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Perceiving Texture Gradients on an Electrostatic Friction Display

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Abstract— **Two experiments tested young adults' ability to discriminate the direction of friction-defined textural gradients rendered by the Senseg FeelScreen™. Gradients were particularly effective when they spanned the low end of the intensity range. This trend likely reflects saturation of the device's rendering capabilities at high intensities, as confirmed by measurements with a manual linear tribometer. The results show promise for use of gradients rendered with variable friction displays to aid non-visual navigation on tablets.**

I. Introduction

Mechanoreceptors embedded in human skin provide rich information about surface texture, as derived from small-scale geometric deviations from the local plane. A number of different textural properties can be distinguished, such as roughness, slipperiness, or geometric density. These properties are critical to how people manipulate objects, for example, by affecting the force required for stable grasp. Texture is also fundamental to how objects are perceived: Fine-grained elements can form the basis for segmenting surfaces into regions and may be sufficient by themselves to determine an object's identity [1],[2]. Texture is also a salient feature that "pops out" on a surface [3],[4].

Given the importance of surface texture to haptic interactions, it is not surprising that a variety of technologies has been directed toward rendering textural properties. Past approaches include arrays of independently driven pins [5], actuation of the skin by a sliding surface [6], and devices that control friction by ultrasonic [7] or electrostatic effects [8],[9],[10]. The latter refers to the induction of static electricity by scanning a finger over a conductive surface connected to a voltage source. The resulting friction force is only apparent to the moving finger; it increases approximately linearly with normal force with little velocity dependence [9]. Although the electrostatic effect is hardly new [11], its exploitation by haptic devices for rendering of surface properties is relatively recent. The present research used a commercial electrostatic device, the Senseg FeelScreen™ Developer Kit. The FeelScreen™ is a Nexus 7 tablet running the Android KitKat operating system, augmented with proprietary electronic components and software.

Our goal was to use the FeelScreen™'s electrostatics to render textural variations, or gradients, that continuously varied in intensity (within rendering capabilities of the device). We chose gradients as the target stimulus on the basis of both device capability and potential usefulness. Considering capability, the spatial variations in friction resulting from electrostatic effects are sufficiently fine-grained to lead to a subjective impression of texture and to induce textural variations across the tablet surface.

A potential utility of textural gradients is to differentiate regions of the tablet surface and, by virtue of graded directionality, to guide users to desired contact points without the need for direct vision. This use case is suggested by contrast with another approach, where regions on a glass plate are designated by discrete boundaries, defined by friction or vibration [12], [13]. When the user enters a target region such as a line on a graph, the device vibrates or the friction on the surface changes, constituting a binary signal as to presence/absence of target. The problem with this approach is that when the finger falls off the target region, there is no indication as to how to find it again, except to return to the remembered location of a previous positive signal or to undertake an active search. Physical edges, in contrast, provide a pressure array under the finger that guides users as to the direction in which patterns are changing and facilitates tracking, even over highly complex configurations [14]. The lack of a corresponding array signal for targets rendered with on/off signaling leads to much slower acquisition than for their physical equivalents. For example, to decode the angle of a line rendered by friction, users required approximately 1 min., about twice as long as for the same angle defined by sandpaper [13]. Providing a gradient at the edge of a target region could reduce the acquisition time by directing users to move in the direction of increasing or decreasing intensity.

With this scenario as motivation, the present experiments were intended to explore whether electrostatic gradients, as formed by systematic amplitude variations, could be perceived, and how much space was required. We asked participants to discriminate the direction of a gradient defined by electrostatic changes, using a two-alternative forced choice task. Their responses were converted to discrimination scores (the sensitivity index d′ [15]). Experiment 1 tested a variety of gradients available with the Senseg API within a 5.1 cm swipe area. Given that high performance was achievable, Experiment 2 focused on the most favorable candidate gradients and evaluated how well the direction was discriminated within a smaller (2.5 cm) region of the tablet relative to the original distance.

