Exploring the Design Space of Programmable Friction for Scrolling Interactions

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ABSTRACT

Scrolling interactions are an important aspect of the design of usable touchscreen interfaces, particularly for handheld devices that can only display a limited amount of information at once. Using a touchscreen capable of dynamically altering its surface friction, we explore the design space of haptically-augmented scrolling interactions and investigate programmable friction's ability to provide appropriate feedback in envisioned usage scenarios. We performed five user experiments to evaluate respectively the identifiability of a set of iconic detents, the countability of detents, the perception of detent density, the synchronization of tactile feedback to on-screen events, and the optimal friction pattern for a spring-like resistance. The results of these experiments provide valuable information that will inform the design of scrolling interactions that leverage programmable friction for an improved user experience.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O, Interaction styles

1 INTRODUCTION

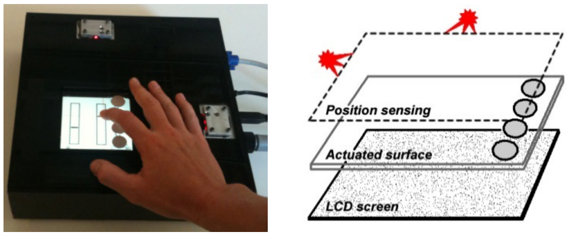
Touch interfaces have a long history [3] but have only recently moved to prominence with successful products ranging from small handheld devices (e.g., Apple's iPhone) to large interactive tables (e.g., Microsoft's Surface). Users' embrace of touch computing is reminiscent of the enthusiasm expressed for direct manipulation interfaces when first introduced decades ago [20]. This enthusiasm stems not only from touch interfaces' flexibility and efficient use of space, but also from something more basic: a touch surface, when used appropriately, can lead to the satisfying experience of a Natural User Interface (NUI), defined by Wigdor and Wixon as "an interface that makes [the] user act and feel like a natural" [25].

Designing usable touch interfaces is nevertheless challenging, as illustrated by their limited commercial success prior to Apple's user experience redesign with iOS. The fingerpad occludes the screen and causes ambiguity in input point – the 'fat finger' problem [24]. Loss of cursor feedback further exacerbates ambiguity, prompting the addition of visual cues to show the touch location, correct device operation and other missing information [24].

Touch interfaces also provide poor tactile feedback, producing only the sensation of a flat glass surface and relying on audio-visual feedback to display information and realistic interactive effects. The need for better tactile feedback was recognized early on [3] and remains a preoccupation as consumers must choose between the performance of physical keyboards and controls, and the flexibility and practicality of touchscreens. The proliferation of impractical tangible add-ons for touchscreens such as attachable joysticks and keypads (e.g. Fling Joystick for iPad, Ten One Design) and continued success of devices with physical controls are evidence of a desire for richer tactile feedback.

The work presented here focuses on bringing rich tactile feedback to scrolling interactions, which we define loosely as sliding input gestures leading to content or controller widget diplacement on the screen. Scrolling occurs ubiquitously in touch interactions, and is crucial for small handheld devices that can display limited information at once. When performed with physical controls, scrolling is often accompanied by haptic feedback – detents in a jog dial or mouse scroll wheel, or resistance as a joystick is pushed.

Specifically, we investigate the design possibilities and outcomes when scrolling interactions are enhanced with Programmable Surface Friction (PSF). We used a Large Area Tactile Pattern Display (LATPaD) [13], an experimental touchscreen that reduces the friction experienced by a sliding finger on its surface by creating a 'squeeze film' of air using imperceptible high-frequency vibration (Figure 1). Vibrations are created by piezoelectric actuators bonded along one side of a glass plate that rests atop an LCD screen, while fingerpad position is measured with a laser-based optical system, resulting in a 57×76 mm haptic touchscreen. Tactile effects are produced by altering the amplitude of vibrations, and hence the amount of friction, as the fingerpad slides against the touchscreen.



(a) (b)

Figure 1: (a) Picture and (b) illustration of components of the Large Area Tactile Pattern Display (LATPaD).

The ability to dynamically vary surface friction raises interesting opportunities to improve the performance and user experience of touch interfaces. We have previously demonstrated that programmable friction can improve the performance of low-level pointing tasks and improve the enjoyment, engagement and sense of realism experienced with a variety of touch interactions [9]. Here, we use a similar approach but focus more narrowly on the design of augmented scrolling interactions, a utility in which PSF was most appreciated by users in our previous, broader exploration. In the present work, we contribute:

1. An exploration of the design space for haptically-augmented scrolling interactions, identifying key potential uses of PSF.
2. A five-study evaluation of PSF's ability to deliver appropriate tactile feedback in support of scrolling interactions.

We begin with a brief survey of scrolling interactions, touchscreen haptics and programmable friction, then outline the design space for haptically-augmented scrolling interactions. We describe five user experiments, each addressing a key question in the design of PSF feedback in envisioned scrolling scenarios; and end with a discussion of design implications and a general conclusion.

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2 BACKGROUND

2.1 Scrolling Interactions

Interaction techniques have been proposed to facilitate scrolling large information spaces on small mobile screens. Providing a contextual document overview can for example improve position awareness and reduce disorientation [6]. Circular or elliptical gestures also support quick and accurate scrolling without clutching, and allow seamless control over multiple parameters such as scrolling rate [12, 21]. Physical metaphors such as momentum-based scrolling and pressure-based rate control can also improve the user experience [1] and are available in commercial interfaces.

