Detection and Identification of Pattern Information on an Electrostatic Friction Display

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***Abstract*—An electrostatic friction modulation device based on a tablet computer was used to present pattern stimuli to the fingertip for two tasks: detecting patches of friction and matching a frictional pattern to the visual image that produced it. In the detection task, friction patterns were displayed on zero, one two or three cells in a matrix. Errors, whether misses or false alarms, were few. Duration of target-present trials was a linear function of the number of patterns in the display. The intercept indicated an average of under 1 sec to test a location for the presence of a friction patch. The slope was 1.0 sec per item, representing the time to confirm friction change, verify the location, and report. In contrast to fast and accurate detection of friction modulation, identification of patterns by matching to a visual display was at chance, although the patterns were differentiated by form and scale. Given that the patterns fall within the normal acuity of the fingertip, along with previous evidence that fingertip motion per se does not preclude pattern recognition, it appears that the failure to match tactual patterns to visual images resides in processes inherent in information pickup from friction-modulation displays.**

***Index Terms*—Haptics, friction, detection, pattern identification, virtual textures**

I. Introduction

Recent years have seen the development of devices that implement tactile signals on glass touch-screens by modulating friction. The basic mechanisms capitalize on ultrasonic [1] and/or electrostatic effects [2]–[4]. In electrostatic devices, static electricity is induced when the finger moves over a conductive surface coated with a thin layer of insulator and connected to a voltage source. As described by Schultz *et al.* [5], under a Columbic kinetic friction model the applied electroadhesive force adds a component to the lateral force proportional to the kinetic coefficient of friction. Related work characterized how impedance of the skin, body, surface, and interface combine to produce the adhesive effect [6]. A model localizing the effects of electrostatic forces within the skin, at the stratum corneum, was presented in [7]. Measures of force, acceleration, and friction during use of such devices have shown complex dependencies on scanning speed [7], [8]. Speed variations and other tribological factors such as skin moisture or micro-structure may underlie the substantial individual differences in measured effects that have sometimes been reported (for example, inferred electrostatic forces varied by a factor of $\sim$5 across participants in [3]).

In principle, the implementation of friction variation in a surface can be used to convey two types of information to the fingertip: patterns and textures. Pattern refers to the layout of edges or other spatially defined features. In friction displays, patterns are primarily 2D, although 3D effects can be simulated [9]. Texture refers to a family of properties conveyed by small-scale variations in a surface. For example, two textural properties subject to rendering by friction are roughness and slipperiness. An important difference between pattern and texture is that the former depends on the locations of features within some spatial frame of reference, such as the screen or object boundaries, whereas texture is generally conveyed by small-scale local variability.

When displayed to the human fingertip, patterns and texture are distinguished not only by scale and location dependence, but also by neural coding. The mechanoreceptor population associated with encoding surface pattern is the Merkel cell complex (or SA I), which has a small receptive field (i.e., high acuity) and produces a sustained response. This population of receptors is capable of conveying the spatial array produced by varying contours or elements on a surface with resolution under 1 mm. The Merkel receptors are also believed to provide information about textures resulting from variations on a surface on the order of 2-mm scale and above [10]. Finer textures are encoded in terms of temporal variation, mediated by signals from rapidly adapting receptor populations [11], [12]. A perceptually based distinction between texture and pattern is further indicated by a lack of correlation between measures of the roughness discrimination threshold (a texture dimension) and the tactile spatial acuity needed to resolve spatial features (pattern) [13].

Early use of electrostatic forces for haptic displays noted their potential for both pattern and texture simulation. Tang and Beebe [14] tested users' ability to resolve and identify patterns with a display based on three 7×7 electrode arrays. They found a threshold of 5.8 mm for edge-to-edge column resolution and accuracy of approximately 70% for recognizing a circle, square and triangle at various sizes. Yamamoto *et al.*

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[15] reported a sensation of roughness achieved by sliding the finger on a surface of parallel electrodes that simulated textures on a tens-of-microns scale.