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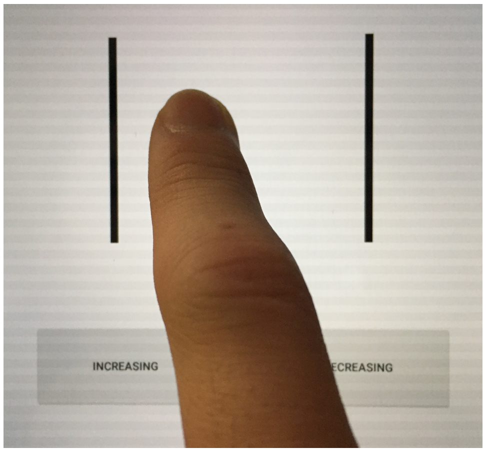

Figure 1. Tablet display during test, showing active region and response buttons.

II. General Methods

A. Participants

The participants were Carnegie Mellon University students who received course credit. All gave informed consent under a protocol approved by the Institutional Review Board. There were 24 in Experiment 1 and 13 in Experiment 2.

B. Stimuli

The stimuli were constructed from two variables provided under the Senseg API: grain type (four) and intensity. Each grain is a temporally-defined waveform for a user-defined area on the touchscreen. The four grains are named "Even," "Smooth," "Bumpy" and "Grainy," respectively. As described by Senseg engineers, "Even" grains have a repeating pattern of 13-ms pulse duration and a 2 ms inter-pulse interval. "Smooth" grains consist of repeating 4-ms pulses. "Bumpy" grains have a repeating pattern of 14-ms pulse duration and a 24-ms inter-pulse interval. "Grainy" grains have a repeating pattern of 4-ms pulse duration and a 17-ms inter-pulse interval. The intensity parameter provided by Senseg's API, which controls the voltage, varies from 0 to 1.0. The exact waveform and voltage used are proprietary to Senseg.

Within each grain type, six gratings were designated according to their intensity range from minimum to maximum: .2 to .6, .2 to .8, .2 to 1.0, .4 to .8, .4 to 1.0, .6 to 1.0. Thus, the grating variable instantiates two component parameters: the lowest intensity presented (.2, .4 or .6), and the range between minimum and maximum (.4, .6 or .8).

For experimental purposes, each grating was rendered across the middle of the short axis of the tablet, so that its intensity increased linearly from the minimum to the maximum value over the designated spatial extent, in the desired direction. Vertical bands marked the boundaries of the active region, so that the participant knew where to sweep (see Figure 1).

In an effort to characterize the proximal stimuli on the fingerpad, a manual linear tribometer was constructed to collect force data from the surface of the Senseg tablet while being scanned by a touchscreen stylus pen (see Figure 2). The pen was used in preference to the finger, in order to eliminate the dependence of force on rapidly varying tribological factors associated with human skin. The moving part of the assembly includes a linear guide (MR15ML, THK, Republic of Korea) with its rail fixed to the table and a wooden link with a stylus pen on its opposite end attached to the linear guide's moving block. The measuring part consists of a 19-cm long balancing beam pivoted in the middle, with a force sensor (ATI Nano 17, ATI Technologies, USA) on one end and a 473-g counterweight on the other end. The FeelScreen™ Developer Kit was placed over the force sensor using a proper seat. The moving link was moved by hand in order to avoid noise in force readings due to the motorized mechanism. The manual scanning started from the left edge of the screen and moved to the right edge at a speed of ~4 cm/s. After a short stop, the stylus pen moved from the right to the left edge. The duration of the scan on the grating was approximately 2 s, and the entire scan lasted about 10 s. (Scanning times were quite consistent; e.g., the durations on the smooth grating for three different intensity ranges were within .01 sec of one another.) Tangential forces were captured by the force sensor at a 10-kHz sampling rate.

The measured in-plane force data were converted to the friction force along the textural grating. They were then band-pass filtered by a 3rd-order Butterworth filter with cutoff frequencies 25 and 500 Hz. Figure 3 shows signal traces for the grain "Smooth." Note that each signal trace contains two measurements of the same grating, increasing in intensity from left to right and right to left, respectively.

