Subjective Evaluation of Tactile Fidelity for Single-Finger and Whole-Hand Touch Gestures

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Abstract. This paper presents a study on the effects of tactile fidelity—the degree of exactness with which real-world tactile stimuli are reproduced—on the perception of single-finger and whole-hand touch gestures. We developed an arm-based tactile display consisting of a four-by-three grid of linear resonant actuator motors to facilitate our investigation. This device supported two extreme levels of tactile fidelity by using an extension of the previously defined Tactile Brush algorithm. At the highest level, all twelve motors could be used to provide an average displayed tactile resolution of one actuation per 12 cm^2. At the lowest level, the four corner motors of the grid could be used to provide an average displayed tactile resolution of one actuation per 36 cm^2. We conducted a study in which every participant blindly compared these two levels of tactile fidelity for four single-finger touch gestures and six whole-hand touch gestures. Our results indicated that the higher level of tactile fidelity was significantly preferred and accepted for all six whole-hand touch gestures and for two of the four single-finger gestures. We discuss the implications of these results for the development of grid-based tactile displays and provide some virtual reality application areas that could take advantage of using whole-hand touch gestures.

Keywords: Tactile Fidelity · Touch Gestures · Displayed Tactile Resolution

1 Introduction

The sense of touch is an important perceptual function that provides vital information about the environment around us. Because of this, many researchers have investigated tactile technologies, control algorithms, and percepts to communicate complex information and symbolic meanings to users. These works are particularly relevant to virtual reality (VR) systems, which heavily rely on virtual objects that have no physical instantiations, and hence, provide no tactile feedback without additional technologies. Depending on the type of touch, it can be challenging to identify the appropriate technology to simulate realistic tactile feedback. More realistic tactile displays can require heavy and expensive hardware, and they are often specialized to provide specific tactile

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sensations. Naturally, researchers and practitioners would prefer simple, more-affordable tactile displays that could accommodate a variety of tactile sensations.

To that end, researchers have studied how perceptual illusions can provide more realistic tactile sensations with limited tactile display technology. For example, phantom sensations and apparent motions are two types of tactile illusions that take advantage of stimuli timing, intensity, and spatial configuration to provide a variety of different tactile sensations with a limited number of vibration points. A *phantom tactile sensation* is the perception of a nonexistent tactile stimulus between two real tactile stimuli [1]. This is also known as the funneling illusion [2] and is created by placing two vibrotactile actuators in close proximity of one another. Another tactile illusion is *apparent tactile motion*, which is the perception of a nonexistent moving stimulus due to a time delay between onsets of multiple real tactile stimuli [3]. With the apparent motion illusion, the real stimuli are not perceived. Instead, only the nonexistent moving stimulus is sensed, provided that the real tactile actuators are close enough to one another and their actuation times overlap [4].

The effectiveness of tactile illusions depends on the properties of the real tactile stimuli. For instance, researchers have studied the appropriate *durations of stimulus* (DOS; how long the stimulus is displayed) and *stimulus onset asynchronies* (SOA; the time interval between onsets of subsequent actuations) [3]. In addition to DOS and SOA, previous studies have investigated the effects of varying the frequencies, amplitudes, and spacing of vibrotactile actuators. However, studies involving spacing have mostly looked at the distance between two actuators for a single degree of freedom (DOF). The study of the average area covered by a single actuator, or *displayed tactile resolution* [5], has been mostly unexplored. Note that displayed tactile resolution is different from “tactile resolution”, which commonly refers to the smallest distance between two stimuli that the user can still perceive the stimuli as different [6].

Prior studies of phantom sensations and apparent motions have focused primarily on touch gestures involving a single point of contact on the skin at any one moment that can be static or dynamic. Static touch gestures involve touching a relatively restricted body location, such as tapping a person on the shoulder, while dynamic gestures involve continuous movement from one point to another, such as running a finger down someone’s arm [7]. In contrast to single-point or single-finger touch gestures, whole-hand touch gestures involve multiple, simultaneous points of contact, such as a whole hand touching the arm or rubbing it up and down. While many researchers have studied single-point gestures, there has been little research on whole-hand touch gestures.

In our work, we studied the perceived realism of different types of single-finger and whole-hand touch gestures on an upper arm. To display the whole-hand touch gestures, we extended the previously published Tactile Brush algorithm [8] to support multiple points of contact. Because prior research has shown that tactile illusions depend on a display’s level of *tactile fidelity* (i.e., the level of exactness with which real-world tactile stimuli are reproduced), we investigated how the level of displayed tactile resolution influences the perceived realism of single-finger and whole-hand person-to-person touch gestures, such as those used in social settings. We focus on displayed tactile resolution since its effects on perceived realism have previously been largely unstudied.