In more recent work on electrostatic textures, roughness perception was systematically studied in relation to friction wave-form and spacing, and dependence of roughness on the rate of change in contact force was evidenced [7]. The just-noticeable-difference (JND) in voltage amplitude for electrostatic gratings has been found to vary with waveform [16]. Textures generated from exploratory-movement data and subjected to multidimensional scaling analysis revealed underlying dimensions of roughness and stickiness similar to those recovered from real surface materials [17].

Recent work has also confirmed early indications that pattern perception fails to reach high accuracy with electrostatic displays. Tests with a device called Tesla Touch [18] found that users took on the order of 2 minutes to explore simple shapes and achieved only 56% correct identification (cf. 33% chance). Another study found accuracy of 64% for forced-choice discrimination of surfaces with bumps and holes (cf. 25% chance), and noted that the stimuli were not readily translated into geometric descriptions [19]. We will return to the factors that might limit electrostatic pattern perception in the discussion.

An attractive potential use for friction-modulated displays is to serve as refreshable control panels, particularly in situations where visual attention is otherwise diverted. Frictional signals could be re-programmed as buttons and dials according to the function desired. Automotive controls are an obvious example; under different programs, the same screen area might be used to control air flow and play the radio.

In previous research, we have explored a scenario where textural cues from friction might guide a user to friction-defined pattern locations that indicate active control points. For the purpose of guidance, we evaluated texture gradients: systematic continuous variations in friction that could be followed with the finger to give directional cues. Electrostatic gradients were developed that were easily identified as to direction (increasing rightward vs. leftward) within a 2.5 cm sweep [20]. Efforts with ultrasonic gradients were less successful, but the directions of roughness variations were nonetheless discriminated at levels well above chance [21].

In the present research, we describe efforts to develop pattern information with friction modulation. We used a prototype version of a commercial electrostatic device (Tanvas Touch Technology), which maps image greyscales to friction levels. Our experiments manipulated the size, form, and scale of pattern in two tasks: (i) detecting the presence of a friction change within a region on the screen, and (ii) identifying a friction-defined pattern by matching it to the visual image that produced it. We chose these tasks because they represent what might be useful in applied contexts like control panels. The detection task is a form of speeded search, which has been extensively studied in cognitive psychology. When the number of elements in a display is varied, the slope of detection time against display size provides an estimate of the time for individual pattern processing. The identification task indicates whether users of an electrostatic control button might easily associate its tactile features with a visual label.

II. METHOD

A. Participants

Twelve Carnegie Mellon University undergraduate students having no prior experience with electrostatic devices participated for course credit. All gave informed consent under a protocol approved by the Carnegie Mellon Institutional Review Board. Subjects were free to use their dominant hand.

B. Stimuli

The stimulus patterns consisted of a coarse fingerprint, fine fingerprint, and star. We chose these patterns because they yielded subjectively strong friction effects and the impression of variable friction levels within the pattern. The two fingerprint designs were chosen to systematically vary in spatial frequency but maintain pattern content, whereas the radial pattern percept was similar to one of the more compelling effects provided by Tanvas, a zipper. (A variety of other patterns, such as random and radial dots and pictures of textured objects like leaves and fur, were excluded because they failed to meet the criteria of within-pattern friction variability and strength.) The fingerprints were drawn by one of the authors (IS) in Adobe illustrator. The fine fingerprint was created by down-scaling the coarse version and layering copies of the result. The star was vector traced from https://www.alamy.com/stock-photo-radial-black-white-lines-with-deformation-abstract-background-93968812.html, with appropriate usage rights. Each texture was formatted in Adobe Illustrator as a black square with a circular center exposing a black and white pattern. The use of black and white produces the maximum friction contrast between regions (black is the resident friction on the glass; white is the maximum increase in friction the device delivers). The original images were 400 × 400 pixels at 72 pixels/in, but they were displayed on the tablet screen as a black mask with an open center circle exposing the image. The presentation sizes were manipulated by variations in the radius of the circle (i.e., not by scale change): 250 pixels for the large image and 170 for the small. Although the temporal frequency encountered would depend on the trajectory adopted by the finger, a span across the vertical ridges in the fingerprints and the radial arcs in the star would correspond to spatial frequencies in cycles per mm of approximately .14 for star, .29 for coarse fingerprint, and .58 for the fine fingerprint. The size of a cycle correspondingly varies from 1.7 mm to 6.9 mm. Sample images at the large size are shown in Figure 1 (not to actual scale).