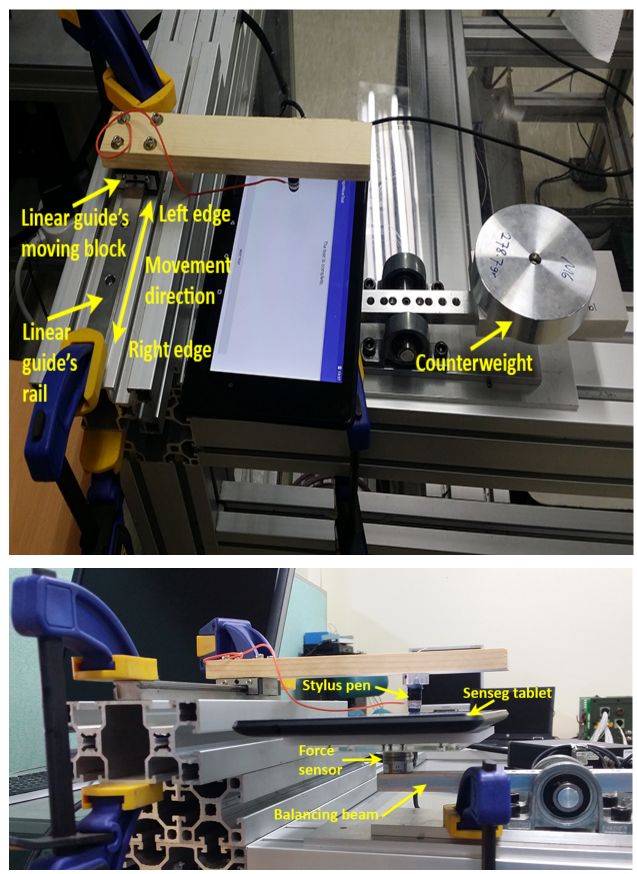

Figure 2. Top view (above) and side view (below) of the manual linear tribometer.

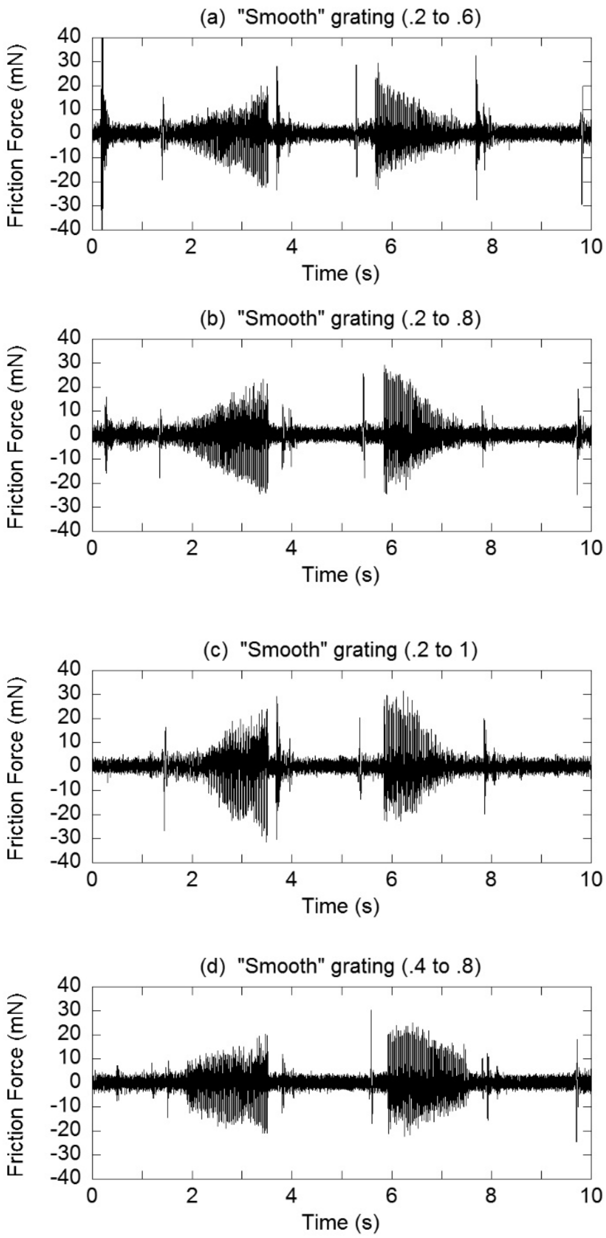

Figure 3. Friction force along the textural grating direction. Shown are measurements taken with gratings using the grain "Smooth." The traces show gratings with intensity range (a) .2 to .6, (b) .2 to .8, (c) .2 to 1 and (d) .4 to .8.