To facilitate our investigation, we created an arm-based tactile display consisting of a 4-by-3 grid of linear resonant actuators (LRAs). The device supported two extreme levels of displayed tactile resolution: a *low tactile fidelity* configuration with one actuation per 12 cm^2, and a *high tactile fidelity* configuration with one actuation per 36 cm^2. We used the display to investigate what level of tactile display fidelity is necessary to effectively reproduce ten different single-finger and whole-hand touch gestures. Participants blindly compared the two levels of fidelity for each touch gesture by watching a video of the real-world gesture and choosing which level they felt best represented the depicted gesture. They then rated its accuracy and acceptability. Our results indicated that the higher level of tactile fidelity was significantly preferred and accepted for all six whole-hand touch gestures and two of the four single-finger gestures. We discuss the implications of these results on the development of grid-based tactile displays and provide some applications that could benefit from the use of whole-hand touch gestures.

2 Related Work

Here, we focus on literature pertaining to grid-based tactile displays, DOS, SOA, frequency, amplitude, and spacing. In overview, researchers have investigated many single-point touch gestures, such as conveying single points of contact, displaying linear and circular directions, and generating two-dimensional curves for tracing alphanumerical characters. However, complex touch gestures with multiple, simultaneous points of contact are largely missing from prior research. Additionally, the spacing of tactile stimuli has mainly been investigated for 1-DOF motions only. Hence, our investigation into the effects of displayed tactile resolution on whole-hand touch gestures addresses multiple gaps in the following literature.

2.1 Grid-based Tactile Displays

One of the earliest grid-based tactile displays was the tactile-vision substitution system (TVSS) developed by Collins [9]. This display consisted of a 20-by-20 grid of vibrating pins that could be simultaneously activated to display an alphanumerical character. Loomis [10] evaluated users' ability to recognize characters with this device and found an average recognition accuracy of 51%. Later, Saida et al. [11] used the apparent motion phenomenon to display the tracing of a character with a 10-by-10 TVSS display. They found that apparent motion afforded a higher recognition accuracy of 95%. By using tactor motors, Yanagida et al. [12] were able to achieve 87% character-recognition accuracy with only a 3-by-3 grid display.

Some researchers have used grid-based tactile displays to investigate a sensory illusion similar to apparent motion called "sensory saltation". To induce sensory saltation, three brief pulses are displayed at the closest actuator, followed by three more at the middle actuator, and finally three more at the farthest actuator. These successive localized actuations are commonly observed as an evenly distributed set of actuations from the closest actuator to the farthest. But unlike the smooth sensation of apparent motion, the saltation phenomenon is characteristically discrete, as if a tiny rabbit was hopping from the closet actuator to the farthest [13]. Tan et al. [14] used this phenomenon and a 3-by-3 grid of tactors to investigate direction recognition. They found users could recognize eight distinct cardinal and intermediate directions with accuracies from 79% to 91%. Schönauer et al. [15] have also investigated sensory saltation with a 3-by-4 tactile display for providing dynamic feedback for a motion guidance application.

2.2 Durations and Asynchronies of Tactile Stimuli

Early on, researchers began investigating the effects of varying the parameters of apparent tactile motion. Two of the first parameters investigated were DOS and SOA. Shimizu [16] looked into the effects of DOS and SOA for a 7-by-9 pin display placed on users' palms. In his first experiment, he found that increasing SOA afforded faster responses for a character recognition task. In his second experiment, he found that increasing DOS improved recognition accuracy. In much more recent research, Niwa et al. [17] used a 2-tactor array on the upper arm to find similar results for recognizing single-axis directions. They found that increasing DOS and SOA improved direction recognition and that recognition accuracies were around 95% when a time interval greater than 400ms was used. Israr and Poupyrev [4] also investigated the effects of SOA on apparent tactile motion, but for the forearm and the back. They found that the range of acceptable SOA varied with DOS and body site. These results indicate that a longer DOS and larger SOA will yield more-accurate recognitions of touch gestures.

2.3 Frequencies and Amplitudes of Tactile Stimuli

Researchers have also investigated the effects of varying frequency and amplitude for vibrotactile stimuli on various perceptions. For example, Cholewiak and Collins [18] investigated the effects of frequency on a localization task, in which users identify where the tactile stimulus is perceived. In four different experiments, they repetitively found no significant effect of varying frequency on their localization tasks. In other work, Seo and Choi [19] investigated the effects of amplitude on perceived intensity and location using two vibrotactile actuators in a mobile device. They found that the perceived intensity of a phantom actuator was much more consistent when the amplitudes of two neighboring LRA motors were logarithmically scaled instead of linearly scaled. However, in a similar study, Israr and Poupyrev [4] found no significant effects of amplitude on the range of SOA. They later exploited this fact to develop their Tactile Brush algorithm [8], an algorithm for producing smooth, two-dimensional apparent motions. In the same work, they also found a significant effect of frequency on the range of SOA.