C. Device

The stimuli were presented on a Tanvas Touch Technology prototype kit (version 1.0), based on a Nexus 9 tablet computer with G6 glass, using a software development kit compatible with Android Studio. The 18.0 cm × 13.5 cm screen displays 2048 × 1536 pixels, which map 1:1 to pixels in the

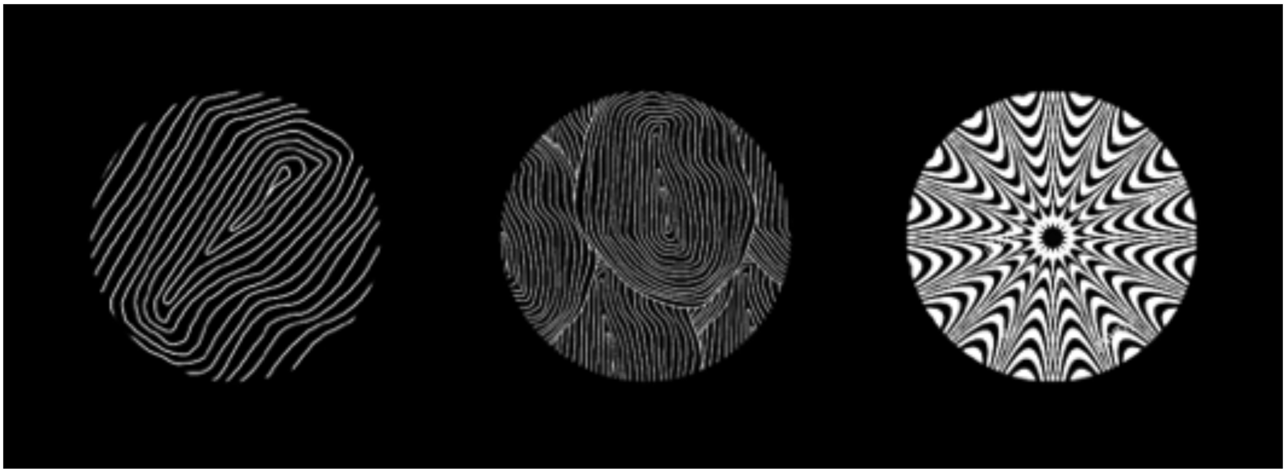

Fig. 1. Coarse fingerprint, fine fingerprint, and star pattern used in the experiments, as masked at larger size. Small size images exposed a circle with 2/3 the radius of the large images but did not differ in scale.

bitmapped stimulus image. The position of the first finger sensed to be in contact with the touchscreen is tracked by its centroid, which is reported to the tablet as a pixel location. The friction value at the corresponding pixel is rendered to an area around that pixel surrounding the fingerpad. As the sensed finger position changes on the touch panel, the rendered friction level is updated from the bitmap, and the rendering area moves with the tracked contact pixel location. Thus, at any given time, one friction level is rendered to the area around the finger centroid, while the rest of the panel is not activated. It follows that the rendering resolution is determined by the finger sensing resolution, which is much finer than the number of pixels activated, and the activated area relative to the actual finger contact area.

For purposes of the experiment, the screen displayed a 4 row by 3 column matrix of squares 3.5 cm on a side, separated by black borders. As shown in Figure 2, each cell contained a number. From 0 to 3 cells at random locations were programmed with a hidden texture, using one of the stimulus images that was held constant for all filled cells. The entire display was 14.5 cm high × 10.8 cm wide. The matrix and numbers were a visual overlay without friction alteration.

