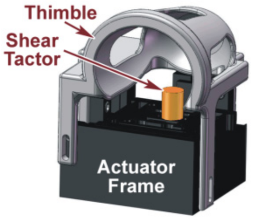

Fig. 15. Miniaturized fingertip shear display concept.

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CHAPTER 3

DESIGN OF A FINGERTIP-MOUNTED TACTILE DISPLAY WITH TANGENTIAL SKIN DISPLACEMENT FEEDBACK

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Abstract—Application of tangential skin displacement at the fingertip has been shown to be effective in communicating direction and has potential for several applications. We have developed a portable, fingertip-mounted tactile display capable of displacing and stretching the skin of the fingerpad using a 7 mm hemispherical tactor. In vivo tests of fingerpad skin stiffness were performed to determine the forces required for effectively rendering stimuli. Other design parameters such as stimulus speed and displacement were derived from our earlier work. The tactile display is capable of rendering ±1 mm of displacement at arbitrary orientations within a plane and with rates of approximately 5 mm/s. Compliance and backlash in the device's drive train were characterized using external measurements and were compensated for in software to reduce the impact on device hysteresis.

◆

1 INTRODUCTION

Humans are highly sensitive to tangential skin displacement at the fingertip and there is great potential for using this stimulus in diverse applications. A variety of users, ranging from a driver on unfamiliar roads to a soldier in an urban setting, could benefit from haptic navigation cues, shown schematically in Fig. 1. Haptic cues have the advantage of leaving the user's eyes and ears free for safety-critical situational awareness. In this paper we present a haptic direction display with potential for integration into portable, handheld devices.

Our previous research has suggested that tangential skin displacement, inducing shear forces and lateral skin stretch at the fingertip, is an effective means of communicating navigational cues [1]. In another potential application, a directional display could be integrated into a computer interface, e.g. a laptop TrackPoint mouse interface, to direct a user's attention to important on-screen information or for use as an all-purpose input/output device. Early work by Gould et al. suggests tangential skin displacement as the ideal means for direction communication, having greater perceptibility than stimuli which slip along the skin, moving normal forces, and pin arrays [2]. More recent findings by Norrsell and Olausson, among others, agree that humans are more sensitive to directional skin stretch than to other tactile directional cues such as skin slip [3]. Several researchers, including Drewing et al. [4], Keyson & Houtsma [5], Placencia et al. [6], and Vitello et al. [7] have sought to characterize thresholds of direction discrimination of lateral skin stretch at the fingertip. While these researchers disagree in their specific findings, their data all suggest that skin stretch could be used for communication of navigational and directional cuing information. Additionally, medical research has found skin stretch at the fingertip to be a useful aid for disabled patients to better control posture and balance (Wasling et al. [8], Dickstein [9]). All of these applications would require a small, portable display, which we have developed and describe in this paper.

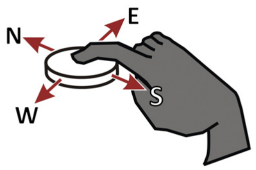

Fig. 1 Communication of direction through tangential skin displacement at the fingertip.

A few fingertip-based devices capable of rendering tactile direction information have been previously developed. Zhou and Miyaoka used a 2-D linear motor developed by Fuji Xerox to impart skin stretch in a Braille-like mouse interface. This device is well suited as a desktop computer interface but is not practical for many mobile applications due to the large footprint and high power demands of the linear motor [10]. Webster et al. developed a small powered trackball-type device, mounted to the end of Phantom haptic device, to render both skin stretch and slip [11]. The trackball-type design is capable of imparting very long slip sensations, but the production of slip is not necessary for our applications. Tsagarakis et al. developed a wearable, fingertip-mounted slip display using two conical rollers, but like the Webster et al. device, this device was designed to render continuous slip sensations rather than directional skin stretch [12]. As we did not seek to render slip, we designed a compact device capable of displacing the skin to render shear forces and lateral skin stretch only.

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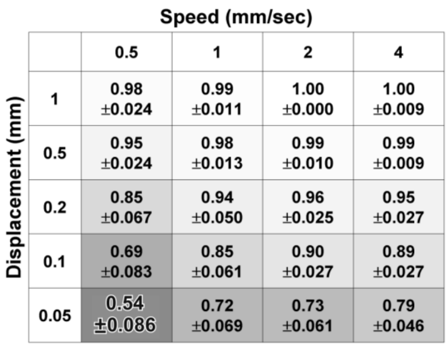
Other researchers have used wearable devices to communicate direction. Direction cues have been effectively rendered using arrays of vibrating motors, as was done by Van Erp, who placed vibrators on a wearable belt [13]. Vibrotactile stimulation, however, is not suitable for integration into small devices, as vibrators typically require large spatial separation in order to be discernable. Another wearable device was developed by Bark et al. to rotationally stretch the skin of the forearm as a substitute for proprioceptive feedback [14]. While wearable devices have been shown to be effective, we sought instead to develop a device with potential for integration into handheld devices.

2 DESIGN REQUIREMENTS AND FINGERPAD CHARACTERIZATION

In previous experiments we characterized important factors for the communication of direction through tangential skin displacement at the fingertip [15]. These experiments were conducted with a large bench-top device, but their results have established the design parameters for our fingertip-mounted device. In these prior experiments we found that stimulus speed and displacement are both important, with larger displacements and faster speeds resulting in greater communication accuracy (see Fig. 2). From these experiments, we concluded that speeds of 2 mm/s and displacements of 0.2 mm were sufficient to communicate direction with high accuracy. However, in an application where the user's attention is shared with other tasks, we would expect lower accuracy rates. We therefore set design requirements to achieve 99+% communication accuracy for our fingertip-mounted display, specifying minimum device displacement and speed requirements of 0.5 mm and 2 mm/s.

To choose appropriate actuators for our device, it was necessary to characterize the stiffness of the fingerpad and understand the forces that would be required for the application of the specified displacement. Wang and Hayward have performed in vivo measurements of fingerpad load-displacement behavior using ~1 mm instrumented tweezers [16]. However, we require data more specific to our device. That is, we need information about the interaction between the skin and our specific (7 mm) tactor, in our required range of speeds and displacements. To provide this data, a series of in vivo measurements were taken to characterize the interaction between our device and the skin.



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. 2. Results of previous direction identification experiments. Each cell shows the accuracy rate and corresponding 95% confidence interval for a range of stimulus displacements and speeds. Cell shading corresponds to accuracy rates. These results are used as design guidelines for our portable tactile display.

Volunteer subjects were recruited for a series of skin force measurements. Six unpaid subjects were tested, four male, two female, ranging in age from 21 to 36 years. Five of the subjects were right hand dominant and one was left hand dominant. The right index finger of each subject was restrained with a splint and foam pads at the middle phalanx. The distal fingerpad was brought into contact with the tactor used in our finger-mounted device (~7 mm textured rubber ThinkPad TrackPoint tactor). The tactor was mounted to a custom-built 3-axis force sensor that was attached to a bench-top, 2 degree-of-freedom, leadscrew driven stage. Both the stage and the force sensor are described in [17]. The stage was driven 2 mm in four orthogonal directions (distal, proximal, radial and ulnar) at 4 mm/s under computer control. During each movement, the forces between the finger and the tactor were recorded using a Sensoray 626 data acquisition card at 1 kHz. The custom force sensor had a range of ±14 N and sensitivity of ~0.8 mN/bit. To best simulate realistic use of the device, subjects were permitted to apply a normal force that felt comfortable and that was sufficient to prevent macroscopic slip between the finger and the tactor. Applied normal forces were between 0.5 and 1.5 N. As discussed in our earlier work [15] we expect that some micro-slip occurred between the tactor and the skin, particularly around the edges of the tactor. The experiment was conducted with approval of the University of Utah Institutional Review Board.

At the speed and displacement used in this experiment, the force-displacement relationship was observed to be nearly linear. After discarding those data affected by acceleration transients at the start of each movement, a line was fit to the remaining data, the slope of which is the measured linear stiffness of the skin. Data measured in the distal direction, along with fit lines, are shown for all six subjects in Fig. 3. These data are characteristic of all four directions. The range of measured stiffnesses in all four directions is tabulated in Table 1. Cardinal directions shown in the table correspond to those in Fig. 1

Our measurements indicate a large variation in fingerpad stiffness between subjects, possibly due, in part, to variations in applied normal force. This variation is in agreement with the observations of Wang & Hayward [16]. For some subjects, the fingerpad is quite stiff, approaching 4 N/mm in the distal direction. Thus, if we hope to render displacement of 0.5 mm or greater for all users, we will require actuators with an output force of at least 2 N.

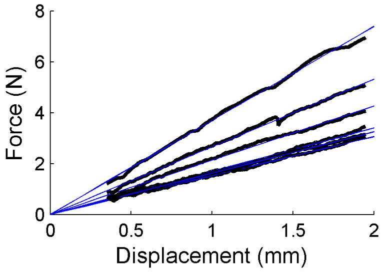


Fig. 3: Force-displacement curves and fit lines for the interaction between the 7 mm tactor and fingerpad. A large range of fingerpad stiffnesses are observed, but all curves are nearly linear. This plot shows measured force-displacement behavior in the distal direction. Results are tabulated in Table 1 for all four orthogonal directions (distal, proximal, radial and ulnar).

3 DEVICE DESIGN

Various design concepts were considered and prototyped, but a device driven by radio-controlled (RC) hobby servos was found to best deliver the high forces that were suggested by our finger stiffness characterization experiments. The fingertip-mounted directional display is built around two servo motors manufactured for the radio-controlled hobby market (Cirrus CS101 Micro Servo; specified torque 98 mN-m). Fig. 4 shows a photograph of the completed device. An exploded view of the device is depicted in Fig. 5, along with the device reference frame. The assembled device has a mass of 39 g. For more detail, see [18].

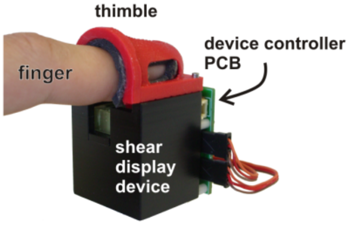


Fig. 4. Photo of tactile display with printed circuit board (PCB) control electronics.

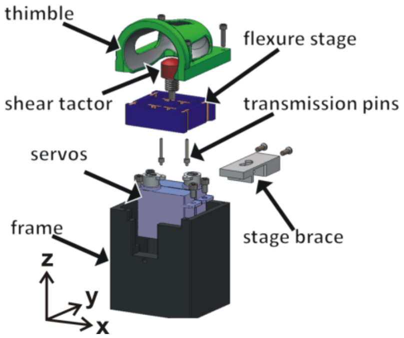


Fig. 5. Exploded assembly view of tactile display, along with device reference frame.

The device uses two RC servos and a compliant flexure stage to create planar motion. The servos can operate simultaneously, allowing motion along any path in a plane. Pins protrude upward from each RC servo output arm into orthogonal slots in the flexure. The flexure is designed such that rotation of a single RC servo induces motion on a single axis. Slots in the

TABLE 1
LATERAL FINGERPAD STIFFNESS IN FOUR DIRECTIONS.

(N/mm)	Proximal (S)	Distal (N)	Radial (W)	Ulnar (E)
min	0.89	1.53	0.87	0.79
mean	1.58	2.22	1.37	1.18
max	2.49	3.69	1.94	1.84
std. dev.	0.66	0.83	0.40	0.37

flexure stage allow the transmission pins to move freely when the opposite servo is actuated, thus decoupling the motions of the two servos. This flexure also serves to decouple the tactor from the small vibrations of the servo gears. The calculated force of the servos on the tactor is 25.1 N, well in excess of the 2 N requirement. The device is capable of rendering displacements greater than ±1 mm on each axis.

The device interacts with the fingerpad through a shear tactor, as seen in Fig. 5. The tactor is a textured rubber ThinkPad TrackPoint interface 7 mm in diameter. This tactor was chosen based on pilot experiments conducted during our earlier research [15]. The fine scale texture on this TrackPoint tactor accentuates applied direction sensations, has high friction to prevent slip, and is widely available.

3.1 Flexure Design

The flexure stage was molded from two different urethanes: one soft urethane (90A shore hardness, IE-90A from Innovative Polymers) and one hard urethane (80D shore hardness IE-80D from Innovative Polymers). The harder urethane formed the main structure of the device while the softer urethane was used to make flexible joints (Fig. 6). The flexure was manufactured through sequential machining and casting operations using Shape Deposition Manufacturing (SDM). SDM uses wax tooling blocks and a CNC milling machine to create molds into which urethane polymers are cast and subsequently machined [19].

To reduce bending compliance between the servo arms and the slots of the SDM flexure, a press-fit tube was bonded to the base of the transmission pins, thus improving the cantilever stiffness between the transmission pins and the servo arms. Additionally, a brace plate was placed below the flexure stage to prevent the stage from deforming downward out-of-plane due to applied finger pressure on the tactor.

3.2 Device electronics and control

The control of the device is accomplished by using a microcontroller (MCU) and custom electronics. The rotational position of the servos is controlled by sending a 50 Hz Pulse Width Modulated (PWM) signal to each servo. Output positions of 0° to 180° are commanded by varying the pulse from approximately 1 to 2 msec in length. The PWM signal is generated by a dsPIC30F2012 MCU programmed to accept input commands from a variety of sources.

A printed circuit board (PCB) was fabricated to facilitate interaction between the user and the display device. The PCB accepts three different control inputs: analog inputs from a 2-DOF analog joystick, parallel digital inputs from a push-button controller, and asynchronous serial (RS-232) inputs. Wired and wireless remote controls with pushbuttons were developed to communicate repeatable signals to the user. The remote control features four direction buttons and can automatically generate repeated stimuli (outbound motion then return to center, ~1x per 2 sec) using timing features programmed on the device MCU. An RS-232 serial communication input to the device enables the display to be controlled by a PC, which is useful for conducting structured experiments.

Power requirements vary with usage, but the device has been found to run for approximately 2 hours of near-continuous use on four 1000 mA-h AAA batteries. This battery life is sufficient for our experimental goals.

4 DEVICE CHARACTERIZATION AND PERFORMANCE

Device backlash, movement speed and repeatability were characterized through empirical testing. The display was found to exhibit significant hysteresis, but much of this was

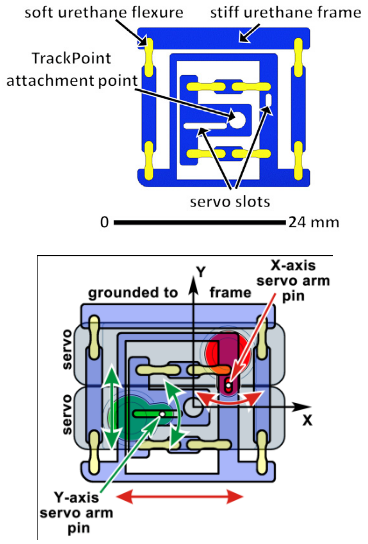


Fig. 6. (left) The SDM flexure stage is comprised of two different materials, stiff urethane for the main support frame and soft urethane for the flexible connections. The slots in the flexure stage allow the pins to couple motions of each servo to only a single axis of motion and prevents the mechanism from becoming over-constrained. The flexure is 7 mm thick. (right) Translucent view (without device frame) showing how the pins on the servo output arms couple with slots in the flexure stage.

corrected for in the control software. The varying properties of different user's fingers affected the rendered stimulus distances, but stimuli were still highly repeatable for any given subject. Because stimuli were rendered at levels that can be easily perceived by subjects, all uncorrected stimulus errors were small enough to permit the use of the device in experiments with both between-subjects and within-subjects experiment designs.