2.4 Spacing of Tactile Stimuli

Cholewiak and Collins [18] investigated the effects of spacing on localization and found that a larger spacing (5.08 cm) afforded significantly better accuracy than a smaller spacing (2.54 cm). However, Cha et al. [20] found that apparent motion was difficult to distinguish when the spacing of the actuators exceeds 8 cm. Israr and

Poupyrev [4] found that the acceptable range of SOA decreased when the spacing of their actuators was doubled from 6 cm to 12 cm for the forearm, but not for the back. Finally, Niwa et al. [17] found in their second experiment that four tactors placed around the arm afforded nearly 100% direction recognition for circular apparent motion while three tactors provided 90% at best. The results of these works indicate that there may be an optimal range for spacing between 2 cm and 8 cm.

3 An Extended Tactile Brush Algorithm

For our research, we wanted to investigate the perceived realism of whole-hand touch gestures that utilized phantom tactile sensations and apparent motion. In prior work, Israr and Poupyrev [8] presented the Tactile Brush algorithm for producing smooth, two-dimensional apparent tactile motions. While this algorithm is effective for displaying single-point touch gestures, it does not support the rendering of whole-hand touch gestures. Hence, we modified the algorithm to better suit the needs of our research. In this section, we explain the original Tactile Brush algorithm and how our extended version renders whole-hand touch gestures.

To produce smooth motions, the Tactile Brush algorithm adheres to an energy summation model to create nonexistent phantom actuators on the gesture path. The intensity of a phantom actuator P_N is determined by setting the amplitudes of the real actuators:

$$A_N = \sqrt{1-\beta} \times P_N, \qquad A_{N+1} = \sqrt{\beta} \times P_N \tag{1}$$

where, β is the distance between P_N and A_N divided by the distance between A_{N+1} and A_N. Apparent motion is then enabled by the DOS of P_N overlapping the SOA of P_{N+1} to generate a continuous movement sensation along the gesture path, as shown in Figure 1. This algorithm allows low-resolution, grid-based tactile displays to produce smooth two-dimensional motions.

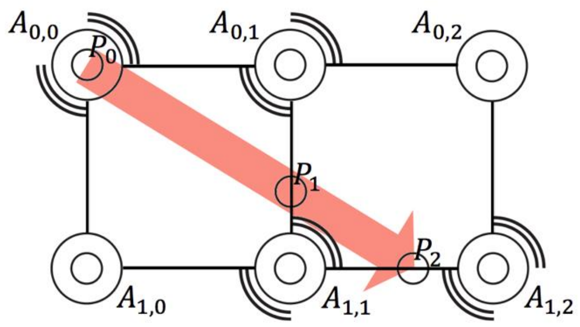

Fig. 1. The Tactile Brush algorithm produces a 2D apparent motion by using the virtual actuation points, P_0, P_1, and P_2. The real actuator $A_{0,0}$ is used for P_0. P_1 is generated by $A_{0,1}$ and $A_{1,1}$, and P_2 is generated by $A_{1,1}$ and $A_{1,2}$.

While the Tactile Brush algorithm produces smooth, two-dimensional motions, it only displays one point of contact at a time. Hence, it only supports single-finger touch gestures. However, we were interested in investigating whole-hand touch gestures, such as a whole-hand rub. To support these gestures, we extended the Tactile Brush algorithm to support multiple, simultaneous points of contact.

Initially, we assumed creating a rectangular area of contact with the Tactile Brush algorithm would be simple. We planned to display the area by activating the four phantom actuators that would define the four corners of the rectangle. However, we quickly realized that two phantom actuators on the same gesture path would require conflicting amplitudes from the contributing physical actuators. To minimize these conflicts, we simplified our whole-hand touch gestures to a multipoint line that moves along the direction of the whole-hand gesture. This line is produced by running the original algorithm on each grid line, in parallel, as demonstrated in Figure 2.

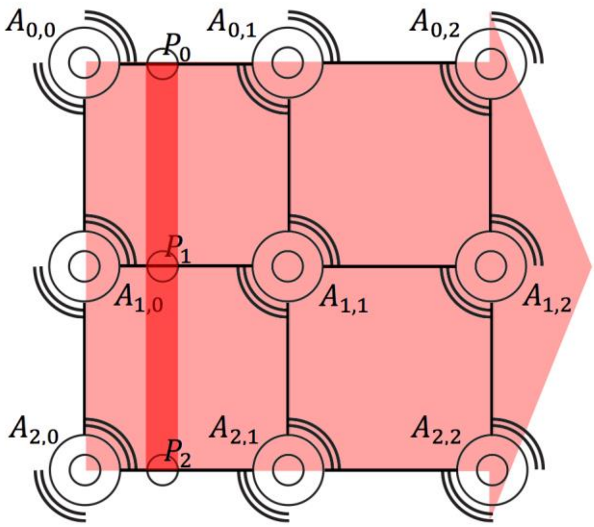

Fig. 2. Our extended version of the Tactile Brush algorithm produces multiple, simultaneous points of contact by running the original algorithm along each grid line, in parallel, to produce a multipoint line that moves along the gesture path.