Several observations can be made from the data in Figure 3. First, friction increased and decreased along the grating as expected. Second, the minimum intensity behaves as expected: The traces (a) to (c) have the same minimum intensity of .2 and show similar minimum friction force too. In contrast, the bottom trace (d) has a minimum intensity of .4 and shows the expected larger minimum friction force for the grating. Third, the friction force appears to saturate for intensity values above .6, as is evidenced by the similar maximum friction force (~0.02 N) for the gratings shown in (a) to (c) despite the difference in maximum intensity values.

C. Procedure

The task was a one-interval, two-alternative forced-choice. The participant was asked to sweep across the pad as many times as desired, and then indicate whether the texture gradient intensity was increasing or decreasing rightward. Sweeps were made with the dominant hand, as self-reported. To respond, participants pressed one of two buttons at the bottom of the pad, left for increasing rightward and right for decreasing. An audible click indicated the response had been entered and the next trial could begin. A practice round preceded the first block of trials, using two gradients per grain, one with a large intensity difference and one with a small; the experimenter provided feedback only for these trials. Subsequent trials were self-paced. As there was no apparent sound from exploration, participants did not wear headphones.

In Experiment 1, each participant tested two of the grain types in independent blocks (referred to as Grain 1 and Grain 2). Within each block, each grating was tested in each direction 10 times, for a total of 120 trials. The block order was counterbalanced across participants. Across all participants, each combination of grains was tested by four participants.

For Experiment 2, stimuli were chosen from conditions in Experiment 1 that had yielded highest performance, i.e., gradients starting with the lowest intensity value. Gratings with minimum intensity of .2 and with maximum values of .6, .8, and 1.0 were tested at each of two widths on the pad, 2.5 cm or 5.1 cm, within each of two grains: grainy and bumpy. Those grains were chosen for their perceptible textural variation, although they did not show any advantage in gradient rendering in Experiment 1 over the other grains available through the API. Trials were blocked by grain (2) and spatial width (2.5 cm vs. 5.1 cm), for a total of 4 blocks. Within each block, the three gratings, as defined by maximum values, were tested on 10 trials in each direction, for a total of 60 trials, presented in random order. The order of the four blocks was counterbalanced, and the variables were entirely within-participant.

III. Results

A. Experiment 1

The standard signal-detection discrimination measure, the sensitivity index d′ [15], was obtained for each of the gratings within each grain, based on the 10 trials in each direction. A hit was upward (increasing right) called upward; a false alarm was upward called downward (d′ is not affected by reverse coding). Hit rates of 1.0 and false alarm rates of 0.0 were converted to .95 and .05, respectively, in order to compute d′.

By our design, each participant tested two of the four possible grains. An initial analysis indicated no consistent direction or difference, across participants, between Grain 1 and Grain 2 for any of the grain pairings. The data were analyzed with separate ANOVAs on Grain 1 and Grain 2. Within each ANOVA, grain type (4) was a between-participant variable and grating (6, as defined by range and minimum) was within-participant. The two ANOVAs are equivalent to replications of the overall design and therefore offer confirming tests. Greenhouse-Geisser corrected degrees of freedom were used. Only the effect of grating was significant, $F(5, 62.6) = 18.11$ and 23.48 for Grain 1 and 2, respectively, $ps < .001$. The effects of grain type and the grain × grating interaction produced $Fs < 1$ in both ANOVAs.

Although the grains were clearly discernable, the data indicate they did not produce differential sensitivity to gradients. Variations in grating, in contrast, produced substantial differences. Recall that the grating variable has two underlying parameters: the minimum intensity of the gradient and its range (maximum minus minimum intensity). As shown in Figure 4, the grating effect on d′ is produced by variations in the minimum intensity; clearly, the range of intensity had little statistical effect. This may reflect a compressive relation between stimulus intensity and the corresponding percept, which would mean that stimuli with the lowest minimum intensity yielded larger changes in perceived intensity. The measurement plots in Figure 3 suggest that the root cause may not be in perceptual transduction, however, but in the stimulus itself, which appears to saturate at high intensities.