4.1 Characterization Methods

Two different characterization methods were employed: one to gather position data and second for velocity data. Position was measured by placing the tactile display in a vise and affixing the probe of a dial indicator to the tactor just below where the tactor contacts the finger. Care was taken to assure that the probe did not interfere with the finger or the flexure stage. The bias-spring was removed from the dial indicator so that the indicator did not apply any appreciable force to the test device. All characterization was done with a finger in the device's thimble and pressing down on the tactor. The characterization processes was completed independently for the two axes of the device.

For velocity and motion profile measurement, data were acquired using an infrared range sensor, as described by Gleeson & Provancher [20] with a Kodak 18% gray card attached to the tactor. The tactile display was moved along its entire travel in orthogonal directions and the motion profile was recorded. A line was fit to the data to determine the average velocity of the tactor. These measurements were repeated twenty times in each direction and the results were averaged. This procedure was completed with the device both loaded and unloaded. These tests used a block of foam rubber as a simulated finger load, providing isotropic resistance and a constant normal force (approx. 1 N). The stiffness of the foam rubber was measured to be 1.6 N/mm, which is within the range of measured fingerpad stiffnesses. A real finger could not be used during velocity measurements because of the difficulty of maintaining constant normal force on the moving tactor.

4.2 Hysteresis

A simple test was conducted to characterize device hysteresis. Each axis was moved along its entire travel, in both directions, while position data were recorded. This was repeated four times for each axis. A representative hysteresis curve for the y-axis is shown in Fig. 7. The x- axis exhibits similar characteristics. The affects of hysteresis were repeatable and showed the strong effects of backlash and compliance at both ends of travel. Knowledge of this behavior informed how stimuli were tuned.

4.3 Tactor Motion Profile

The loaded and unloaded motion profiles of the tactor were observed to be approximately linear. A typical motion profile is shown in Fig. 8. The average velocities of the tactile display, unloaded and loaded, were 8.7 mm/s and 5.6 mm/s, respectively. The velocity was observed to vary as a function of direction, varying as much as 2.2 mm/s slower than the mean. These variations cannot be explained by device construction or mechanism geometry, but could be an effect of anisotropy in the internal servo position control or could be due to manufacturing variances in the servos. However, since the slowest observed velocity (3.4 mm/s) is well above our design specification of 2 mm/s, these variations are not a concern. Additionally, it was observed in Gleeson et al. that subject performance was largely insensitive to changes in stimulus velocity, for all velocities above 1 mm/s (Fig. 2) [15].

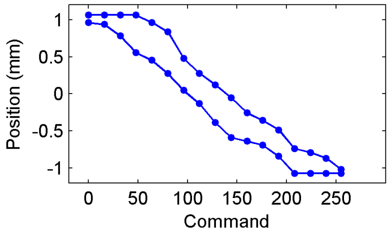


Fig. 7. A single hysteresis loop for y-axis tactor motion of the tactile display. Position is shown as a function of the input command. Input commands to the device's RC Servos were PWM signals encoding positions with 8-bit resolution (0-255 corresponding to 1-2 msec. pulses). The effects of backlash and compliance can be seen at both ends of the curve.

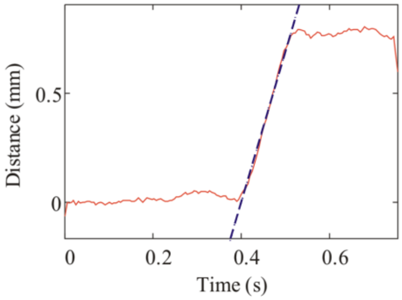


Fig. 8. Motion profile for the loaded tactile display with fit line.

4.4 Stimulus Tuning

Using the information obtained from the hysteresis curves, a control method was developed and tuned to help correct for compliance and backlash. The device was capable of rendering motions up to ±2 mm but due to compliance in the system, this was reduced to approximately ±1 mm when loaded. Seeking to render stimuli as clearly as possible, the displacement and repeatability of the rendered stimuli were maximized. To account for backlash, state-dependent commands were empirically determined for stimuli in four orthogonal directions. A controller was implemented in software that recorded past movements, predicted the backlash state, and issued the appropriate commands.

4.5 Mechanical Performance Verification

Participants were recruited with a variety of finger sizes and tested to verify the performance of the device. Six male subjects were tested, aged 21 to 36 years. Each test consisted of 10 movements, going from center, to positive displacement, back to center, and to negative displacement. This was repeated on both axes. At each location, the position of the tactor was measured with the modified dial indicator.

Device performance varied between subjects, but was quite constant for each individual subject. The controller did not compensate perfectly for hysteresis with all subjects, due to the varying stiffness of subjects' fingerpads. See Fig. 9 for a simplified schematic illustration of the device-finger interaction. The motor applies force and position, x_1, is measured internal to the servo. The resultant position of the tactor, x_2, depends on k_1, the stiffness of the flexure, and k_2, the stiffness of the fingerpad. The stiffness of the flexure is constant, but the stiffness of the fingerpad is variable between subjects. With k_2 unknown, it is not possible to precisely control the position of the tactor, x_2, without individual calibration. This is a limitation of the device design, but an acceptable one, as will be shown.

The consequence of the variable fingertip stiffness is that hysteresis could not be entirely eliminated for all subjects. Thus, some uncorrectable error in rendered stimulus displacement remained. The average lengths of the rendered stimuli on each axis, along with RMS error are 1.10 ±0.10 mm and 0.99 ±0.10 mm for the X- and Y-axes, respectively. This remaining position error was found to be negligibly small. Before the implementation of state-dependent hysteresis correction, position errors exceeded 0.5 mm.

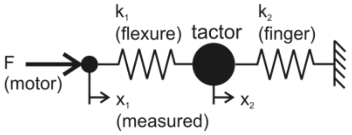


Fig. 9. A simplified schematic of device-finger interaction. With the stiffness k_2 variable between subjects, it is not possible to precisely control the position of the tactor, x_2, without tuning the device for each user.

While the actual length of the rendered stimuli varied between subjects, stimuli varied little for each individual subject, as measured by the distribution of rendered stimuli. The average within-subjects standard deviation of rendered stimulus distances was around 0.05 mm.

4.6 Device Validation Perceptual Experiment

The ability of the device to effectively communicate direction was confirmed in a short user study. Participants wore the portable shear display on their right index finger and were asked to identify the direction of 32 randomly ordered stimuli. Responses were entered using the arrow keys of a computer keyboard. This validation study was conducted as part of a larger experiment, and due to the nature of that experiment, stimuli were only presented in two directions: left and right. The experiment was conducted on 10 subjects, 5 female, all right handed and ranging in age from 20 to 26 years (average age, 23 years). Subjects were compensated for their time. The experiment was conducted with the approval of the Purdue University Institutional Review Board.

All subjects correctly identified the direction of 100% of the stimuli. Because rendering errors are similarly small on both axes (Section 4.5) and because users perceive the stimuli equally well on both axes ([1]), the results of this study can be generalized to stimuli in the proximal-distal direction. Although this experiment was conducted using only two directions, the error-free subject performance strongly supports the use of this device for effective tactile direction communication.

4.7 Discussion

Because fingerpad stiffness varies between users, the device did not perform exactly the same for all subjects. The error resulting from fingerpad stiffness variability, however, is negligible. Our previous direction identification experiments characterized identification accuracy over a range of stimulus speeds and displacements (Fig. 2) [15]. For the speed at which the miniature shear display operates, 5.6 mm/s, these experiments found accuracies of 99+% for displacements larger than 0.5 mm. Because all stimuli rendered by the miniature shear display are approximately 1 mm, we can be certain that direction will be accurately communicated. This conclusion is supported by the results of a human-subjects direction identification experiment.

5 CONCLUSIONS AND FUTURE WORK

We have designed, built, and tested a fingertip-mounted tactile device to render tangential skin displacement at the fingertip. Device design parameters were derived from earlier research and in vivo measurements of fingerpad stiffness. A compliant flexure stage is used to transform the rotation of two RC hobby servos into planar, translational motions. The compliance of the flexure, along with backlash in the servo gears, results in significant device hysteresis. This hysteresis is largely corrected for by control software, but the variation in fingerpad stiffness between subjects resulted in some uncorrectable error. Results from earlier research and validation tests on human subjects show that remaining error is unimportant. In the future, our portable device will enable us to conduct application experiments with mobile subjects receiving navigation cues at their fingertip. We will also investigate complicating factors, such as how direction information is perceived when the position and orientation of the user’s finger changes. Further device refinements and miniaturization are being considered.

ACKNOWLEDGMENT

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CHAPTER 4

PERCEPTION IMPROVED TACTILE SHEAR FEEDBACK: TACTOR DESIGN AND AN APERTURE-BASED RESTRAINT

© 2010 IEEE. Reprinted, with permission, from IEEE Transactions on Haptics, B. T. Gleeson, C. A. Stewart, and W. R. Provancher, "Improved Tactile Shear Feedback: Tactor Design and an Aperture-Based Restraint," *In Press, IEEE Trans. on Haptics,* 2010.

Abstract—Tactile feedback could replace or augment visual and auditory communication in a range of important applications. This paper advances the field of tactile communication by presenting performance data on a variety of tactors and a finger restraint that is suitable for use in portable devices. Tactors, the contact elements between the device and the skin, and finger restraints were evaluated using a tangential skin displacement direction-identification task. We tested tactors of three sizes and two different textures. Rough textured tactors improved communication accuracy compared to smooth tactors, but tactor size did not have a statistically significant effect. Aperture-based restraints of three sizes were evaluated on both the index finger and the thumb. The aperture-based restraint was effective when used on both the index finger and the thumb, with performances on par with our previously tested thimble-based restraint. Participants performed better with larger apertures than with smaller apertures, but there was no interaction between aperture size and finger size, meaning that the same aperture could be used with a range of finger sizes. Subjects' perceptual acuity varied with stimulus direction. We discuss the effects of contact force, finger size, and differences in perceptual acuity between the index finger and thumb.

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1 INTRODUCTION

AS electronic devices have become more powerful and more ubiquitous, we have to come to rely on them as a source of useful, everyday information. With this increase in available information, however, has come an increased demand on our attention. The majority of electronic devices communicate through visual and auditory channels. In some situations, these modes of communication can distract a user from their environment, causing inconvenience and safety hazards. In applications where a person's visual and auditory channels are saturated, or are needed for other tasks, haptic communication could be used as a third channel for information. The cognitive advantages of haptic communication in situations of visual and auditory information overload are described by Wickens [1].

The development of an effective and practical means of communicating navigational information through haptic cues could improve the safety and convenience of common tasks where a person's eyes and ears are occupied with safety-critical observation of the environment. Navigational information is typically communicated visually (e.g., a map, a GPS display) or auditorily (e.g., spoken directions from a person or GPS). For a driver in traffic, a soldier in combat, or an emergency worker in a disaster area, this visual and auditory communication makes additional demands on one's attention, potentially impeding one's ability to observe the environment and to maintain situation awareness. As an example, Kun et al. [2] observed that the visual information provided by a GPS display distracts attention from the road and impacts certain driving abilities. A haptically-enabled navigation system, however, would leave a user's eyes and ears free, reducing distraction and potentially improving safety. In other applications, haptic cues could be employed to improve the convenience or utility of common devices such as phones and music players.

In our current research we focus on tangential skin displacement at the fingertip as a means of communicating directional information. Our previous work has established the efficacy of this form of haptic communication [3]. Before a haptic direction display can be integrated into devices like a steering wheel or a mobile phone, certain requirements must be met. The user must be able to interface with the haptic display in a way that is convenient, effective for haptic communication, and amenable to ergonomic device design. Towards this goal, we investigated a simple aperture-based restraint: a tapered hole that restrains the motion of the finger and allows the user's fingerpad to contact the haptic device. Such an interface could be integrated into a range of devices without encumbering the user. This paper evaluates the efficacy of this aperture-based restraint and discusses the effects of finger size and aperture size. To provide a greater range of ergonomic design options, we evaluate the aperture-based restraint on both the index finger and the thumb. In addition to having a practical finger restraint, the haptic device must contact the finger in such a way as to maximize

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communication accuracy. In this paper, we also test a range of tactor (haptic contact element) designs, evaluating the importance of tactor size and texture on communication accuracy.

2 BACKGROUND

2.1 Haptic Direction Cues

Several researchers previously addressed haptic communication of direction using a variety of methods. Tan et al. used an array of vibrating motors embedded in a vest to communicate direction [4] and later used similar vibrotactors embedded in the back of a chair to direct a user's attention to a specific location on a computer monitor [5]. Van Erp also successfully used vibrotactile feedback for the communication of direction, placing the vibrating motors in a belt around the torso [6]. Vibrotactile feedback to provide direction cues proved effective in these wearable devices and has been used in a steering wheel (e.g., Kern et al. [7]), but is not suitable for integration into portable devices for mechanical reasons; delivering several discrete vibratory signals to an area as small as the fingertip, and packaging the actuators into a small, portable device, would be a significant engineering challenge. Lylykangas et al. used the forces exerted by a single leadscrew pressed against the fingertip to communicate direction, but were only able to communicate three directions [8]. Eves & Novak developed an electrocutaneous display capable of communicating both direction and magnitude [9]. Wang et al. have used an array of bending piezoelectric pins to provided small amounts of localized skin stretch and were able to communicate direction using saltating stimuli [10]. In our previous work, we communicated direction using tangential skin displacement, as described below.

2.2 Tangential Skin Displacement

While a variety of haptic stimuli can be effective in communicating direction information, we focus on tangential skin displacement in our research. In our implementation of this form of haptic communication, the fingerpad is pressed against a hemispherical rubber tactor, which moves laterally in a given direction, applying a shear force and displacing the skin. The nature of this stimulus is somewhat complex, with multiple sensations contributing to the perceptual experience. We believe that the most salient factors are the displacement and stretching of the skin, but other important factors may include vibration from the device and micro-slip of the tactor on the skin. The perception of skin stretch and shear force is mediated through SA-II afferent nerves, with contributions from SA-I and FA-I afferents, as shown by Birznieks et al., Vallbo & Johansson, Srinivassan, and Olausson et al., among others [11] [12] [13] [14].

In our earlier work, this type of haptic stimulus has proven effective for the communication of direction. A study of stimulus magnitude and speed found that both factors contribute to communication accuracy, with correct direction identification rates increasing with longer displacements and faster speeds [3]. In a bench-top study testing four-direction identification, subjects achieved accuracy rates better than 99% with displacements of 0.5 mm or more and at speeds of 2 mm/s and above. With displacements as small as 0.2 mm, accuracy rates of 95% were still possible. It is important to note, however, that such high accuracy rates might be difficult to achieve in applications where the user’s attention may be divided between multiple tasks or where the orientation of the hand is variable. As a step towards the integration of these haptic stimuli into common devices, we have developed a miniaturized, wearable version of the skin displacement display [15].