4 Experiment

The goal of our experiment was to evaluate the effects of displayed tactile resolution on whole-hand touch gestures. While many researchers have investigated single-point touch gestures, whole-hand touch gestures with multiple, simultaneous points of contact are largely missing from prior research. Additionally, the spacing of tactile stimuli has mainly been investigated for 1 DOF only. Hence, our investigation into the effects of 2-DOF displayed tactile resolution on single-finger and whole-hand gestures addresses these limitations of prior research.

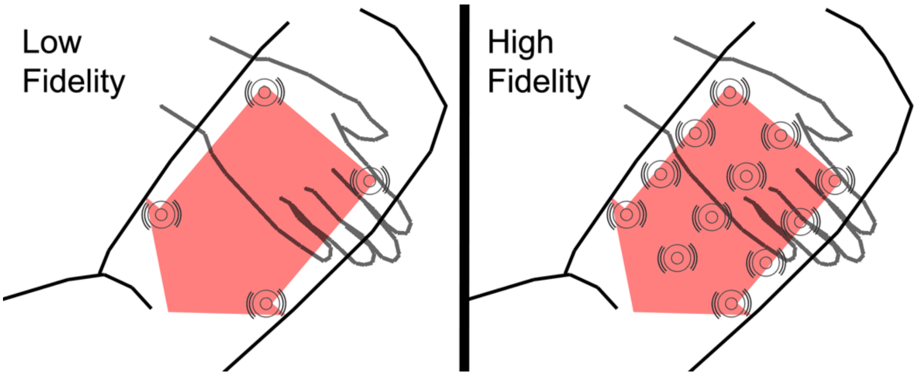

Fig. 3. For our experiment, we investigated two levels of tactile fidelity by comparing low and high displayed tactile resolutions.

4.1 Experimental Design

As discussed in section 2, most prior research studies have focused on objective tasks, such as localization or gesture recognition. However, all of these studies were investigating touch gestures that involved only one point of contact at any given time. Based on anecdotal evidence from the formative evaluations that we conducted during the development of our tactile display, we were confident that displayed tactile resolution would not have a significant impact on accurately recognizing whole-hand touch gestures, due to their distinguishable multiple points of contact.

However, we did hypothesize that displayed tactile resolution would have an impact on the subjective perception of the whole-hand gestures, with the higher resolution providing more-realistic tactile experiences for users. Therefore, we designed a subjective evaluation of displayed tactile resolution, in which users would blindly compare the two levels of fidelity and choose the one that best correlated with a visual representation of the touch gesture. In addition to their preferences, we also wanted to know what users thought of the accuracy and acceptability of the level of tactile fidelity.

4.2 Touch Gestures

For our subjective evaluation, we decided to investigate single-finger and whole-hand touch gestures. We chose a total of ten touch gestures to investigate: four single-finger and six whole-hand. The single-finger touch gestures were: 1) a single-finger touch near the elbow, 2) a single-finger touch near the middle of the upper arm, 3) a single-finger touch near the shoulder, and 4) a single-finger stroke from the shoulder to the elbow. We used the original Tactile Brush algorithm to render these.

The whole-hand touch gestures were: 5) a whole-hand touch near the middle of the upper arm, 6) a repetitive whole-hand pat near the middle, 7) a whole-hand stroke from the shoulder to the elbow, 8) a repetitive whole-hand stroke between the shoulder and the elbow, 9) a whole-hand stroke across the middle of the upper arm from front to back, and 10) a repetitive whole-hand stroke across the middle between the front and back. We used our extended Tactile Brush algorithm to render these. Based on prior research results, we hypothesized that displayed tactile resolution would have a significant effect on the perception of the whole-hand touch gestures, but not on the perception of the single-finger touch gestures.