D. *Detection Task*

On each trial of the task, the participant was instructed to explore all squares to find from 0 to 3 textured patches. They were informed that the test was timed, so they should go as quickly as possible while being sure to find the "boxes" with rough patches. The trial began with a screen displaying "start next test" and showing a "yes" button. When the button was pressed, the numbered matrix appeared, and a timer was initiated. Whenever a textured cell was found during exploration, or at the end of the trial, as desired, the participant verbally reported the cell numbers (1-12) where it occurred. At the end of the trial, the participant pressed a "done" button that terminated the clock and changed the display to the next test screen.

The experimental design manipulated two variables: pattern type (6: 3 patterns at 2 sizes) and display size (number of cells in the 3 × 4 matrix that contained a pattern, from zero to three). Note that the same pattern was used for all cells of the display, if present at all. A crossing of these factors resulted in 24 distinct trial types, which were presented twice in sequence with no break between the sequences, for a total of 48 trials. Different randomizations were generated for each block and participant. Participants were given two trials for practice.

E. *Identification Task*

The same display was used as in the detection task, but now with just the cell of the matrix previously numbered 5 outlined. Hidden from the participant was a single pattern, in the larger size used previously. The experimenter also displayed a paper printout of the three test images, with the three patterns numbered (1 = coarse fingerprint at upper left, 2 = fine fingerprint at center below, 3 = star at upper right). The trial began with a start next trial screen, as before. When start was pressed, the cell appeared onscreen and a timer was initiated. The participant's task was to feel the texture as long as desired, press the "done" button, which stopped the timer, and indicate which of the three visually displayed patterns it matched. In practice, participants sometimes reported before pressing "done," rendering timing somewhat inexact. Each of the stimuli was presented 3 times, in random order.

III. RESULTS

A. *Detection Accuracy and Speed*

Errors in the detection task were infrequent. As a proportion of total number of targets presented (filled cells) in the entire experiment, the miss rate (failure to name a filled cell) was 3.9%, and the false alarm rate (naming an unfilled cell) was 4.1%. More than half the false alarms were committed by one subject and occurred particularly when no cells were filled, suggesting a bias to give some positive response. Misses predominated when display sizes were 2 and 3 (they were not possible for display size = 0, and only one miss occurred for

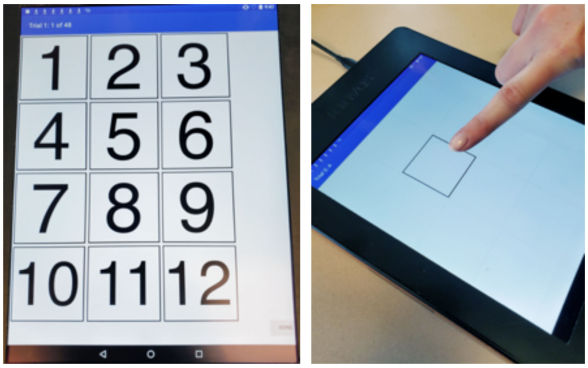

Fig. 2. Tanvas display used for detection task (left) and identification task (right).

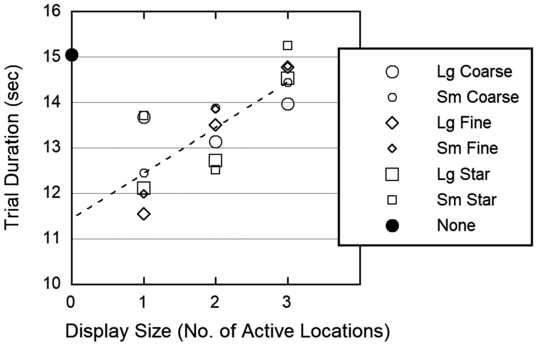

Fig. 3. Trial duration for exploration phase of experiment by display size and pattern (Lg and Sm correspond to large and small). Linear trend line for average by display sizes 1-3 is also shown.

display size = 1), suggesting memory limitations may have contributed.