In our experiments we have only asked subjects to distinguish between stimuli in four cardinal directions. Other researchers have tested stimuli with continuously variable direction to characterize subjects' angular discrimination threshold for skin stretch and tangential skin displacement. Keyson & Houtsma used a large, powered trackball-type device and found angular thresholds of approximately 14 degrees [16]. Drewing et al. stretched the skin with a 1 mm diameter steel cylinder and found different angular thresholds for different people, ranging from 14 to 34 degrees [17]. Vitello et al. used the same device in a different experiment and found thresholds from 30 to 40 degrees [18]. Placencia et al. also characterized the angular discrimination tangential skin displacement, using a 6 mm diameter rounded nylon probe, but did not report their results in a way than can be easily compared to the above studies [19]. While these studies disagree somewhat on specific angular threshold measurements, they all suggest that tangential skin displacement stimuli could be used to communicate more than the four directions tested in our previous work. All of the above studies also found that thresholds were dependent upon stimulus direction, but disagreed on which directions were the most sensitive. The disagreements in thresholds are likely due to differences in device design and methods of finger restraint.

2.3 Tactor Design

In an effort to improve the performance of our skin displacement device, we have investigated the effect of tactor design on communication accuracy. The tactor contacts the fingerpad and imparts shear forces, stretching and displacing the skin. The importance of tactor design is implied by the studies of tangential skin displacement discussed in Section 2.2, which employed different tactor designs and observed widely varying levels of subject performance.

Several studies have investigated skin stretch as a means of understanding and diagnosing disorders of the somatosensory system. These studies typically use a small metal pin glued to the surface of the skin (e.g., Olausson et al. [20]). Gluing the tactor to the skin is an effective method for laboratory experiments but is not practical for most applications. Other researchers have used variations on rotating devices to stretch the skin and to slip against the skin, including Keyson & Houtsma, Webster et al., and Salada et al. [16] [21] [22]. These devices were too large to easily integrate into a portable device. Bark et al. developed a wearable device that used two contact points to twist a portion of the skin, not for communication of direction, but as a form of sensory substitution for proprioceptive information [23]. Other researchers have used translating probes, including Gleeson et al. who used a 7 mm diameter rounded rubber tactor [3], Drewing et al. and Vitello et al., who both used a 1 mm diameter steel cylinder [17] [18], Placencia et al. who used a 6 mm diameter rounded nylon tactor [19], and Srinivasan et al. who stretched the skin with a flat glass plate [13] . The above studies develop and use several tactor designs, but none has investigated the effects of tactor design on perception. In this paper we investigate two components of tactor design: texture and size.

The texture of the tactor will affect the friction properties of the finger-tactor interface, presumably with rough tactors providing better mechanical coupling. Studies by Srinivasan et al. and Salada et al. have shown that small surface features improve the perception of direction in devices that stretch or slip against the skin [13] [22]. While we have designed our haptic device to prevent slip, we suspect that some localized micro-slip occurs, particularly around the edges of the tactor.

The effect of tactor radius on direction perception cannot be easily predicted from the literature. Goodwin and Wheat have shown that people are sensitive to small changes in the curvature of objects on the scale of our tactors [24]. As tactors of varying size move against the skin, they will impart different contact pressures and displace different sized patches of skin, thus inducing different stress/strain states in the fingerpad. Dandekar et al. have shown that different strain energy states cause different afferent activation, which implies a change in perceptual experience [25]. These two studies suggest that users will be able to perceive the difference between tactors of different sizes, but how that perceived difference might affect direction communication is unclear. In a study on the perception of moving normal forces, Olausson found that larger tactors resulted in better direction discrimination, but this study stimulated the skin with rollers that moved without stretching the skin [26]. In a separate experiment, Olausson et al. tested the perception of tangential skin displacement using a small pin glued to the skin. They found that, although the tactor was small, its motion activated stretch sensitive receptors more than 15 mm away from the stimulation site [20]. If even a small tactor can stimulate receptors in a large area of skin, as this study found, the tactor size might not matter. To address this uncertainty regarding tactor size, we conducted the experiments using hemispherical tactors of variable size.

2.4 Aperture-Based Restraint

To effectively render most tactile stimuli, including tangential skin displacement, it is necessary to restrain the motion of the fingertip. This restraint is most commonly accomplished with a thimble-based interface that encloses the finger. Past devices using a thimble-based interface include a display of slip and skin stretch by Tasgarakis et al. [27], devices capable of rendering the making and breaking of tactile contact by Kuchenbecker et al. and Gleeson & Provancher [28] [29], and our previously tested displays of tangential skin displacement [3] [15]. While thimble-based restraints have been highly effective in lab use, they would be inconvenient on a portable device like a mobile phone, and potentially dangerous on a moving interface like a steering wheel.

In this paper we evaluate a restraint method that is more suitable for integration into portable devices: an aperture-based restraint. This restraint consists of a conically tapered hole in a flat surface (Fig. 1). The taper of the hole and friction between the flat surface and the skin prevent unwanted motion of the finger. The hole allows access to the tactile display, with the flesh of the fingerpad protruding into the aperture to contact the tactor.

Our design of the aperture-based restraint was based on an earlier design used in a study by Salada et al. [30], and later adapted by Webster et al. [21]. The skin displacement device used by Drewing et al. and Vitello et al. also used an aperture-type interface, but this aperture was rectangular, with a straight-sided hole, and was adjustable to suit the size of the finger [17] [18]. These earlier studies established the efficacy of aperture-based restraints but did not perform any further investigation of the design. One concern with the aperture-based restraint is the immobilization of the skin surrounding the aperture. Olausson et al. found that such immobilization prevents activation of mechanoreceptors in the surrounding skin and decreases tactile acuity [20]. In this paper, we test apertures in a range of sizes, compare their performance to a thimble-based interface, and analyze the interaction between aperture size and finger size.

2.5 Index Finger and Thumb

An aperture-based restraint has the potential to interface with any finger. Depending on the geometry of the device and its intended use, it could be better to deliver haptic feedback to the thumb, for example on a haptic-enabled mobile phone. Unfortunately, there is little information in the literature to predict how tangential skin displacement would be perceived with the thumb. All previous work with our haptic display has been conducted on the index finger [15] [3]. Previous studies by Salada et al. and Webster et al. using an aperture-based interface have also tested only the index finger [30] [21].

Physiological, anatomical and psychophysical studies suggest that the thumb should perform equally well, but these results are difficult to apply to the current study. Vallbo & Johansson have shown that all four types of tactile afferents occur with approximately equal densities on the distal ends of the index finger and thumb [31]. Two studies of tactile afferent activation thresholds, also by Johansson & Vallbo, reported equal activation thresholds for all afferent units of a given type, regardless of location, but found that psychophysical thresholds were lowest at the fingertips and greater in other areas, such as the palm [32] [33]. These studies suggest that psychophysical thresholds, as measured with pinpricks and von Frey hairs, should be equal on the distal ends of all digits, but the experiments sampled little data from the thumb. While the previous studies examined only point normal force perception, Van der Horst & Kappers studied curvature perception and also found approximately equal thresholds for the index finger and thumb [34]. This evidence all suggests that the thumb and index finger should be equally effective, but no studies have examined tangential skin displacement. Additionally, in the present study, the situation is complicated by the interaction between the fingerpad and the aperture. If the geometry of the finger and the nature of finger-aperture contact affect perception, then we would expect to see different results from the two digits. To resolve this uncertainty, we conducted tangential displacement experiments on both the index finger and thumb.

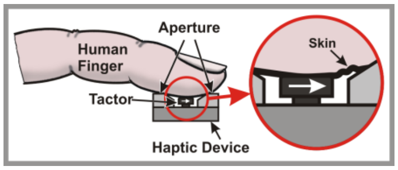


Fig. 1. Schematic of aperture-based finger restraint.

3 METHODS

3.1 Test Device

Tactor designs and aperture-based restraints were both evaluated with a tangential skin displacement device. In all experiments, the tactor was actuated with a Parker Two-Axis Linear stage (Fig. 2a). The stage was driven by two Maxon RE36 DC motors, geared to 4.8:1, and position was encoded by US Digital E2 encoders with 1250 ticks/revolution resolution. A PC running RTAI 3.1 on Linux Red Hat 9 controlled the position and velocity of the tactor using a PD controller running at 5 kHz. Although we previously developed a portable display of tangential skin displacement, the bench-top device was used for this experiment so as to provide greater stimulus rendering fidelity.

The test stimulus consisted of an out-and-back tactor movement. Starting from the center of the fingerpad, the tactor displaced a set amount, at a constant speed, stretching and displacing the skin of the fingerpad. At the end of its travel, the tactor paused for 300 msec before returning to the

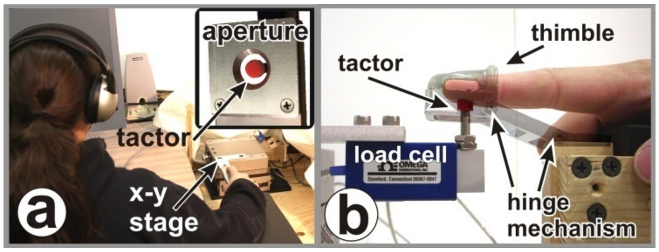


Fig. 2. (a): Experimental setup and test device, with mounted aperture-based restraint (inset). Covering cloth removed for clarity. (b): Thimble-type restraint and tactor.

center position. The experiments used stimuli with displacements ranging from 0.05 mm to 0.5 mm, all moving at 2 mm/sec. The test device rendered stimuli with total displacement errors less than 2.5 μm and speed errors less than 0.08 mm/s. Contact force between the tactor and the finger was measured with an Omega LCEB-5 single axis load cell to within ±0.03%. Force coupling in the load cell led to inaccurate measurements in the presence of lateral forces, i.e., when the tactor was stretching the skin. Consequently, we collected all force data immediately before each stimulus, when the skin was relaxed. Additional details on the test device and stimuli can be found in [3].

During tests, subjects sat with their right arm on a padded rest and their finger restrained over the tactor, as shown in Fig. 2. The finger restraint prevented the finger from moving so that the tactor would stretch and displace the skin of the fingerpad, rather than moving the entire finger.

During the tactor experiments, the finger was restrained with a thimble attached to a hinge mechanism (Fig. 2b). The bottom of the thimble is open to allow access to the fingerpad. We chose to use a thimble restraint for this experiment because the thimble is an established interface with well-understood performance characteristics [35].

For the aperture experiments, the thimble was removed and the aperture-based restraint was held in place by a rigid aluminum beam extending from the armrest (Fig. 2a). The aperture mounting beam was designed to allow either the index finger or the thumb to rest comfortably in the aperture. To place their thumb in the aperture, subjects supinated their wrist 90° and wrapped their fingers loosely under and around the aperture mounting beam.

3.2 Tactors and Apertures

We constructed six different tactors in order to evaluate two aspects of tactor design: size and texture. Tactors were fabricated with hemispherical contact surfaces of three different diameters: 3, 7, and 15 mm (Fig. 3). All tactors were machined from Delrin and coated with Performix PlastiDip spray-on rubber coating to increase the friction between the tactor and the skin. One tactor of each size was given a rough textured coating by embedding industrial abrasive in the rubber coating. As a texturing material, we chose Barton 80 HPA garnet with particle sizes normally distributed between 0.125 mm and 0.354 mm (mean ≈ 0.25 mm). When the tactors showed signs of wear, they were re-coated and re-textured.

The custom-built tactors were used only in the tactor experiments. The aperture experiment utilized the same off-the-shelf tactor that we used in our previous work, facilitating better repeatability and comparison between the aperture experiment and our earlier results. This tactor is a rubber IBM ThinkPad TrackPoint tactor, measuring approximately 7 mm in diameter. The tactor has a rounded surface with a sandpaper-like texture.

The experimental apertures were machined from aluminum in three sizes, referred to as *S, M* and *L – standing for small, medium, and large, respectively*. Aperture sizes and dimensions are shown in Fig. 4. When the aperture-based restraints were mounted, the top surface of the aperture plate sat 0.5 mm above the top of the tactor. The tactor was placed just below the top surface of the aperture in order to allow future

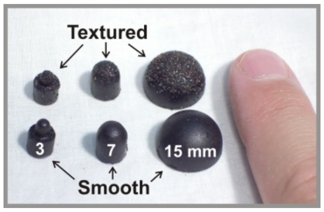
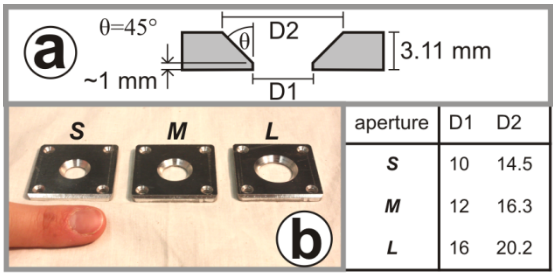


Fig. 3. Experimental tactors with a finger, for scale.



aperture	D1	D2
S	10	14.5
M	12	16.3
L	16	20.2

Fig. 4. (a) Aperture design, (b) experimental apertures with finger for scale, and table of aperture dimensions.

use of the tactor as an input device, as is commonly done on laptop computers.

3.3 Test Procedures

The experimental tactors and aperture-based restraints were evaluated with a four-direction discrimination task. Subjects were presented with a single repetition of a stimulus in one of four cardinal directions (distal, proximal, medial or lateral), and then asked to identify the direction of the stimulus by clicking on one of four arrow buttons on a graphical PC interface. All subjects interacted with the device using their right hand as shown in Fig. 2. During the experiments, both the test device and the subject's hand were covered with a white cloth (not shown in the figure). Headphones played audio cues signaling the start of each stimulus while external speakers played white noise to mask any sounds from the test device. All experiments were conducted with the approval of the University of Utah Institutional Review Board.

Experiments were organized into blocks, with each block testing a single tactor/aperture/finger. Subjects were allowed a few minutes to rest between blocks. In all experiments, the order of test blocks was balanced between subjects using Latin Squares ordering. Within each block, stimuli were presented in a pseudo-random order, with the restriction that stimuli of different directions/displacements were distributed approximately evenly throughout the block.

3.3.1 Tactor Experiment

The tactor experiment was conducted on 12 volunteer subjects, 11 male, and 1 female. Ten of the subjects were right-handed and two were left-handed, by self report. Subjects ranged in age from 22 to 43 years (mean = 27.9 years). Stimuli were rendered in 4 directions with two displacements: 0.05 and 0.1 mm. Stimuli with displacements up to 1.0 mm were evaluated in pilot testing of 5 subjects and they produced accuracy rates saturating at 100%. The main experiment was conducted on shorter, less salient, stimuli so that the effects of the tactor design could be better detected. Each test block included 10 repetitions of each stimulus, for a total of 80 stimuli per block. This experiment was conducted in two sessions, each session testing three tactors and requiring approximately 20 minutes to complete. The two test sessions were separated by at least a full day for all test subjects.