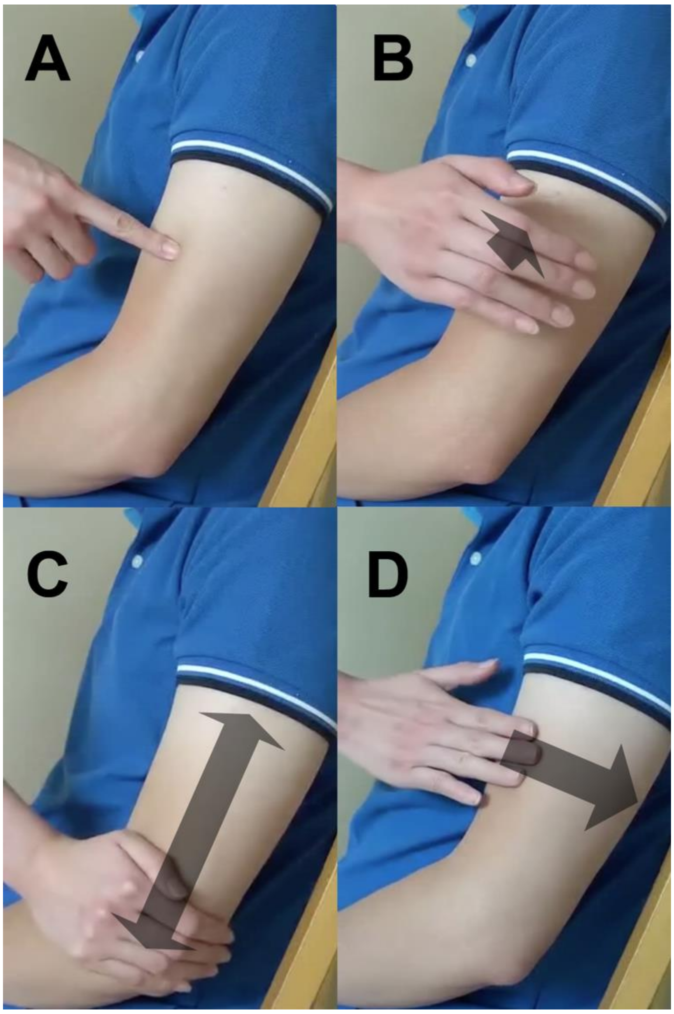

Fig. 4. Examples of the simple and complex touch gestures used in our subjective evaluation: A) a single-finger touch near the middle of the upper arm, B) a repetitive whole-hand pat near the middle, C) a repetitive whole-hand stroke between the shoulder and the elbow, and D) a whole-hand stroke across the middle from front to back.

4.3 Tactile Display

To enable our investigation of displayed tactile resolution and whole-hand touch gestures, we created a grid-based tactile display like the one presented by Tang et al. [21]. Our tactile display consisted of an Arduino Mega 2560 microcontroller, a 4-by-3 grid of LRA motors, and an elastic compression sleeve, seen in Figure 5. The display supported two extreme levels of display tactile resolution. At the lowest level, the four corner LRA motors of the grid were activated to provide one actuation per 36 cm^2. At the highest level, all twelve motors were activated to provide one actuation per 12 cm^2. To calculate the displayed tactile resolution for each level, we followed the convention presented by Pasquero and Hayward [5]. First, we calculated the area covered by the tactile grid. Since our tactile sleeve is elastic, we calculated this based on an average user using the medium sleeve size, which yields an area of 144 cm^2. We then determined the ratio of actuators to area to calculate the displayed resolution.

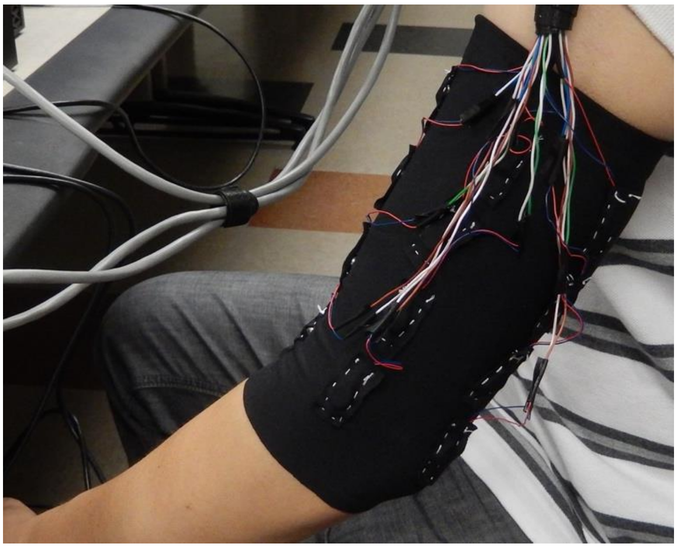

Fig. 5. Our tactile display. A 4-by-3 grid of LRA motors covers the exterior of the user's upper arm. Small, medium, and large versions were created to accommodate users with different-sized arms. Proper placement aligns the center column of motors with the center of the exterior arm.

4.4 Procedure

After giving informed consent, participants were given a background survey to collect general demographic information (e.g., gender, age, dominant hand, etc.). The participants were then asked to try on the three different-sized tactile sleeves to determine which one best fit their left upper-arm. At this time, the experimenter ensured that the center column of actuators aligned with the center of the exterior portion of the upper arm for proper placement.