Trial duration is shown in Figure 3 by display size (number of active locations in the matrix) and pattern type. An ANOVA on these factors showed a significant effect of display size, F (2,22) = 6.98, p = .004, $\eta_p^2 = .39$. The effect of display size on mean duration for displays with patterns present (i.e., excluding the empty display) was highly linear, $R^2 = .96$, with a slope of 1.0 sec/item and an intercept of 11.4 sec. There was no effect of pattern ($p > .50$). The interaction reached significance, F (10,110) = 1.99, p = .041; however, effect size was small, $\eta_p^2 = 15$. Follow-up ANOVAs on the factor of pattern within counts of 1-3 showed that none reached significance, and pattern effects will not be discussed further.

B. *Identification Accuracy and Speed*

The average rate of correct identifications was 30.6%, 38.9%, and 38.9% for the coarse fingerprint, fine fingerprint, and star patterns, respectively. Table I shows the confusion matrix. The average accuracy of 36.1% is near chance (33%). Excluding one trial where the button was not pressed to stop the clock, the average exploration time was 15.1 sec, 16.7 sec, and 17.7 sec for the coarse fingerprint, fine fingerprint, and star patterns, respectively (*s.d.s* = 9.0 sec, 12.0 sec, and 11 .5 sec, respectively). No pair of patterns differed significantly with respect to exploration time, by t-test. The median time was 13.2 sec. Although some noise may have been introduced into this measure because of occasional trials where the participant failed to press the "done" button and the experimenter had to do so, it undoubtedly is indicative of a deliberative and slow process.

TABLE I
CONFUSION MATRIX IN IDENTIFICATION TASK: COUNT OF EACH RESPONSE PATTERN FOR THE 36 PRESENTATIONS OF EACH STIMULUS PATTERN

Actual	Response		
	Coarse finger	Fine finger	Star
Coarse finger	11	11	14
Fine finger	10	14	12
Star	10	12	14
Total	31	37	40

IV. DISCUSSION

The data show a clear distinction between detection of frictional patterns and ability to match to a visual source. Detection was both accurate (nearly error-free) and rapid. With one or more patterns present, participants took an average of 13.5 sec to explore the 12-element array, or just over 1 second per cell. The slope of duration by number of patterns present, about 1 sec per item, presumably reflects the additional time needed for confirming pattern presence. This combines whatever slowing of exploration occurred due to the added friction on the display, but likely more critical components are cognitive in origin: the time to generate a positive decision and encode the corresponding number. Negative decisions were slightly slower, which is not uncommon for response-time data. Neither accuracy nor time of detection was reliably different across these stimuli, even as feature scale increased by approximately a factor of 5, size decreased by 3:2, and patterns varied from whorls to radial stripes.

In contrast to the speed and accuracy of detection, participants were nearly at chance in associating a pattern with the visual stimulus that produced it. This does not reflect a mix of good and poor performance; no participant had more than 5 items correct out of 9 trials. It also does not reflect a mix of good and bad patterns or a response bias, as the rate was near chance for all three patterns, and the confusion matrix is nearly uniform.

In considering the cause of the difficulty with pattern identification, various factors can be considered. The scale of the stimulus images is unlikely to be an issue, because even the smallest cycle size was above the basic spatial acuity of the fingertip. For example, Bruns *et al.* [22] reported acuity thresholds below 1.5 mm for a variety of tests (e.g., 2-point fusion and grating orientation). If we consider the image size in relation to thresholds measured with a frictional display, gap detection on the order of .25 mm has been demonstrated; finer frictional patterns become textural rather than spatial [23]. Again, the present images are scaled above the threshold.

Another possibility for the chance identification level is difficulty in mapping edge distributions on the fingertip to a visual display. This again seems unlikely as a root cause of performance, because pattern perception on the fingertip has been demonstrated with pattern sets as complex as letters. For example, Loomis [24] reported a recognition rate for raised alphabetical stimuli, briefly explored for 2 sec by pressing with the fingertip, of up to 50% (cf. 4% chance). Novel character sets included in his study also led to above-chance recognition, so familiarity with the visual pattern is not essential.