3.3.2 Aperture Experiment

Twenty volunteer subjects completed the aperture experiment, 10 of each gender, with ages between 19 and 41 years (mean = 24.6). All subjects were right handed, by self report. Six of the subjects were uncompensated while 14 subjects participated in the experiment for course credit. A post-hoc analysis showed no significant effects of compensation [F(1,239)=0.01, p=0.938]. Before each test, the thickness, width and length of the distal phalanxes of each subject's index finger and thumb were measured using calipers. Our measurements of finger width, along with values representing the general population, are shown in Table 1.

The tests consisted of four blocks, testing four combinations of fingers and apertures: index finger and *S*, index finger and *M*, thumb and *M*, thumb and *L*. Stimuli were rendered in four directions and three displacements: 0.05, 0.1 and 0.5 mm. Each block included 10 repetitions of each stimulus, for a total of 120 stimuli. This test required approximately 40 minutes to complete. As with the tactor experiment, stimuli with displacement of 1.0 mm were evaluated in pilot testing of 5 subjects. These long displacements resulted in accuracies at or near 100% for all test conditions. Apertures with intermediate sizes (inner diameters = 11 and 14 mm) were also evaluated in pilot testing. These apertures

TABLE 1
MEASURED FINGER WIDTHS

men	min (1%)	mean (50%)	max (99%)	std. dev.
index	14.8 (15)	16.2 (18)	17.1 (21)	0.85 (0.54)
thumb	19.2 (14)	21.0 (23)	24.9 (32)	1.23 (0.82)

women	min (1%)	mean (50%)	max (99%)	std. dev.
index	12.8 (13)	14.7 (16)	16.6 (18)	1.73 (1.69)
thumb	16.6 (16)	18.6 (19)	20.2 (22)	1.11 (0.71)

Measured finger sizes, along with 1st, 50th, and 99th percentile values for the general population, in parenthesis. All units are in mm. Population measurements are from Henry Dreyfuss Assoc. and were taken at the prominence of the distal knuckle [36]. Our measurements were taken at the base of the fingernail.

produced results similar to those produced by similarly sized apertures. As such, the three apertures used in the experiment were chosen to provide the greatest range of sizes. Apertures smaller than *S* were not considered because they did not allow room for the moving tactor. Apertures much larger than *L* were deemed too large for practical use in a portable device.

3.4 Analysis Methods

Direction identification accuracy rates were computed separately for each stimulus type (displacement), each test condition (tactor/aperture/finger), and each subject. For most analyses, stimuli of all four directions were pooled together. Except where noted below, analyses used difference scores rather than raw accuracy rates. Difference scores were computed separately for each subject by taking the difference between a given accuracy rate and the subject's overall mean accuracy. This method removes the offsets caused by differences in baseline subject performance and allows the effects of the tactors/apertures to be seen more clearly. Accuracy rates and difference scores were then pooled between all subjects and the results subjected to standard statistical tests. Specific analysis methods are described in Section 4, as required.

4 RESULTS AND DISCUSSION

4.1 Tactor Experiment

In this experiment, test subjects attempted to identify the direction of tangential skin displacement stimuli delivered by tactors of differing size and texture. The results of this experiment are shown in Fig. 5. The rough tactors produced slightly higher accuracy rates than the smooth tactors, but tactor size did not have a significant effect. For clarity, Fig. 5 shows absolute accuracy rates, but all analyses were conducted on difference scores, computed as described in Section 3.4.

An ANOVA on accuracy deviation scores showed texture and stimulus distance to have main effects, while tactor radius had no

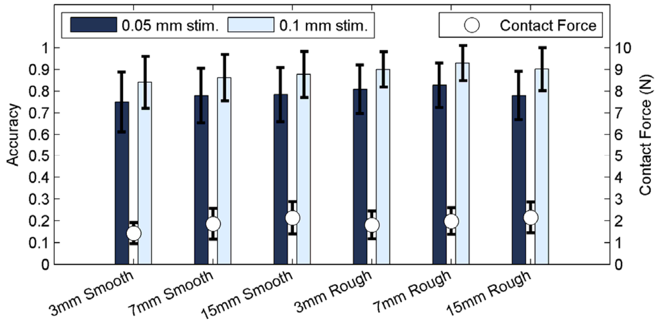


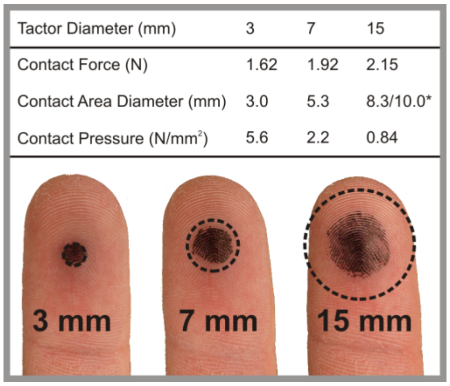
Fig. 5. Effects of tactor design on direction identification accuracy. Rough tactors performed better than smooth tactors, but tactor size did not affect performance.

statistically significant effect [Texture: F(1,143) = 6.75, p = 0.010. Stimulus Distance: F(1,143) = 35.74, p < 0.0001. Radius: F(2,143) = 0.78, p = 0.461]. There were no significant interactions between factors. On average, the textured tactors increased accuracy by 0.04 when compared to the smooth tactors. The average accuracy for 0.1 mm stimuli was 0.10 higher than the 0.05 mm stimuli. The significance of these results was confirmed with subsequent t-tests [Texture: t(142) = 2.349, p = 0.020. Stimulus Distance: t(142) = 5.922, p < 0.0001].

The positive effect of tactor texture on communication accuracy is in agreement with prior work. As discussed in Section 2.3, small features slipping against the skin have been found to improve the perception of direction [13] [22]. These previous experiments used large slip displacements, but our results suggest that small-scale features can improve direction detection with even very small amounts of micro-slip, as we suspect occur around the edges of the tactor. The detection of directional skin stretch is mediated primarily through SA afferents, but the addition of fine features moving against the skin can excite additional FA afferents, making the stimulus more salient [13].

Because tactor size did not impact direction perception, we conclude that the contact area between the tactor and the skin, as well as the amount of pressure applied by the tactor and the induced stress-stain state, are not important factors in the perception of tangential skin displacement. To better understand the interaction between the different sized tactors and the finger, we applied ink to the tactors and pressed them against the finger using forces representative of those measured in the main experiment. The results of this exercise are shown in Fig. 6. Subjects generally applied less force to the smaller tactors, but due to the small contact area, much larger pressures resulted. Previous research has shown that the differences in tactor curvature and induced pressure should have altered the perceptual experience [24] [25]. Subjects did report that they could clearly differentiate between the three tactor sizes, but apparently this did not affect the communication of the direction cues. We conclude that all of the tactors, regardless of size, displaced and stretched a large area of skin and activated mechanoreceptors in this larger area, as has been previously observed in other experiments [20].

The results of this experiment contain important information for designers of tactile devices. Tactors should have a rough texture, but the size of the tactor can be chosen to suit the physical constraints of the device and the preferences of the user. In our experiment, users generally expressed a preference for the larger tactors, finding the 3 mm tactor uncomfortable. We therefore recommend rough-textured tactors 7 mm or larger for use in displays of skin displacement and skin stretch. We acknowledge that tactors larger than 7 mm may not be practical in portable devices, so the 7 mm ThinkPad tactor size appears to be well chosen.



Tactor Diameter (mm)	3	7	15
Contact Force (N)	1.62	1.92	2.15
Contact Area Diameter (mm)	3.0	5.3	8.3/10.0*
Contact Pressure (N/mm^2)	5.6	2.2	0.84

Fig. 6. Contact area and contact pressure resulting from each tactor. Contact forces reported here are the average of those recorded during experiments. The dashed lines represent the diameters of the tactors. *The 15 mm tactor had an oblong contact area. The two numbers reported correspond to the width and length of the contact area.

4.2 Apertures for the Index Finger and Thumb

Subjects attempted to identify the direction of applied tangential skin displacement while using aperture-based finger restraints of three sizes on either their index finger or thumb. Results are shown in Fig. 7, along with data from a previous experiment [3], which was conducted using a traditional, thimble-type interface. For clarity, this figure shows absolute accuracies. Except where noted, all analyses were conducted using difference scores computed as described in Section 3.4. When multiple, non-orthogonal comparisons were required, Dunnett's test was used to control the family-wise error rate. In these cases, the test statistic is denoted t_d. The 0.5 mm stimuli produced uniformly high accuracy rates under all test conditions, and were therefore omitted from the analyses discussed below.

4.2.1 Main Effects: Restraint and Finger

The size of the aperture had a main effect on communication accuracy, with accuracy rates

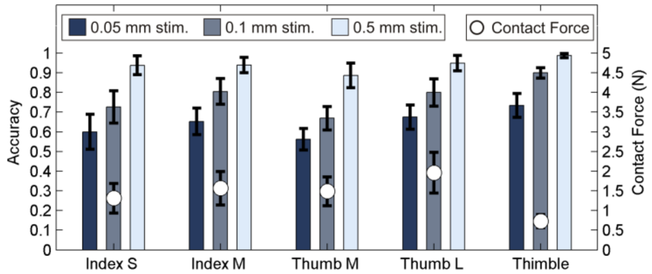


Fig. 7. Effects of aperture size on direction identification accuracy. Subjects performed better with large apertures than with small apertures. The index finger performed better than the thumb in a direct comparison. Overall aperture-based restraint performance is slightly less than, but comparable to, the performance of a traditional thimble-based restraint. Thimble-based data were collected in a separate experiment conducted on the index finger [3].

generally higher when larger apertures were used [F(2,239) = 5.28, p = 0.0057]. When 0.1 mm stimuli were delivered to the index finger, the average accuracy was 0.08 greater with aperture *M* than with *S* [$t_d(76) = -2.801$, $p < 0.05$]. The differences were not statistically significant for 0.05 mm stimuli [$t_d(76) = -1.682$, $p > 0.10$]. When stimuli were delivered to the thumb, the larger aperture resulted in accuracy improvements of 0.11 and 0.13 for the 0.05 and 0.1 mm stimuli, respectively [0.05 mm: $t(38) = -4.148$, $p < 0.0001$. 0.1 mm: $t(38) = -5.215$, $p < 0.0001$]. These statistically significant results suggest that an increase in the exposed area of skin results in improved communication. As was previously reported by Olausson et al., when a portion of the skin is displaced, mechanoreceptors in a large area of surrounding skin are activated [20]. When the surrounding skin is masked off, mechanoreceptors in that area are not activated and the stimulus becomes less salient. Thus, when using skin stretch and skin displacement, it is best to leave free as large an area of skin as is practical.

The aperture-based restraints and the standard thimble-based restraint performed comparably well, although the thimble resulted in a small improvement in performance. Compared to the index finger using aperture *M*, thimble accuracy rates were higher by 0.047±0.043, 0.094±0.075 and 0.081±0.090 for the 0.5, 0.1 and 0.05 mm stimuli, respectively (reported with 95% confidence intervals). These differences in performance can be attributed to the larger area of exposed skin and possibly to more effective finger immobilization provided by the thimble. While the aperture-based restraints produced somewhat lower communication rates than the thimble, their size and ease of use make them the better choice for portable and handheld applications. Note that the thimble-based data were collected in an earlier experiment conducted on different subjects [3]; the differences observed between the thimble and aperture could be due, in part, to differences in two groups of test subjects. When using the aperture-based restraint in a practical application, stimuli with longer displacements would ensure sufficiently high accuracy rates. In our pilot testing, all apertures achieved accuracy rates at or near 100% when using 1 mm stimuli.

By testing both the index finger and the thumb on aperture *M*, we were able to directly compare the performance of the two digits. An ANOVA showed a main effect, with the index finger performing better than the thumb [F(1,119)=16.4, p=0.0001]. Compared to the thumb, the index finger's accuracy rates were higher by 0.090 and 0.136 for 0.05 and 0.1 mm stimuli, respectively [0.05 mm: $t_d(76) = -2.883$, $p < 0.05$. 0.1 mm: $t_d(76) = -4.847$, $p < 0.05$]. This result runs contrary to previous studies measuring approximately equal afferent densities on the two digits and equal responses to stimuli [32] [33] [34]. It is possible that the differences we observed were not due to variations in innate sensitivity, but the result of the geometric properties of the digits. The index finger and thumb have dissimilar shapes and curvatures and could interact differently with the apertures. It is also possible that perception was impacted by differences in the mechanical properties of the skin, e.g., more callused tissue on the thumb. This difference in performance between the two digits could be interpreted to mean that devices should interface with the index finger rather than the thumb. However, we also observed similar accuracies between the index *M* and thumb *L* conditions. Compared to the thumb in aperture *L*, the performance of the index finger in *M* was not significantly different [0.05 mm: $t_d(76) = 0.720$, $p > 0.10$. 0.1 mm: $t_d(76) = -0.178$, $p > 0.10$]. This tells us that either the index finger or the thumb can be used effectively, so long as the correct aperture is chosen.

4.2.2 Other factors: Finger Size and Contact Force

In order to better understand how subject-specific factors influence the performance of the aperture-based restraint, we analyzed the effects of finger size and contact force. Our results suggest that people with smaller fingers perform better than people with larger fingers, and higher contact forces result in a minuscule increase in accuracy. Curiously, these trends were true for the index finger only.

As can be seen from the force error bars in Fig. 7, the forces that subjects applied to the tactor in this experiment varied over a fairly large range, as compared to the limited range of forces measured during the thimble experiment; force error bars from the thimble experiment are so small that they are barely visible in Fig. 7. To separate out any effects of other variables, we separated the data according to subject, aperture, and finger, and then computed accuracy differences scores individually for each subset. We then pooled difference scores between subjects and used Spearman Rank Analysis to test for a correlation between applied normal force and accuracy. We found a statistically significant correlation for the index finger, with accuracy increasing slightly with greater applied force [Aperture *S*: $r_s = 0.087$, $p = 0.0005$. Aperture *M*: $r_s = 0.154$, $p < 0.0001$]. We did not observe the same correlation for the thumb; the correlation was statistically insignificant for the thumb in aperture *M*, and negative for the thumb in aperture *L* [Aperture *M*: $r_s = 0.023$, $p = 0.364$. Aperture *L*: $r_s = -0.085$, $p = 0.002$]. While the force-accuracy correlation was, in some cases, statistically significant, the effect size was trivially small, with r_s values less than 0.2 and linear slopes less than 0.006 (Δ accuracy/N). Because of the very small effect size, we do not consider the effects of contact force on accuracy to be important.

Unlike contact force, finger size had a more noteworthy effect. We again used Spearman's Rank Analysis to test for a correlation between finger size and accuracy, using the width of the finger at the base of the fingernail as the measure of finger size. Accuracy decreased with increasing finger size, but only for the index finger [Index: $r_s = -0.310$, $p = 0.0052$. Thumb: $r_s = 0.004$, $p = 0.974$]. With the index finger, accuracy decreased by 0.045 for every additional mm of finger width. This result is consistent with the findings of Peters et al., who found smaller fingers to be more sensitive in a grating-spacing differentiation task [37]. They proposed that the higher mechanoreceptor density measured in smaller fingers resulted in greater perceptual acuity. It is interesting that we did not observe the same relationship for the thumb that we did for the index finger. This difference between the digits may be grounds for future studies.