The participants were then presented with a simple graphical user interface for evaluating the fidelity levels. For each gesture trial, the interface would play a video of the real-world touch gesture. A “Replay Video” button allowed participants to view the video multiple times. The interface also included two radio buttons for “Config 1” and “Config 2”. For each trial, the two levels of fidelity were randomly assigned to these radio buttons. This allowed for a blind comparison of the two levels and avoided any potential effects of ordering. A “Run” button would render the fidelity configuration currently indicated by the radio buttons to the tactile sleeve. Each configuration could be ran multiple times. Once the participants decided upon which configuration they preferred for the gesture, they were asked to use five-point Likert scales to rate: a) how accurately the tactile sensation matched the sensation they expected from the video, and b) how acceptable that sensation would be for simulating the gesture. Participants completed ten trials, one for each gesture. The order of the trials was randomized to avoiding ordering effects.

After participants completed the ten gesture trials, they were given an ergonomics questionnaire regarding the tactile display sleeve. The questionnaires addressed potential issues relating to discomfort, device weight, excessive pressure, and slippage. Finally, participants were asked to provide any additional comments.

4.5 Participants

We recruited 30 unpaid participants (25 males, 5 females) for our experiment. The age range of the participants was 18 to 50 years old with a mean age of 24.4 years. Only three participants were over the age of 30. All the participants were right handed. Hence, everyone wore the display on his or her non-dominant arm given our setup.

4.6 Results

We analyzed the selections of preferred touch gestures by using a Pearson’s chi-squared test for each gesture to compare the probability of tactile fidelity selections to the neutral split that would be expected due to chance alone. Table 1 shows these test results, and Figure 6 shows selection frequency per gesture. The higher level of displayed tactile resolution was significantly preferred for all gestures except gesture 1 (a single-finger touch near the elbow) and gesture 3 (a single-finger touch near the shoulder). Considering the type of gesture, we note that the higher level of tactile fidelity was significantly preferred for all six complex touch gestures. For simple touch gestures, higher fidelity was significantly preferred for two of the four gestures (the preferred gestures were a single-finger touch near the middle of the arm and a single-finger stroke from the shoulder to the elbow). We interpret these results to mean that higher displayed tactile resolution is more important for touch gestures occurring within squares of the display grid.

Table 1. Analysis of tactile resolution preferences with Pearson's chi-squared tests show that the higher fidelity was significantly preferred at $p < 0.05$ for all gestures except 1 and 3.

	Gesture	χ^2	p	**Sig. Pref.**
1	Single-finger touch near elbow	0.133	0.715	-
2	Single-finger touch near middle	8.533	0.003	High
3	Single-finger touch near shoulder	2.133	0.144	-
4	Single-finger stroke from shoulder to elbow	6.533	0.011	High
5	Whole-hand touch near middle	10.800	0.001	High
6	Whole-hand pats near middle	6.533	0.011	High
7	Whole-hand stroke from shoulder to elbow	10.800	0.001	High
8	Whole-hand strokes between shoulder and elbow	22.533	< 0.001	High
9	Whole-hand stroke from front to back	4.800	0.028	High
10	Whole-hand strokes between front and back	13.333	< 0.001	High

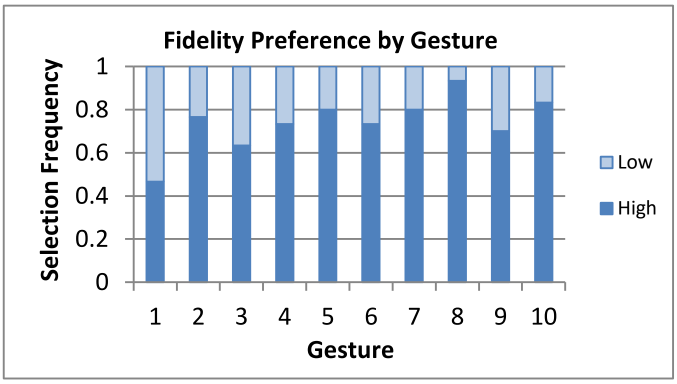

Fig. 6. Selection frequency of low and high levels of tactile fidelity show that the higher level was preferred over the lower level for all gestures except gesture 1.