B. Experiment 2

As before, d′ was computed for each participant within each condition. Hit rates of 1.0 and false alarm rates of 0.0 were again converted to .95 and .05, respectively. Mean d's are shown in Table 1. A within-participant ANOVA performed on the factors of grain, grating, and gradient spatial width (2.5 vs. 5.1 cm.) showed no significant effects. This pattern of null effects reflects a very high level of discrimination that was achieved in all conditions. The average d′ over all participants and gradients was 2.68 (participant-based s.e.m. = .14). The d′ measure is in standard deviation units, like a z-score; under a normal distribution a value of 2.68 or higher would be achieved with a probability of < .01. The corresponding average d′s computed separately for the 2.5 cm and 5.1 cm widths were 2.65 and 2.71, respectively. Thus, participants succeeded in discriminating the direction of a gradient as small as 2.5 cm (1 inch), given that it was anchored at a low intensity value.

Table 1. Mean d' values in Experiment 2 by grain, maximum intensity of grating, and width.

Grain	Max.grating intensity	Width = .2.5 cm	Width = 5.1 cm
Grainy	0.6	2.67	2.61
	0.8	2.55	2.78
	1	2.62	2.61
Bumpy	0.6	2.59	2.73
	0.8	2.63	2.70
	1	2.83	2.84

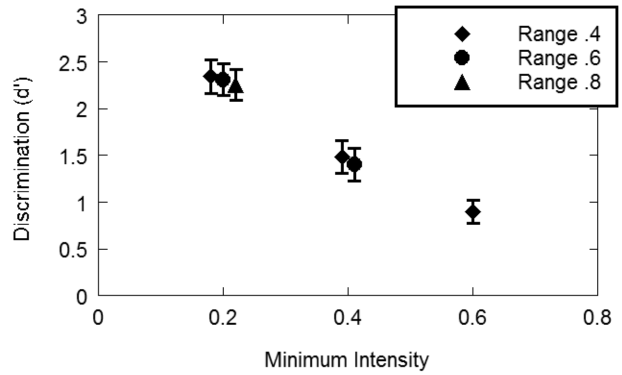

Figure 4. Discrimination performance (d′) in Experiment 1 by grating type, as defined by minimum intensity and range, averaged over grain. Data points are slightly offset for clarity. Also shown are the standard errors.

IV. Discussion

The main take-away message from the present research is that friction-rendered gradients can be rendered in a region as small as 2.5 cm so as to enable a high level of direction discrimination. For comparison, the width of a sample of adult fingers averaged .99 cm in a study by Loomis et al. [16]. The effective gradient width, then, approximates a two-finger-span. This width no doubt under-estimates the potential of the graded-intensity approach, as it was achieved with unpracticed users and sets a very high bar for discrimination. Functional use of gradients might be achieved with much smaller regions.

The functional width is also likely to depend on the device. The results of Experiment 1, showing greater perceptual sensitivity to gradients that used the low end of the intensity range, are consistent with the tribometer measurement of the Senseg FeelScreen™ gradients, which indicated saturation at high intensity levels. In future work, we intend to assess gradient discrimination with the TPaD device based on ultrasonic friction [17].

Any device that denotes gradients by friction has the limitations that the textural changes are only apparent to the moving finger, and the friction levels depend on normal force. Variations in applied force as well as other tribological factors (e.g., sweat) could add noise and affect the perception of a rendered pattern.

It should further be noted that the present participants had unlimited time to explore. Of course, the time to explore a gradient depends on its friction, but no doubt most variability is explained by differences in users' encoding ability and decision criteria. If the effectiveness of spatially small gradients inherently trades off with exploration time due to such factors, the utility of the graded friction approach would be reduced. The experimenters informally noted that most participants were able to encode direction with a small number of swipes. Prior knowledge of gradient structure could speed up this process, as experienced users would be recognizing gradients as familiar patterns rather than determining their direction anew. Further research restricting exploration and with practiced users is essential to determine how quickly frictional gradients can be perceived and to measure space/time tradeoffs directly.

Implementation of gradients into tablet applications is an intriguing possibility. We noted in the introduction that gradients might be useful in solving the problem of following pattern displays on glass surfaces that offer only binary on/off signals. Texture-guided navigation on the otherwise smooth glass surface could not only be useful to people with vision loss, but could also reduce the distraction of gaze from other pursuits, such as driving a car, that are often performed in conjunction with tablet use. Experienced users might find texturally graded displays useful to guide swiping for selection of keyboard characters. The present study offers a basis to consider further use for friction gradients.

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