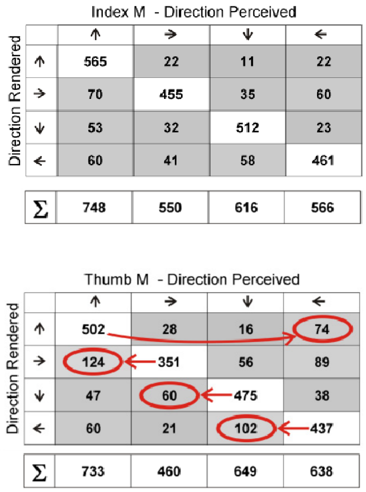
4.2.3 Interaction: Aperture Size and Finger Size

We initially hypothesized that there would be an interaction between finger size and aperture size, such that small fingers would have more freedom of movement in the larger apertures and would perform poorly. We did not, however, observe any such interaction. While our tests included a wide range of finger sizes, it should be noted that fingers larger or smaller than those tested might behave differently.

Subjects were divided into two groups, based on finger size, and an ANOCOVA tested for an interaction between finger size and aperture size. Data from the index finger and from the thumb were treated independently. The results of this analysis reflected the overall performance difference between large and small fingers, but we found no interaction between finger size and aperture size [Index: $F(1,36)=0.00$, $p=0.963$, Thumb: $F(1,36)=1.66$, $p=0.205$]. From this result, we conclude that exposed skin area is one of the most important parameters in aperture design, dominating over other factors such as absolute finger-fit and restraint quality. The important implication of this analysis is that aperture size need not be adjusted to finger size; the same aperture may be used with a wide range of finger sizes.

4.2.4 Stimulus Direction: Confusion and Accuracy

We investigated the effect of stimulus direction on accuracy and found direction bias, direction confusion, and direction dependent accuracy. Fig. 8 shows confusion matrices, summarizing subject performance on aperture *M*. When the subjects perceived stimuli with the index finger, they were biased in the distal direction, responding most frequently in that direction. In cases where stimuli were misidentified, subjects showed no clear pattern of confusion. Incorrect responses were subject to the same distal bias as correct responses, but were otherwise distributed randomly across all directions. The same



Index M - Direction Perceived

Direction Rendered	↑	→	↓	←
↑	565	22	11	22
→	70	455	35	60
↓	53	32	512	23
←	60	41	58	461
Σ	748	550	616	566

Thumb M - Direction Perceived

Direction Rendered	↑	→	↓	←
↑	502	28	16	74
→	124	351	56	89
↓	47	60	475	38
←	60	21	102	437
Σ	733	460	649	638

Fig. 8. Confusion matrices for the index finger (top) and thumb (bottom) in aperture *M,* along with response totals. Each cell contains the total number of stimuli perceived to be in a given direction, as a function of the actual, rendered direction. The bottom row of each table shows the total number of stimuli perceived in each direction. Data are pooled from stimuli of all three displacements. The arrows represent directions as follows: distal (↑), lateral (→), proximal (↓), and medial (←). When perceiving stimuli with the thumb, subjects showed a counter-clockwise pattern of direction confusion, illustrated by the arrows.

observations hold for data gathered using the index finger in aperture *S*.

Data gathered from the thumb show a different pattern of response confusion. The distal bias remains, but there is also a systematic trend to the incorrect responses. When subjects responded incorrectly, they were most likely to misidentify the stimulus direction as 90° counter-clockwise of its true direction. Data collected using the thumb in aperture *L* show the same pattern. This pattern is consistent with comments made by the test subjects. Several subjects described the stimuli as feeling diagonal when delivered to the thumb; subjects stated that distally directed stimuli felt as though they were moving at some angle between the distal and medial directions. This effect was especially prevalent at the beginning of tests using the thumb. This is interesting, as it suggests a perceptual reference frame that is skewed from the global reference frame. It is possible that this skewed perceptual frame is an innate property of the thumb, or it may be an effect of the orientation of the hand during testing. When subjects placed their index fingers in the aperture, their palms remained parallel to the ground and their index finger was aligned with their forearm, but in order to place their thumbs in the aperture, subjects were required to rotate their wrists approximately 90°. Previous studies by Volcic & Kappers have shown that haptic perception of direction and orientation is influenced by the orientation of the hand [38]. While further research is required to fully understand this direction confusion, these results do suggest a potential difficulty when delivering directional cues to the thumb.

To gain a fuller understanding of the effects of stimulus direction, we computed d’, a non-biased measure of accuracy, for each direction (see Macmillan & Creelman for an explanation of d’ [39]). Fig. 9 shows the results of this analysis, along with data collected using a traditional thimble-type interface in a separate experiment [3]. These data, particularly those representing

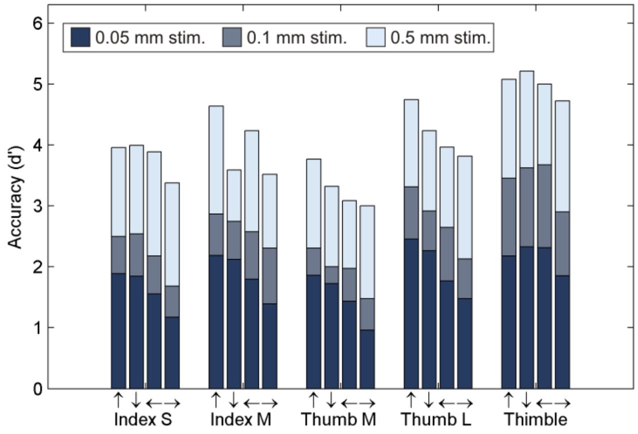


Fig. 9. Un-biased accuracy as a function of stimulus direction. Performance data for the thimble-based restraint were collected in an earlier experiment [3]. The arrows represent directions as follows: distal (↑), lateral (→), proximal (↓), and medial (←).

0.05 and 0.1 mm stimuli, show a regular trend for stimuli of all displacements: greatest accuracy in the distal direction, followed by the proximal, medial, then lateral directions. This effect of stimulus direction parallels our prior experiments conducted using a thimble-based restraint [3]; however, this effect is far more pronounced when using the aperture-based restraint.

In our previous research using the thimble-based restraint, it was difficult to determine the cause of observed accuracy anisotropy, due to the asymmetric design of the thimble. The radially symmetric apertures used in this study allow us to better speculate about the directional properties of the finger. Because the fingertip is approximately symmetric along the proximal-distal axis, we suspect that the difference in accuracy between the medial and lateral directions is an innate property of the finger and not an effect of our interface. Interpreting the results regarding the distal and proximal directions is less clear. Because the distal and proximal ends of the fingertip have different curvatures, they may have interacted differently with the aperture, resulting in restraint-dependent differences.

Earlier work by Birznieks et al. supports the notion of inherent perceptual anisotropy in the fingertip. They observed a directional response bias in the afferents of the fingertip when stimulated with a force comprised of both normal and tangential components. They found that SA-I afferents were biased in the distal direction, SA-II afferents in the proximal direction, and FA-I afferents in the proximal and radial (medial direction in our experiment) directions [11]. These afferent response biases correspond to the direction-dependent accuracies observed in our experiment.

Earlier studies of tangential skin displacement, discussed in Section 2.2, addressed the issue of direction-dependent accuracy, but disagreed in their specific findings. In general, they suggest that perceptual accuracy is not equal for stimuli in all directions, but which directions are most sensitive may be different for each specific device and finger restraint [16] [17] [18] [19].

5 CONCLUSIONS AND FUTURE WORK

We tested a range of tactor and aperture designs for use in tactile communication. Our results include important guidelines for the design of future interfaces. Tactors should have a rough texture to maximize communication accuracy, but tactor diameter can be chosen based on design constraints and user preference. Most of the users in our study preferred large tactors to small tactors. The aperture-based restraint was designed to be a practical finger restraint in portable applications. It functioned nearly as well as a traditional thimble-based restraint. Larger apertures provided better communication accuracy than smaller apertures, and there was no interaction between aperture size and finger size, meaning that a single aperture could be suitable for all users. The aperture-based restraint can be used equally well on either the index finger or the thumb. However, some results suggest caution when interfacing with the thumb; subjects showed evidence of systematic direction confusion when using their thumb. The index finger performed better than the thumb in a direct comparison.

Aside from these practical design principles, our study also produced results of broader impact. The results of both the tactor and aperture experiments emphasized the importance of skin surrounding the point of stimulation. In the tactor experiment, our results suggest that a similar area of skin was deformed regardless of tactor size, resulting in performance that was independent of tactor size. In the aperture experiment, we found that smaller apertures hampered performance by masking off surrounding skin. Both of these results underscore the importance of mechanoreceptors distant from the stimulation site and the value of leaving the surrounding skin free to move. The importance of aperture size raises a possible question with earlier studies that have used adjustable apertures; changing the size of the aperture for each subject may have affected each subject's ability to perform the required task.

In this paper, we also present intriguing differences between the index finger and the thumb. In a direct comparison, the index finger showed higher perceptual acuity than the thumb. Additionally, while the size of the index finger affected accuracy, the size of the thumb did not. In an analysis of stimulus confusion, we found a pattern of incorrect responses that suggests a skewed perceptual reference frame for the thumb but not for the index finger. Further research is necessary to determine whether these results represent inherent differences in the digits, or if these effects stem from factors unique to our experiment.

Important characteristics of tactors and apertures not evaluated in our experiments include tactor and aperture shape, the angle of the aperture bevel, aperture surface texture, the height of the tactor within the aperture, and the interaction between different apertures and tactors. The effect of these tactor and aperture features will be the subject of future work. Additional future work will investigate the use of directional tactile stimuli in mobile applications. This will address questions including the influence of the orientation of the user's hand on stimulus perception and a comparison of haptic, visual and auditory cues. In conjunction with this research, we will seek to integrate tactile stimuli into a useful mobile device, such as a global positioning system.

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CHAPTER 5

MENTAL ROTATION OF DIRECTIONAL TACTILE STIMULI

Abstract

In this chapter, we present three studies on the mental rotation of directional tactile stimuli. Each participant placed his/her right hand in several fixed orientations and received directional skin stretch stimuli on the distal end of their right index finger. Participants indicated the direction of each stimulus using a joystick in the opposite hand. A correct response required a mental rotation from the reference frame of the participant's right index finger to that of the joystick. The first experiment examined intuitive responses and found no single natural response pattern (i.e., allocentric vs. egocentric frame), although the majority of participants interpreted the stimuli in the finger-aligned (egocentric) frame. The second experiment tested several orientations produced by rotating the forearm about the elbow in the transverse (horizontal) plane and found a sinusoidal relationship between forearm angle and response time. The third experiment tested a variety of finger orientations achieved through combinations of finger flexion, wrist rotation, and rotation of the arm about the elbow. There was no significant relationship between the results of this experiment and the earlier intuitive response experiment, indicating that a participant's natural response method does not affect their ability to respond in a specific pattern, once trained. A comparison of models revealed that all three joint rotations had similar impacts on response time, but with

certain interactions between joints. The results of these studies improve our understanding of spatial reasoning and perception of directional tactile cues. These results will be informative to designers of haptic interfaces, especially those designing portable, handheld devices with haptic feedback.

Introduction and Background

Haptic direction cues have the potential to improve safety and enhance the user experience for a range of devices. For example, drivers in traffic, soldiers in combat, and emergency workers in a disaster area must devote their visual and auditory attention to maintain situation awareness and personal safety. In such situations, a haptically-enabled device could provide important directional or navigational information while leaving the user's eyes and ears free. In situations of visual and auditory information overload, haptic communication can provide cognitive advantages [1]. For all users, and particularly for the blind, haptic interfaces could provide an unobtrusive means of receiving information from common devices like portable phones or music players.

In this chapter, we address an important problem inherent to many types of haptic direction communication: mental rotation of haptically perceived stimuli. Any time there exists a difference between the haptically-perceived frame and the task-space in which the cues are to be interpreted, some mental transformation will be required. As an example of this problem, consider navigational information delivered to the fingertip by a portable device. The device would render a direction on the fingertip (the haptically-perceived frame) and a user would have to interpret that information as it relates to his or her surroundings (the task-space). When the user's finger is held in alignment with the task-space, the interpretation of the haptic cues would be simple. If, however, the user's finger were in any other orientation, a potentially taxing mental transformation would be required (Fig. 5.1). Previous work conducted on mental rotation of visual objects has shown that these rotations incur a cognitive cost and can burden spatial working memory [2], potentially interfering with other spatial tasks. This chapter presents three experiments exploring mental rotation of haptic stimuli, investigating how haptic directions are instinctively interpreted, how a user mentally rotates the cues into alignment with the environment, and how this rotation task depends on finger orientation.

Prior Work with Mental Rotation and Haptic Direction Perception

Many researchers have addressed mental rotation of visually perceived stimuli, beginning with a study showing that the time required to complete a mental rotation task increases linearly with the required angle of rotation [3]. This result implies that we perform spatial tasks by using analog, realistic 3D mental representations rather than by using more symbolic, abstract mental representations.

How one would complete a similar task using haptically-perceived stimuli is less

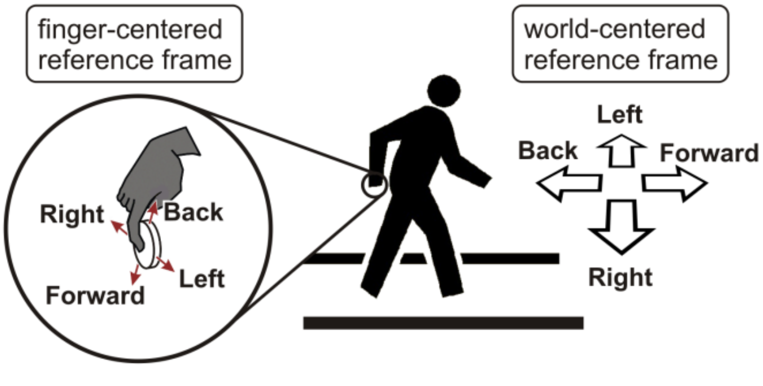


Fig. 5.1 When using a portable haptic interface, it may be necessary to mentally rotate haptic cues from the finger-centered frame, where they are perceived, to the world-centered frame, where they are to be applied.

clear. The existing literature suggests that mental rotation of haptically-perceived stimuli might exhibit different characteristics than similar tasks with visually-perceived stimuli. The cognitive characteristics of mental rotation vary significantly depending on the type of object perceived and on the kind of rotation required [4]. Of particular relevance to haptic research are observations that the mental processes and neural structures involved in rotation tasks are linked to perceptual systems. Several behavioral studies revealed that mental rotation of body-relevant objects (images of hands, feet, bodies, etc.) involves embodiment effects, where participants projected their own reference frame onto the object and mentally simulated motor actions [5] [6] [7] [8]. Neural imaging experiments confirmed these results, showing that the somatosensory system engages in motor simulation of body-relevant rotations [4] [9] [10] [11]. In all of the above embodiment studies, the relationship between rotation angle and response time was fundamentally different for body-relevant objects than for neutral objects. In our experiments, which involve different physical orientations of the hand, we expect to see embodiment effects as the participants mentally rotate their own hand.