In addition to selecting the preferred level of fidelity for each gesture, participants rated the accuracy and acceptability of the chosen tactile sensation. Participants rated accuracy on a five-point Likert scale, from 1 (the gesture does not match at all) to 5 (the gesture definitely matches). They rated the acceptability of the touch gesture also on a 5-point scale, from 1 (completely unacceptable) to 5 (completely acceptable). Mean accuracy and acceptability ratings are shown in Figure 7 and Figure 8, respectively. Note that the participants only rated their selected level of fidelity for each gesture, so the number of ratings per gesture/fidelity combination is dependent upon the frequency of the combination shown in Figure 6. Nevertheless, the accuracy ratings are relatively high with all mean ratings being between 3 (the midpoint) and 5 (definitely matches). Overall, we interpret these ratings as evidence that the tactile sleeve and our modified Tactile Brush algorithm performed reasonably well for simulating the simple and complex touch gestures.

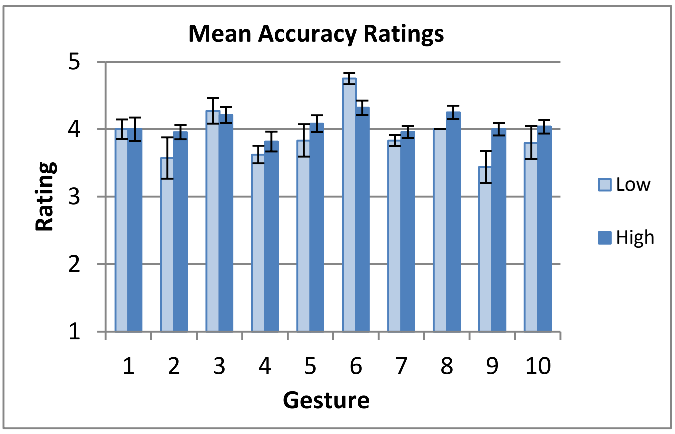

Fig. 7. Selection frequency of low and high levels of tactile fidelity show that the higher level was preferred over the lower level for all gestures except gesture 1.

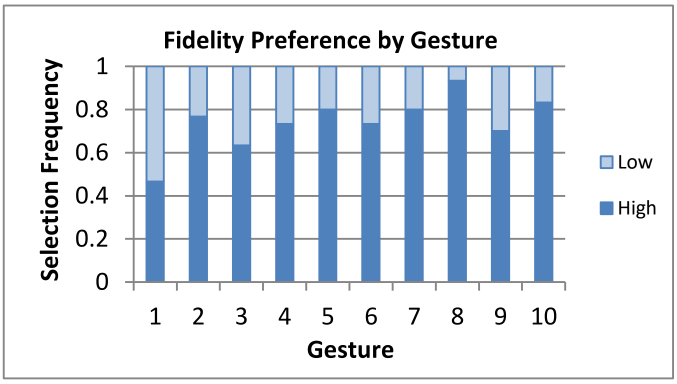

Fig. 8. Selection frequency of low and high levels of tactile fidelity show that the higher level was preferred over the lower level for all gestures except gesture 1.

However, the acceptability ratings indicate that some participants were not happy with gesture 7 (a whole-hand stroke from the shoulder to the elbow) and gesture 8 (repetitive whole-hand strokes between the shoulder and elbow). Figure 8 shows that acceptability ratings for the low and high fidelity versions of each gesture are relatively close for all except these two gestures. Our interpretation of these differences is that the few participants who selected the low fidelity versions of gestures 7 and 8 were not convinced that the rendered gestures simulated the feeling of whole-hand strokes along the arm. Considering that the majority of participants preferred and accepted the high-fidelity versions of these gestures, these results indicate that some participants may have higher expectations than others when it comes to the acceptability of touch gestures. We note that the rating differences were not affected by gender.

With regard to the ergonomics of our tactile display, there were very few negative reports. Three of the 30 participants reported discomfort from wearing the sleeve, with all three citing numbness due to the vibrations. One of the participants reported that the device was heavy due to the wires connecting the actuators and haptic drivers. The biggest complaint was excessive pressure, with six participants reporting pressure just above the elbow crease due to the compression sleeve.

5 Discussion

Given the results of our study, there are several implications for the design of grid-based tactile displays, as well as potential VR application areas for whole-hand touch gestures. We also believe that whole-hand touch gestures could be used to identify participants that suffer from anaphia—the total or partial absence of tactile sense.

5.1 Implications for Grid-based Tactile Displays

Considering the mean accuracy ratings for both the low and high fidelity versions of the touch gestures, we consider our extended Tactile Brush algorithm a success. As described in section 3, our extended algorithm produces apparent motion for multiple points of contact. This is an advancement over previous versions of the algorithm, which could only produce a single point of contact (though Israr and Poupyrev eluded to multiple-contact versions [8]). Given the high acceptability ratings for the high-fidelity complex gestures, we believe our extended Tactile Brush works best with higher displayed tactile resolutions, though it sufficed for most of the low-fidelity touch gestures. The biggest constraint for our algorithm is that it currently requires the contact area's width to coincide with the display's grid lines, but we believe this issue can be overcome with further research.