This leaves a potent variable, namely, the fact that the frictional display only allows the pattern to be apprehended under motion. Loomis and Lederman [25] reviewed a number of studies on character recognition with different modes of exploration. The mode imposed by the frictional display resembles what they called "slit scan," i.e., as if a slit moved across the pattern displaying one section at a time. Recognition accuracy achieved with this mode under the index finger was well above chance [26], [27]. With the present display, the slit is the finger itself, but in contrast to previous data, matching to known patterns was at chance.

It seems likely that the inability of the present participants to match the current tactual patterns to vision resides in further factors resulting from the frictional basis of the display. The extant literature on fingertip pattern perception is largely based on devices with spatially separated vibrating pins or embossed stimuli. The mechanoreceptor populations that contribute in these cases are most likely to be slowly adapting and specialized for pattern information. Friction modulation, in contrast, is essentially a vibrotactile stimulus that would activate rapidly adapting receptors. In support, Vardar *et al.* [7] took measurements of the finger sliding on an electrostatic waveform and found that the frequency components with highest energy in measured forces, accelerations, and displacements matched the known sensitivity of the Pacinian Corpuscles, a rapidly adapting population.

An additional concern is that friction becomes available as a cue exclusively when the finger is moving, which in turn means that by the time a friction change is sensed, the hand has moved beyond the location that gave rise to it. Several findings suggest that movement adds noise to encoding the spatial layout essential to conveying patterns. In [28], participants reported 3-4 edges when only 2 friction reductions were presented for longer than 90 msec, possibly because fast finger motion interfered with perception of friction transitions. Pronounced masking effects have also been demonstrated, whereby frictional noise interfered with the threshold for detecting sinusoidal bursts and caused virtual edges to feel less sharp [29]. Similar temporal interference effects might arise when electrostatic patterns with closely spaced features are explored at high speed.

Beyond temporal masking, the nature of friction rendering by surface haptics introduces another form of noise, in that activation is applied to an area around the pixel determined to be in contact with the finger. The entire fingerpad thus experiences the same level of friction, rather than an array of varying values as would occur with physical textures. The friction level changes only when the device senses that a pixel with a differing value has been contacted, and the new level is again applied to the finger as a whole. Thus, as was noted above, rendering resolution is limited by the area that is simultaneously under friction activation as well as by the capability to determine when the finger has moved to a new pixel value. These factors limit the effectiveness with which the device delivers fine pattern layout to the sensory system. Edge transitions even on larger patterns may prove problematic to detect [30].

In keeping with findings suggesting that human touch appears to separate pattern from textural channels [13], the minimal texture offered by any of the patterns presented here seems sufficient to trigger detection, but given the limitations of rendering and human perception, the pattern information appears insufficient to allow identification, in terms of visual matching. The implications for design of control elements with friction displays are, accordingly, twofold: friction should be highly useful for confirming the location of a control button, but differentiation of buttons may need to be augmented by an additional perceptual channel.

We urge caution, however, with regard to the latter implication. The present stimuli were designed to produce strong friction signals, and it is therefore not surprising that they were detected easily. On the other hand, the patterns were also designed for visual discrimination, and it is therefore more surprising that matching was so poor. It would be useful to explore image parameters that might support accurate identification when presented as a friction pattern. Use of larger-scale patterns might enable matching, but at the potential cost of precluding rapid friction detection [31]. It might be possible for users to associate labels other than visual images with such stimuli, although there are limitations on the number of arbitrary associations that can be made (Miller's span of absolute judgment [32]). It is also possible that extensive practice could improve performance, but anecdotally, the present authors did not reliably succeed in the identification task even after considerable experience with the stimuli in both tactual and visual form, and the need for practice seems likely to discourage casual users of the display in applied settings. Further work is clearly necessary to determine the boundaries on these findings, in an effort to create discriminable and readable friction patterns on the scale of the fingertip.

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