The few studies addressing mental rotation of tactile stimuli have generally produced results similar to those obtained in visual studies. Most of these experiments have involved an embossed shape pressed against an unmoving fingertip, such as alphanumeric characters [12] [13] [14] or other abstract shapes [15] [16]. While the above studies reported evidence of mental rotation following trends similar to those observed in visual studies, a study using vibrating pins failed to produce evidence of mental rotation [17], and experiments with brail-like dots only showed mental rotation behavior under certain conditions [18]. These differing results show that the stimulus type and the nature of the experimental task can both determine how a participant processes spatial stimuli. In a study where participants felt and attempted to identify models of human hands as left or right hands, response times increased with the angle between the model hand and a canonical hand orientation [19], showing evidence of both mental rotation and embodiment. Because our experiment includes both changing hand orientation and tactile stimuli at the fingertip, we expect to see both embodiment effects and evidence of spatial rotation of fingertip stimuli.

In our experiment, the participant's hand changes position and orientation, potentially affecting the participant's spatial perception. In studies of orientation perception, Kappers et al. found systematic deviations from veridicality based on hand orientation [20] [21]. They concluded that the perceived reference frame is a weighted average between the veridical allocentric (world-centered) reference frame and a second, hand-centered reference frame. The effects of hand orientation and changing perceptual reference frames extend to spatial processing and mental rotation [22]. The effects of hand orientation and changing haptic reference frame are also demonstrated in a study of haptic perception and comparison by Prather and Sathian [23] and a study of haptic control of virtual reality environments by Ware and Arsenault [24]. These results warn that hand orientation could potentially interfere with the accurate perception of haptic direction cues.

Prior Work with Tactile Direction Cues

Haptics researchers have developed a range of methods to communicate directional information using tactile stimuli. Arrays of vibrating motors can successfully communicate direction cues and have been build into wearable devices including vests

[25] [26] and belts [27]. Vibrotactile cues have also been delivered through a chair [28] [29] or a steering wheel [29]. Examples of hand-held or fingertip-mounted devices include those that use inertial forces to communicate direction (e.g., [30]) and others which use shear forces, slip or skin stretch at the fingertip (e.g., [31] [32] [33] [34]). In our previous work, we evaluated the uses of directional tangential skin stretch at the fingertip. We found this method of tactile communication to be highly effective; when the skin of the fingerpad was displaced 1 mm at 2 mm/s or faster, participants were able to identify the direction of stimulus with better than 99% accuracy [35]. In all previous studies of directional tactile stimuli, the stimulus reference frames were aligned with the response reference frames. In the present study, we investigate the use of tactile stimuli in cases where these two reference frames are not aligned and the participant must transform the stimuli between two rotated frames.

General Methods

Test participants completed three experiments on mental rotation of tactile stimuli. Participants passively perceived a tactile stimulus on index finger of their right hand, which was often rotated with respect to the allocentric (world-centered) reference frame. They were then asked to respond to this stimulus with a world-aligned joystick in their left hand. The three experiments are summarized as follows: 1. Intuitive Mapping of Stimuli, which sought to characterize the natural perceptual reference frame of tactile stimuli, 2. Simple Rotation, which established the response time-rotation angle relationship around a single axis of rotation in the transverse plane, and 3. Complex Rotation, which examined the effects of rotations involving multiple joints.

Participants

All experiments were completed by 15 volunteer participants, 10 male, 5 female, aged between 19 and 33 years (mean = 25.9). The same participants were used in all three experiments.

Tactile Stimulus

All experiments utilized directional skin stretch as a tactile stimulus. In all previous studies of mental rotation, participants perceived static shapes, while in the present study, the fingerpad is stimulated with a moving device. With the finger held stationary, a 7 mm diameter, hemispherical, rubber contact element pressed against the fingerpad moved tangentially on the skin, displacing and stretching the skin of the fingerpad in a given direction. For each stimulus, the contact element completed a 1 mm out-and-back motion, as shown in Fig. 5.2, in one of four cardinal directions: proximal, distal, radial or ulnar. In earlier perceptual studies, subjects were able to correctly identify the direction of this stimulus with 99+% accuracy [35].

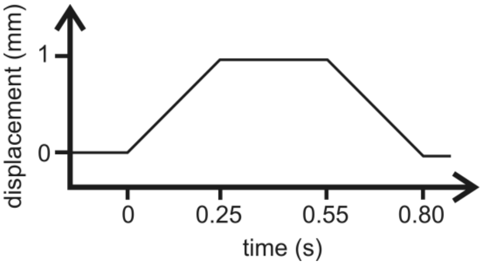


Fig. 5.2 Tactile stimulus motion profile. The contact element moves 1 mm at 4 mm/s, stretching the skin of the fingerpad. After a pause of 0.3 s, the tactor returns to the center position.

Apparatus

Test participants sat as shown in Fig. 5.3, with the tactile display device worn on the right index finger. All experiments utilized a custom-built tactile device capable of rendering directional skin stretch stimuli. This device is described in depth in [36]. After receiving a tactile stimulus, subjects would indicate their response using a four-direction joystick operated with their left hand. Participants received instructions from a monitor positioned in front of the test apparatus. A PC running Matlab and the Psychophysics Toolbox [37] controlled the tactile device, displayed instructions on the monitor, and recorded inputs delivered from the joystick with ±1.5 ms timing accuracy. Wooden fixtures determined the location and orientation of the tactile device and the participant's hand, see Fig. 5.3 (inset). Velcro on the fixtures, the tactile device, and the test environment allowed for easy repositioning. During experiments, participants wore headphones playing white noise and the test environment was covered so that participants

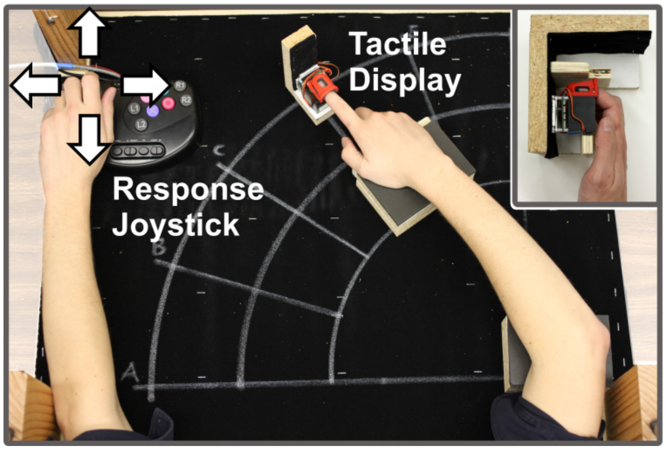


Fig. 5.3 The test environment. Participants wore the tactile device on the right index finger while the left hand registered responses by operating a four-direction joystick. Repositionable fixtures (inset) provided for repeatable positioning of the hand and finger.

were not able to see their hands. Participants were seated for all experiments.

Test Conditions

All three experiments utilized the same apparatus but differed in the finger orientations tested and the instructions given to the participant.

Experiment 1: Intuitive Mapping

Experiment 1 tested eight finger orientations in the horizontal plane and one out-of-plane orientation. The horizontal plane positions included all combinations of three joint rotations: finger flexion, wrist rotation, and rotation of the forearm about the elbow. This experiment evaluated rotation angles of 0 and 90 degrees, resulting in orientations A-H shown in Fig. 5.4. These eight orientations comprised a representative sample of rotations and orientations possible in the horizontal plane. A ninth orientation featured

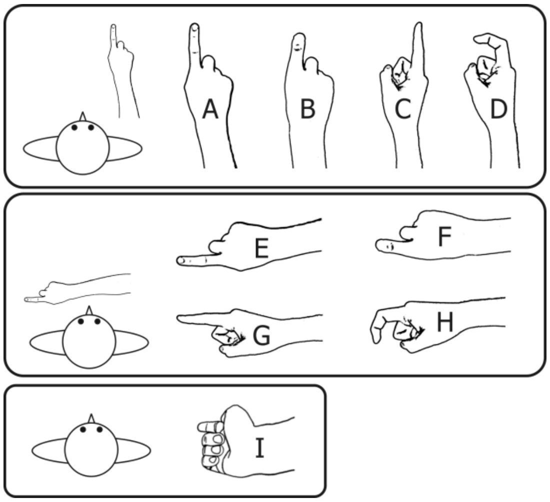


Fig. 5.4 Finger orientations tested in Experiments 1 and 3. Orientations A-D were tested with the forearm extended straight forward as follows: A: No joint rotation, B: finger flexed 90°, C: wrist supinated 90 °, D: finger flexed 90° and wrist supinated 90°. Orientations E-H utilized the same finger and wrist rotations as A-D, but added a 90° rotation of the forearm about the elbow. In orientation I, the participant's arm was straight down at his/her side, with the index finger pointing at the ground.

the hand down at the participant’s side with the finger pointing down, Fig. 5.4 (I). This orientation mimics a common posture for holding a portable device (e.g., mobile phone) and is of interest to tactile interface designers.

In Experiment 1, participants were not instructed how to map between tactile stimuli delivered to the right index finger and the response joystick aligned with the allocentric reference frame. They were told to respond “…in the direction that you feel best correspond with the tactile stimulus.”

Participants responded to 8 repetitions of each direction in each orientation, for a total of 288 stimuli (4 stimulus direction x 9 orientations x 8 repetitions = 288). Participants required an average of 24 minutes to complete the experiment.

Experiment 2: Simple Rotation

Experiment 2 tested six orientations produced by rotating the forearm about the elbow. Hand orientations were evenly spaced between 0° and 90° (every 18°), as shown in Fig. 5.5.

In this experiment, participants were explicitly instructed to interpret the stimuli in the reference frame of the fingertip and respond in the allocentric (joystick) reference frame. That is, a distal stimulus on the fingertip was to correspond with a forward response on the joystick, regardless of the orientation of the finger. A training session before the experiment ensured that participants understood the task. Participants were not permitted to proceed with the experiment until they achieved 90% or better accuracy in the training session.

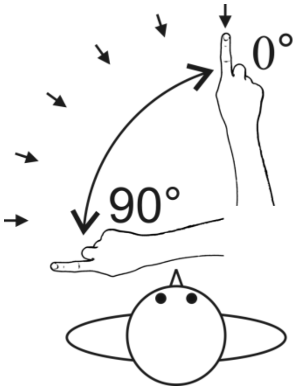


Fig. 5.5 Finger orientations tested in Experiment 2. Orientations were separated by 18° of rotation about the elbow.

Participants responded to 24 repetitions of each direction in each orientation, for a total of 576 stimuli (4 stimulus direction x 6 orientations x 24 repetitions = 576). Participants required an average of 30 minutes to complete the experiment.

Experiment 3: Compound Rotation

Experiment 3 tested the same orientations as Experiment 1 (Fig. 5.4), but gave explicit instructions to interpret direction cues in the reference frame of the fingertip, as was done in Experiment 2. Participants successfully completed a training session before the main experiment, as was done in Experiment 2.

Participants responded to 24 repetitions of each direction in each orientation, for a total of 864 stimuli (4 stimulus direction x 9 orientations x 24 repetitions = 864). Participants required an average of 41 minutes to complete the experiment.

Experimental Design

All participants completed the three experiments in order, with Experiments 1 and 2 completed in the same session and Experiment 2 completed in a separate session, approximately one week later.

Within each experiment, the presentation order of finger orientations was balanced between participants. To minimize the effects of learning or fatigue, each experiment tested each orientation twice, with the stimulus repetitions evenly divided between the two presentations. For example, in Experiment 3, a participant would respond to 12 repetitions of each stimulus in each orientation, and then repeat the same order of finger orientations, responding to another 12 repetitions in each orientation. The presentation order of the stimuli (i.e., the selection of stimulus direction) was pseudorandom, with an equal number of stimuli presented in each direction.

Data Analysis

In Experiment 1, a least-squares analysis compared participant response patterns with egocentric and allocentric reference frames. Data analysis in Experiments 2 and 3 focused on relative response times (relative RT). Response time (RT) is the time elapsed between the onset of the stimulus and the participant's joystick response. Relative RT is (RT – baseline RT) where baseline RT is the average response time in the baseline condition (finger straight forward, aligned with the allocentric frame, see A in Fig. 5.4). Baseline RT values were calculated individually for each participant. The use of relative RT in the analysis eliminates baseline differences between participants and makes the effect of hand orientation easier to detect.

In the analysis of Experiments 2 and 3, all incorrect responses were rejected from the data set, along with outlier relative RT values that were more than three standard deviations from the subject's mean for a given orientation. In Experiment 2, 241 trials were rejected due to errors (3.0% of total data) and 172 trials were rejected as outliers (2.1% of total data). Additionally, all data from one participant were rejected from

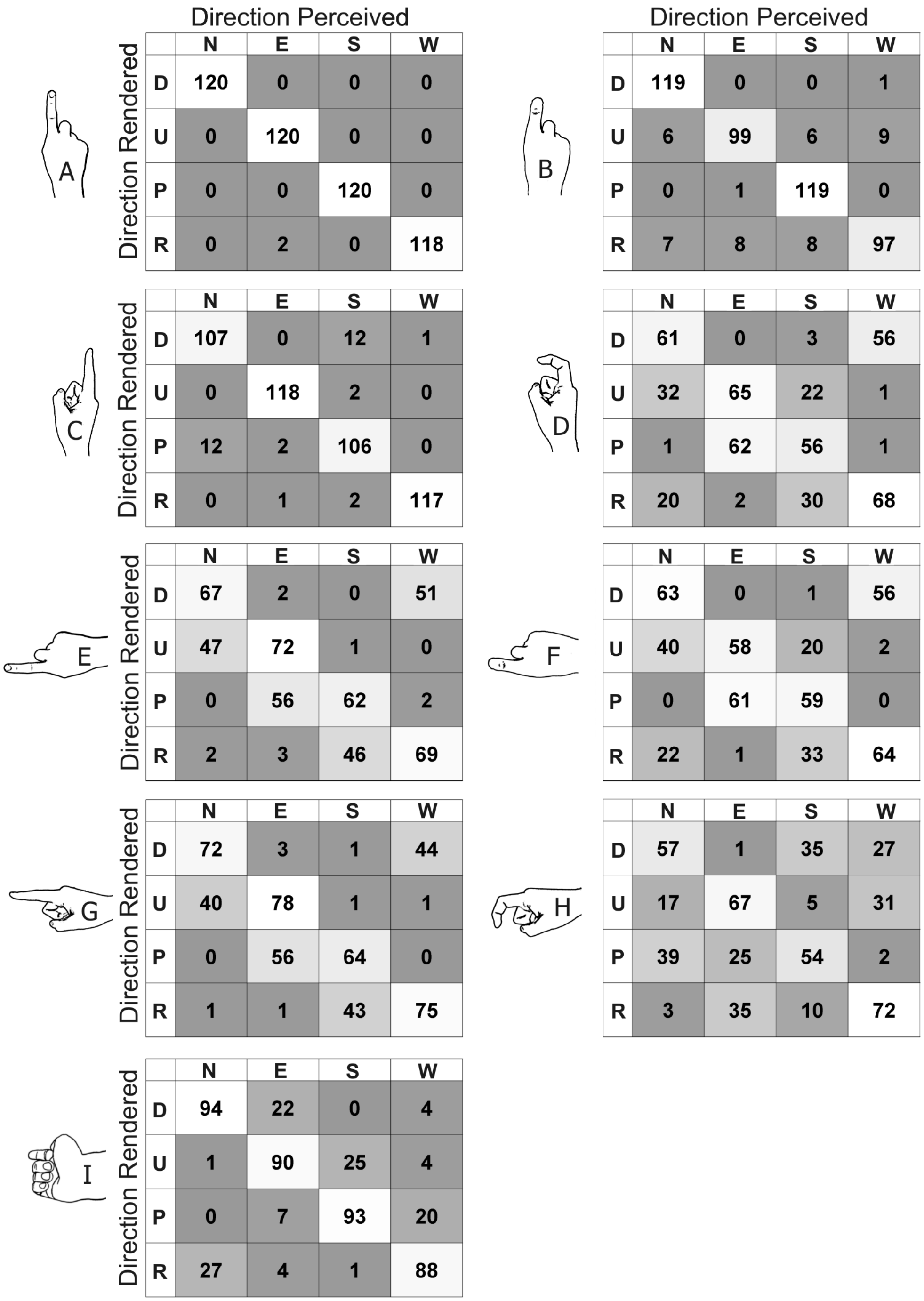
Experiment 2, due to the participant's unusually high error rate (> 3 standard deviations above the group mean). In Experiment 3, 564 trials were rejected for incorrect responses (4.6% of total data) and 258 trials were rejected as outliers (2.0% of total data).