Another implication for grid-based tactile displays is that more is better. Higher displayed tactile resolution was significantly preferred for all gestures except for two single-finger touch gestures, and it was not preferred significantly less for those two gestures. This indicates that grid-based tactile displays, particularly those consisting of LRA motors like ours, should strive for displayed tactile resolutions of one actuator per 12 cm^2. However, we believe there is an upper limit to increasing the resolution based on Cholewiak and Collins work [18]. One actuator per 2 cm^2 is probably too much.

Finally, another design implication based on our research is that small actuators can be used to display touch gestures on small body regions. Since small actuators are exponentially cheaper than large ones and displayed tactile resolution is important, the best approach to providing tactile feedback to the entire body may be to develop many small-region devices, as opposed to using a few large-region devices. The biggest hurdle to this approach will be how to synchronously communicate to so many devices.

5.2 VR Applications for Complex Touch Gestures

In VR, the most obvious application of complex touch gestures, like our whole-hand gestures, is improved tactile feedback for large-area contacts with a virtual environment. For example, when a user is moving down a virtual hallway and leans into a virtual wall, a large contact area can be displayed moving across the user's upper arm from front to back. This could provide a more realistic experience than just vibrating the entire grid, which in turn should increase presence [22].

Another potential VR application area is telepresence. In recent work, Huisman et al. [23] developed a tactile sleeve for conveying social touch over a distance. While their 4-by-3 *TaSST* display was very similar to our display, they were using simple algorithms based on touch-sensitive compartments to render touch gestures. With our extended Tactile Brush algorithm, telepresence users' hands can be tracked in 3D space, virtually modeled to determine collisions with remote users' tracked bodies, and then rendered as realistic social touches to increase co-presence.

Finally, a third VR application area for our whole-hand touch gestures is Autism Spectrum Disorder (ASD) interventions. ASD is a pervasive developmental disorder that is characterized by restrictive interests, repetitive actions, and impaired social and communicative behaviors [24]. Individuals with ASD often exhibit secondary difficulties with sensory-perceptual anomalies that cause hypo-sensitivities and hypersensitivities [25-28]. Several first-hand accounts of individuals with ASD describe how they struggle with both hypo and hypersensitivities, limiting their contact with other people [29-31]. An example would be feeling overwhelmed from a hug because it feels like sandpaper to the touch. Researchers have already investigated and developed VR technologies and systems as promising intervention methods for ASD patients [32-35]. By utilizing our research on whole-hand touch gestures, VR intervention methods could allow hypersensitive patients to explore the physical sensation of touch without being overwhelmed by actual human contact. We are currently working on integrating our research with prior VR intervention applications to give ASD patients a chance to learn how to manage their hypersensitivities to human contact through experiences of being touched by virtual avatars [36].

5.3 Screening Tool for Anaphia Participants

Anaphia is the total or partial absence of the sense of touch. For research on tactile technologies and feedback, participants with anaphia can have a negative impact on potentially positive results. Traditionally, tactile researchers have relied on self-reports to exclude such participants. However, this method is inherently flawed as self-reports have been shown in many studies to be unreliable.

As an alternative to using self-reports to identify participants with anaphia, we propose that the selection trial for gesture 8 from our study could be used as a screening tool. For gesture 8 (the repetitive whole-hand strokes between the shoulder and elbow), the higher level of displayed tactile resolution was preferred by all but two participants, and those two participants poorly rated the lower level of tactile fidelity. Hence, we believe this complex gesture trial could be used to flag participants that do not choose the higher level of tactile fidelity as potential anaphia participants.

6 Conclusions and Future Work

Although much research has been conducted on phantom tactile sensations and apparent tactile motion, most investigations have been limited to touch gestures involving single points of contact. By extending the Tactile Brush algorithm, we were able to simulate multiple points of contact. These areas enabled us to develop whole-hand touch gestures that involve multiple points of contact, such as a whole-hand pat on the arm. Using a 4-by-3 tactile display sleeve that we developed, we investigated the effects of displayed tactile resolution on preference, perceived accuracy, and acceptability of four single-finger touch gestures and six whole-hand touch gestures. Our results indicate that our extended Tactile Brush algorithm produces accurate whole-hand touch gestures, that greater displayed tactile resolutions will produce more-acceptable touch gestures than lower resolutions, and that small actuators can be effectively used to display touch gestures on small body regions.

In the near future, we are planning on investigating moderate levels of displayed tactile resolution with our tactile display sleeve, such as 2-by-3 and 4-by-2 resolutions. In addition to subjective evaluations, we will incorporate objective aspects, such as gesture recognition tasks. Later on, we plan to revisit our extended Tactile Brush algorithm. We hope to find a method of addressing its current constraint of the apparent motion being restricted to a multipoint line.

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