Except where specified below, data were pooled between all trials and all participants. Curve fits were applied to pooled subject means for each orientation using a least squares optimization. Standard statistical methods were employed in data analysis.

Results and Discussion

Direction Cue Error Rate and Reaction Time

Experiments 2 and 3 use response time (RT) as a measure of task difficulty. Participants were not instructed that time was an important factor in Experiment 1, so these data were not analyzed for the first experiment. We tested the correlation between RT and error rate to ensure that the interpretation of our data was not confounded by speed-accuracy tradeoff effects (c.f. [19]). This analysis of correlation addresses the following question: do larger RTs accurately indicate greater task difficulty, or are participants merely choosing a different point on the speed-accuracy continuum for each finger orientation? The data show a positive correlation between RT and error rate, the opposite of what one would expect in the case of a speed-accuracy tradeoff, implying that RTs can be used as a measure of task difficulty. The positive correlation, as measured by Pearson's r, is statistically significant for all three experiments, Exp. 1: ($r = 0.81$, $p = 0.008$), Exp. 2: ($r = 0.94$, $p < 0.001$), Exp. 3: ($r = 0.96$, $p < 0.001$).



	N	E	S	W
D	120	0	0	0
U	0	120	0	0
P	0	0	120	0
R	0	2	0	118

	N	E	S	W
D	119	0	0	1
U	6	99	6	9
P	0	1	119	0
R	7	8	8	97

	N	E	S	W
D	107	0	12	1
U	0	118	2	0
P	12	2	106	0
R	0	1	2	117

	N	E	S	W
D	61	0	3	56
U	32	65	22	1
P	1	62	56	1
R	20	2	30	68

	N	E	S	W
D	67	2	0	51
U	47	72	1	0
P	0	56	62	2
R	2	3	46	69

	N	E	S	W
D	63	0	1	56
U	40	58	20	2
P	0	61	59	0
R	22	1	33	64

	N	E	S	W
D	72	3	1	44
U	40	78	1	1
P	0	56	64	0
R	1	1	43	75

	N	E	S	W
D	57	1	35	27
U	17	67	5	31
P	39	25	54	2
R	3	35	10	72

	N	E	S	W
D	94	22	0	4
U	1	90	25	4
P	0	7	93	20
R	27	4	1	88

Fig. 5.6 Pooled results from Experiment 1. Confusion matrices for each finger orientation show the distribution of participant responses for each rendered stimulus direction. See Fig. 5.7 for direction naming conventions. Numbers on the diagonal indicate a finger-aligned (egocentric) interpretation of the stimuli. Off-diagonal terms appear when participants use an allocentric, or other, interpretation. Orientations with an unambiguous allocentric interpretation show a discrete band of off-diagonal terms (e.g., condition E). Orientations without a clear allocentric interpretation show a great variety of responses (e.g., condition H).

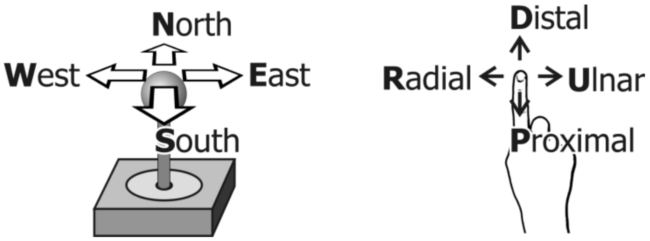


Fig. 5.7 Direction naming convention. Rendered directions are described in the finger frame. Perceived directions, as recorded by the joystick, are described in the world frame, with North pointing forward and away from the participant.

Experiment 1: Intuitive Mapping

Fig. 5.6 and Fig. 5.7 shows confusion matrices for the pooled results of Experiment 1. In general, participants responded consistently within each finger orientation. That is, for each participant and hand orientation, there was generally a 1-to-1 correspondence between stimuli and responses. That is, participants consistently gave the same response for any given stimulus direction. The median consistency, measured as the number of consistent responses divided by the total number of stimuli, was 93%.

We used a least-squared analysis to compare participant response patterns to three predicted patterns: the finger-aligned (egocentric) frame and two different world-aligned (allocentric) frames. In the finger frame, cues are interpreted in the finger-aligned reference frame with distal stimuli always corresponding to forward on the joystick. In the world frame, cues are mapped directly onto the joystick, with the participant always moving the joystick in the same absolute direction as the stimulus, regardless of finger orientation. In our experiment, however, the interpretation of the world frame is complicated when the plane of the fingerpad is not aligned with the plane of the joystick (i.e., orientations D, E, G, H and I). In these orientations, stimuli which move out-of-plane (down, towards the ground, or up, away from the ground) have no single unambiguous mapping to the joystick. We therefore tested two world-aligned response patterns which differed only in their treatment of out-of-plane stimuli: 1) World Frame 1, with downward stimuli mapped to the joystick direction coincident with the outward normal vector of the fingernail, and upwards stimuli mapped to the joystick direction coincident with the outward normal vector of the fingerpad, and 2) World Frame 2, with upward stimuli mapped to the joystick direction coincident with the fingernail normal, and downward stimuli mapped to the joystick direction coincident with normal the fingerpad normal. Note that, for some finger orientations, multiple models predicted the same response pattern. For each participant and each condition, response patterns were classified according to the minimum least-squares difference between the data and the predicted patterns. Table 5.1 shows the number of participants classified into each perceptual model.

The majority of participants interpreted the stimuli in the finger-aligned (egocentric) reference frame. In the second half the experiment, where participants experienced each finger orientation for a second time, more people interpreted direction cues in the finger-aligned frame than in the first half of the experiment. This shift suggests that users more readily interpret cues in the finger-aligned frame as they gain experience with the skin stretch stimuli used in this task. For those participants that chose an allocentric frame, the up/down stimuli (out of the horizontal plane) that had no clear allocentric mapping were generally interpreted according to World Frame 1 (downward

Table 5.1 Intuitive Response Pattern Classification

Condition	Finger Frame	World Frame 1	World Frame 2
A	**15** (15,15)		
B	**15** (15,15)		**0**
C	**15** (15,15)		**0**
D	**8** (7,10)	**3.5*** (4,4)	**3.5*** (4,1)
E	**8** (7,10)	**7** (8,5)	
F	**8** (7,9)	**7** (8,7)	0
G	**8** (8,10)	**7** (7,5)	0
H	**9** (8,10)	**3.5*** (5.5*,2.5*)	**2.5*** (1.5*,2.5*)
I	**11** (12,11)	**3** (3,3)	**1** (0,1)

Each cell indicates the number of participants whose data best fit the given model. Bold numbers give the classification of all experimental data. Numbers in parentheses give the classification of participants' responses during the first and second half of the experiment, respectively. Cells combined between multiple conditions indicate that model predictions were equivalent for the given conditions. *The responses of one subject were equally divided between two models.

stimuli mapped to the joystick direction coincident with the outward normal of the fingernail).

While most participants interpreted stimuli in the finger-aligned (egocentric) frame, there is no universal intuitive mapping behavior. For designers of tactile interfaces, these results imply that it is not feasible to design an interface that is intuitive for all users in all finger orientations. Designers could capitalize on the observed patterns, but in general it will be necessary to instruct a user how to interpret directional tactile stimuli and how they are to be mapped to the task frame. However, establishing such conventions for somewhat ambiguous information is quite common.

Experiment 2: Simple Rotation

The results of Experiment 2 demonstrate a clear relationship between RT and rotation angle, as shown in Fig. 5.8. From this result, we conclude that participants were performing a mental rotation, rotating the tactile stimuli from the fingertip frame to the allocentric frame of the response joystick using analog spatial representations, as opposed to symbolic repetitions (cf., [3]).

Participants were able to perceived the tactile stimuli and perform the requested rotation with high accuracy (mean accuracy = 97%). In general, participants made more errors at greater arm angles, but there were too few errors to perform any meaningful quantitative analysis of error patterns.

The experimental data show a sinusoidal, rather than linear, relationship between rotation angle and RT (Fig. 5.8) [Sine fit: $R^2 = 0.41$, Linear fit: $R^2 = 0.36$]. Note that curves were fit to pooled subject data, while Fig. 5.8 shows pooled means, for clarity.

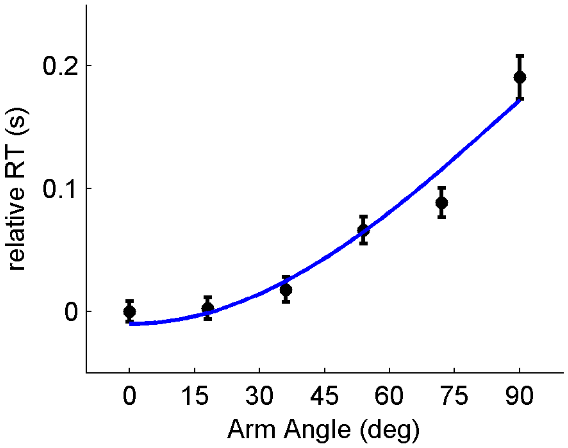


Fig. 5.8 Pooled data from Experiment 2, along with a sinusoidal fit. Error bars indicate 95% confidence intervals. For reference, the mean baseline value (absolute RT at 0°) was 0.546 s.

Other non-linear curves shapes, e.g., a parabola, fit similarly well, but a sinusoid was chosen as the most physically relevant model, following the example of prior studies [19]. The non-linear shape of our data allows us to place our results in context with earlier studies. Mental rotation time of visually perceived abstract shapes tends to depend linearly on rotation angle (e.g., [3]). Studies of mental rotation of shapes tactilely perceived with the fingertip also generally show linear trends (e.g., [15], [13], [16]). Non-linear and sinusoidal trends, however, most often appear in cases where participants exhibit embodiment effects during the mental rotation of visually or tactilely perceived human hands (e.g., [38], [6], [19], [8]) or while controlling an object through physical hand rotation [24]. The implication, therefore, is that participants in our study were mentally rotating their hand into the allocentric frame (0° position), and then interpreting the stimulus in that orientation.

Experiment 3: Compound Rotation

Results from Experiment 3 indicate that rotations of the arm, finger and wrist all increase RT, as seen in Fig. 5.9 and Fig. 5.10. An analysis of variance of all pooled data showed main effects from all three joint rotations, as well as interactions between the orientations of all joints [Main effects — Participant: $F(14,12137) = 46.4$, $p<0.0001$; Arm: $F(1,12137) = 258.8$, $p<0.0001$; Wrist: $F(1,12137) = 779.1$, $p<0.0001$; Finger: $F(1,12137) = 687.8$, $p<0.0001$]. The trend in error rate followed the same pattern as the trend in RT, but there were too few errors to conduct a meaningful analysis of error rate. Participants responded correctly to 95.7% of all stimuli, with the highest mean accuracy at orientation A (97.9%) and minimum mean accuracy at orientation H (89.7%). The increased error rate at the more extreme hand orientations could be due to the difficulty

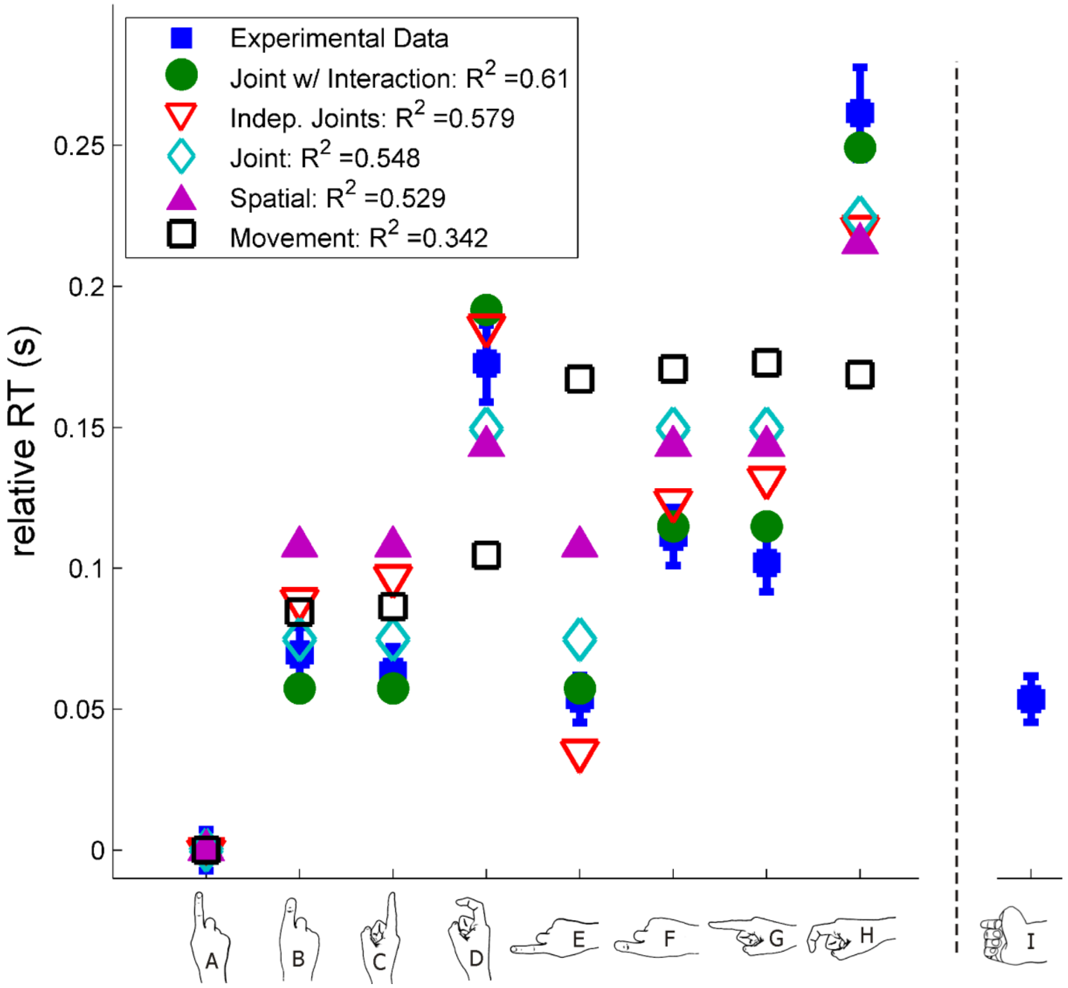


Fig. 5.9 Results of Experiment 3, along with model predictions. Error bars indicate 95% confidence intervals. For reference, the mean baseline value (absolute RT at in orientation A) was 0.484 s. Note that models were not fit to orientation I.

of the mental rotation task, or to the skewed perceptual reference frame of such hand orientations (e.g., [20]), or to a combination of these factors.

Participants' response patterns in Experiment 1 did not predict their performance in Experiment 3. We hypothesized that participants who intuitively interpreted stimuli in the fingertip frame would respond faster in subsequent experiments, but this was not the case. In general, a participant's mean Experiment 3 relative RTs did not correlate with the

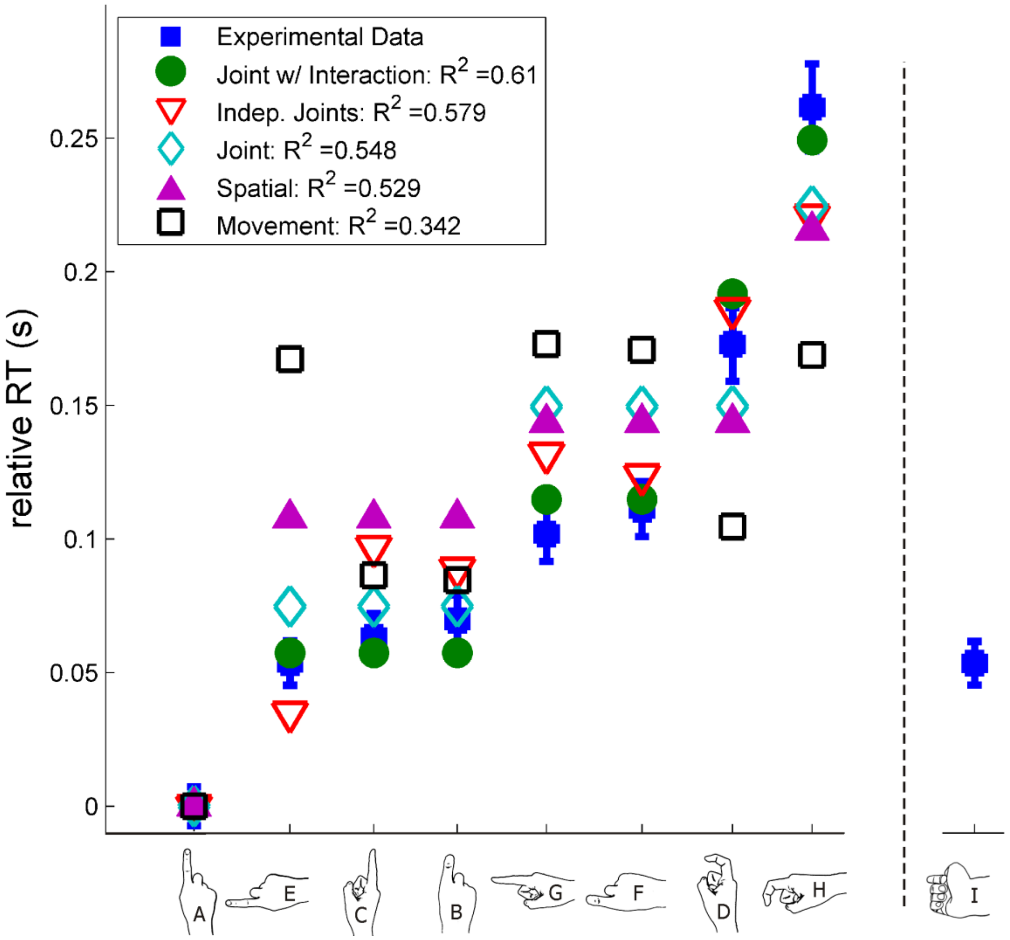


Fig. 5.10 Results of Experiment 3, showing the same information as Fig. 5.9 but with hand orientations shown in increasing order of response time cost. Note that models were not fit to orientation I.

participant's tendency to respond in the fingertip frame in Experiment 1. The exception is that this correlation was significant for condition I (r = 0.55, p = 0.034), but was not significant for any of the other eight conditions (in all other cases, p > 0.32). This result implies that the participants' ability to perform mental rotations is independent of their intuitive mapping behavior.

Models of Mental Rotation

In an effort to better understand which factors influence the cognitive cost of the mental rotation task, we tested five predictive models, as described below. All models were only applied to hand orientations A-H. Data produced by orientation I, with the hand rotated out of the horizontal plane, did not fit well into any model. Further discussion concerning condition I is revised at the end of this section. Data from Experiment 2 could not be included in the models even though Experiments 2 and 3 have two orientations in common; RTs collected from the two experiments are significantly different (for both common orientations: $t > 9.287$, $p < 0.0001$), due to the small differences in experimental task and effects of practice and fatigue. Additionally, the models tested here do not predict the intermediate angles tested in Experiment 2.

Model: Movement Execution Time

Behavioral and neural imaging studies suggest that we execute mental rotation of body parts by embodying the rotation, mentally simulating the movement of our limbs through the required rotation (e.g., [4]). Parsons compared the time required to perform mental rotations of hand images to the time required to physically execute the equivalent hand motion and found the two to be proportionally related [38]. To test the relationship between mental rotation time and physical movement time in our study, we modeled RT as

$$RT = C \cdot t_{move} \qquad [1]$$

where C is a constant and t_{move} is the time required to execute the physical movement.

Movement times were empirically determined in a small experiment conducted with four participants. For each hand orientation, the participant would move their right hand from each experimental orientation (B-H) to the baseline orientation (A) at a natural rate. The participant would press a button with their left hand when they began the motion. Contact switches were positioned to be triggered by the right index finger at the end of motion. The elapsed time required for each motion was recorded 10 times for each participant. Data were pooled between participants and averaged to obtain the values in Table 5.2.

This model fit the data poorly (R^2 = 0.342), as seen from the data labeled "Movement" in Fig. 5.9. When participants moved their hand and arm, they would move all joints simultaneously, so that additional joint rotations added no additional movement time. The mental rotation data, however, show a clear additional cost for additional joint rotations. We therefore conclude that movement time is a poor predictor of the cognitive

Table 5.2 Model Parameters

Condition	Joint Angle (finger, wrist, arm) (deg)	Spatial Angle (deg)	Movement Time (s)
A	(0,0,0)	0	0
B	(90, 0, 0)	90	0.37
C	(0, 90, 0)	90	0.38
D	(90, 90, 0)	120	0.46
E	(0, 0, 90)	90	0.74
F	(90, 0, 90)	120	0.76
G	(0, 90, 90)	120	0.77
H	(90, 90, 90)	180	0.75

cost of mental rotation, and suggest that, in this case, embodiment and mental simulation do not fully account for the observed data.

Model: Spatial Rotation

A second model considered pure spatial rotation, without regard for principle axes or joint anatomy. For example, orientation D was modeled as a single rotation of 120° around an oblique axis. This model represents the optimal rotation method with the smallest possible rotation angles, using parameters shown in Table 5.2 and the following equation

$$RT = C \cdot \theta_{spatial} \qquad [2]$$

where C is a constant and $\theta_{spatial}$ represents the optimal rotation angle. This model predicts RT only moderately well ($R^2=0.529$), as shown from the data labeled "Spatial" in Fig. 5.9, implying that participants did not use simple spatial rotations in the experimental task. This result agrees with earlier work showing that participants have unable to effectively perform mental rotations around such oblique axes [39].

Model: Joint Rotation

As pure spatial rotations could not account for the observed data, we considered a model where the cognitive cost is proportional to the sum of all joint rotations:

$$RT = C \cdot \sum \theta_{joints} \qquad [3]$$

where C is a constant and $\Sigma\theta_{joints}$ is the sum of all joint rotations, as given in Table 5.2. The slightly improved fit of this model ($R^2=0.548$), as shown by the data labeled "Joint" in Fig. 5.9, suggests that mental rotations may have been processed on the joint level in this experiment. However, as each joint rotation may have different cost and interactions between joints may be significant, more complex joint rotation models were also investigated.

Model: Independent Joint Rotation

While the previous model assumed that rotation around all joints incurred the same cost, this model considers an independent cost for each joint:

$$RT = C_1 \cdot \theta_{figner} + C_2 \cdot \theta_{wrist} + C_3 \cdot \theta_{arm} \qquad [3]$$

where C_i is a constant and θ_x is a joint rotation. While this model fits the data better than the previous model ($R^2=0.579$ vs. $R^2=0.548$), as seen from the data labeled with "Indep. Joints" in Fig. 5.9, the fit is not statistically significant [$F(3,116) = 2.09$, $p = 0.106$]. That is, these three constants (three individual joint angles) do not account for a statistically significant amount of the variance in the data. We therefore conclude that rotations of the finger, wrist and arm do not have significantly different costs.

Model: Joint Rotation with Interaction

Fig. 5.9 shows that rotation of both the finger and wrist (i.e., conditions D and H) incurs a greater cost than the sum of the costs associated with the two individual rotations. We therefore tested a model with interaction between the finger and wrist. An analysis of variance justified the choice of this interaction term; while all interactions are statically significant, the interaction between the finger and wrist is the strongest [F(1,12137)=107.44, p<0.001]. The model is shown below:

$$RT = C_1 \cdot \sum \theta_{joints} + C_2 \cdot \theta_{finger} \cdot \theta_{wrist} \qquad [4]$$

where C_i is a constant and θ_x is a joint rotation. This model fits the data well ($R^2=0.610$), as seen from the data labeled with “Joint w/ Interaction” in Fig. 5.9. Unlike the previous model ("Model: Independent Joint Rotation"), this fit is statistically significant [F(2,117) = 4.25, p = 0.017]. Moreover, when treating "Model: Joint Rotation" and "Model: Joint Rotation with Interaction" as nested models, the addition of the interaction term is a statistically significant improvement [F(1,5)=29.83, p=0.0028]. Thus, we conclude that in the tested mental rotation task, the cognitive cost of the rotation is proportional to the sum of all joint angles, that all joints contribute an approximately equal cost, and that rotations of the index finger and wrist interact, adding additional cost.

Special Case: Orientation I

The poor fit of orientation I is predicted by the literature; the time required for mental rotation of images of hands depends on the axis and direction of rotation [38]. The RT for condition I is not significantly different than RTs for conditions C and E, both of which feature a straight finger and a single rotation [F(2,4123)=0.0367, p=0.197]. This suggests that the rotation of the arm down out-of-plane may not incur as large of a cognitive cost as other rotations, although additional experiments are required for any definitive conclusions about out-of-plane rotations. The low cost of orientation I is encouraging for device designers, as this orientation represents a common carrying position for a handheld device.

Conclusion

Our results suggest that directional haptic cues could be used effectively in applications where some mental rotation would be required. Despite the combined difficulties of the mental rotation task and the skewed perceptual reference frames at extreme finger orientations, participants were able to identify the direction of the tactile stimuli quickly and with high accuracy.

The relationship between finger orientation and RT show that, even with such simple four-direction stimuli, participants mentally processed the stimuli using analog spatial representations. The sinusoidal nature the angle-RT curve suggests that rotations of small angles (say, 0-40°) can be executed without great cost, but that larger rotations should be avoided, if possible, when designing a haptic interface. We infer from the results of Experiments 2 and 3 that rotations of all joints will incur a similar, sinusoidally varying cost, but this must be verified in future work. The strong interaction between finger and wrist rotation recommends an interface design that prevents such hand postures. Our study of intuitive mapping between reference frames failed to find a single pattern common to all users. However, as participants' intuitive mapping behavior did not significantly relate to their later performance, the variations in mapping should not adversely impact the utility of a haptic interface.

In future work, we continue to refine the models relating finger orientation and cognitive cost. To verify that RT is a function of the sine of rotation angle, we will test angles greater than 90° and less than 0°. The model relating rotations of the various joints to RT will be improved by gathering data from several intermediate angles. Because our models were unable to accurately predict the results obtained from orientation I, we will conduct separate studies to investigate hand positions that lie outside of the transverse (horizontal) plane. Other opportunities for further research include the effect of continuously changing finger orientation and the interaction of mental rotation with other simultaneously executed tasks.

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CHAPTER 6

CONCLUSION

Lateral skin stretch is an effective and practical means for providing tactile feedback. Users unambiguously and intuitively perceive the direction of the skin stretch stimuli with little confusion between directions. Because only very small displacements are required, a small, portable device can easily render useful skin stretch stimuli, making these stimuli practical for use in handheld devices. The aperture-based interface provides a convenient means of incorporating a skin stretch device into a consumer product without sacrificing communication accuracy. The issue of mental rotation inherent to finger-based tactile stimuli does complicate the interpretation of directional stimuli, but the cognitive cost of these rotations is acceptably small and direction identification accuracies remain high over a range of finger orientations.

Future Work

All benchtop experiments conducted with lateral skin stretch support the use of this stimulus, but there remain several unanswered questions regarding the use of tactile communication in real-world applications. Most importantly, we must understand how tactile cues affect a user's ability to perform other important tasks and to remain aware of their environment. As most existing applications utilize audio or visual communication, we must directly compare tactile communication to these traditional channels and investigate the interactions between stimuli of different modalities.

Planned experiments include two investigations comparing audio, visual and tactile cues. The first is a desktop experiment where the participant will be required to use a joystick to track a target on a screen. At the same time they are performing this attention-demanding task, the participant will also be required to respond to directional stimuli communicated by audio, visual or tactile channels. We will monitor the participant's performance on the tracking task to discover the amount of distraction caused by the various direction cues. A second experiment will involve a more realistic, mobile task. In this experiment, participants will move through an obstacle course, receiving navigational guidance from a handheld device capable of delivering audio, visual or tactile stimuli. While walking the course, the participant will also attempt to respond to visual targets that will appear at various locations around the course. We hypothesize that the mode of navigation cuing will affect the participant's ability of to remain aware of and respond to the external visual targets. Through these experiments, we will gain a greater understanding of how tactile communication can be used in realistic applications.