While these interactions typically occur without haptic feedback, physical controllers such as wheels, knobs, joysticks and jog dials have long provided rich tactile feedback in the form of detents, clicks, textures and resisting forces. Actuated knobs and sliders can replicate these effects in digital interactions, for example allowing the flow of frames to be felt while editing video, or locations to be marked within an audio stream [22]. In the context of mobile devices, vibrotactile feedback has primarily been considered in support of tilt-based interactions that map device orientation to scrolling velocity or absolute position. Applications for maps and long lists have been investigated, and performance advantages found for the latter [19, 14, 15]. Others have proposed improving awareness of scrolling velocity with vibrotactile clicks [7].

Scrolling interactions such as list and document navigation have also be investigated with the THMB, a mobile device that produces travelling sensations through a slider-mounted tactile array [10, 17]. The distinguishability of tactile icons was investigated [10], as well as appreciation for augmented web browsing [17]. Scrolling through a long list was also found to require fewer glances at the screen, hence less visual attention, with tactile feedback [16].

2.2 Touchscreen Haptics

Mobile haptics most commonly takes the form of vibrotactile feedback applied through an entire casing [5, 19], a touch sensitive surface [18, 23], or an actuated pen [8]. These vibrations convey alarms, transient events such as a button click [5], and rich but abstract symbolic messages [23]. More recent developments have focused on using other tactile feedback modalities at the surface of a touchpad or touchscreen. Electrovibration, for example, renders textures at a touchscreen's surface by producing time-varying oscillations in electrostatic friction with electric fields, and has been used to augment interactive applications [2].

The work presented in this paper relies on Programmable Surface Friction (PSF), a different approach to surface haptics that uses high-frequency vibrations to alter the friction felt by a sliding finger at the surface of a touchscreen [26, 13, 4]. We use a revision of Northwestern University's LATPaD (Figure 1), a 57 × 76 mm touchscreen that reduces its friction coefficient from approximately 1 to 0.15 with 26 kHz piezo-actuated vibrations [13]. Still in early development, the prototype is housed in a large enclosure, produces audible noise, and reduces friction non-uniformly at some locations (2 narrow strips parallel to longer screen axis). These limitations were accommodated in this work and are expected to be resolved in future hardware revisions.

A multi-dimensional scaling experiment with an early LATPaD prototype found spatial frequency to be most salient for textures, and intensity variations to be subtle [27]. Unpublished experiments nevertheless estimate the just-noticeable-difference in friction at 30-40%, sufficient for several distinguishable levels. More recent work has demonstrated that target acquisition is facilitated when sliding to targets having higher friction, an effect that is robust to the presence of friction-augmented distractors [9, 4]. The impact of PSF on the subjective appreciation of touchscreen widgets has also been investigated with an alarm clock, a game, a text editor, and a file manager, with results suggesting improvements to the enjoyment, engagement and sense of realism experienced by users.

PSF may be complementary to vibrotactile feedback, with the former providing feedback on sliding interactions and the latter mainly on tap or tap-and-hold interactions. PSF produces realistic sensations with minimal latency but requires constant sliding contact. Vibrotactile feedback, on the other hand, excels at producing feedback on brief contacts, e.g. click confirmation, but often feels artificial and can be slow to react, depending on the technology used [2]. Examining the comparative benefits of each technology more closely is beyond the scope of this paper.

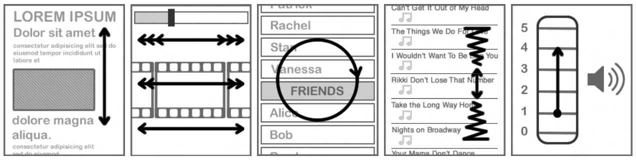
3 DESIGN SPACE EXPLORATION

Our initial exploration of the design space of programmable friction, partially reported in [9], broadly covered friction patterns, tactile effects and their uses in the design of touch interfaces. As part of that work, we evaluated four exemplar widgets, sampling the space, and identified scrolling interactions as a promising role for PSF when participants reacted positively to the addition of tactile detents on the hour and minute wheels of an alarm clock.

In the present work, we examine in depth the promise of PSF scrolling. To capture the extent of this space, we first envision five scrolling scenarios (Figure 2) that exemplify interaction styles and applications of PSF in this context:

- ***Scenario 1 – Document navigation with vertical scrolling.*** A document is scrolled by dragging its content along the length of the screen. *Feel:* distinct detents and textures as elements of the document (headers, images, markings) scroll through the screen.
- ***Scenario 2 – Video navigation with multi-rate scrubbing.*** A stream is navigated by sliding against different horizontal sliders, each controlling scrubbing at different rates. *Feel:* different densities of detents on each slider, indicating the rate; distinctive detents distinguish minor and major tick marks, display annotated locations, and indicate transitions between sliders.
- ***Scenario 3 – List navigation with circular scrolling.*** A long list is navigated with a continuous circular gesture. *Feel:* rate of flow as a stream of detents; and distinct detents on transitions between groups of items or on marked items.
- ***Scenario 4 – List navigation with rate control.*** A long list is navigated by engaging a joystick-like controller, with scrolling rate proportional to the pressure applied. *Feel:* resistance when engaging the spring-like controller.
- ***Scenario 5 – Numeric entry with slider.*** A numerical value is entered by sliding horizontally against a controller. *Feel:* distinct detents on minor and major tick marks.

These concrete scenarios illustrate the range of interaction styles and tactile effects that PSF should ideally be able to support. The tactile feedback primarily takes the form of brief detents, and occasionally of larger textured areas. Several scenarios would benefit from the availability of multiple distinguishable or identifiable detents, i.e. "haptic icons" [11], for example to distinguish between



(a) (b) (c) (d) (e)

Figure 2: Five scrolling scenarios sampling the design space: (a) document navigation with vertical scrolling, (b) video navigation with multi-rate scrubbing, (c) list navigation with circular scrolling, (d) list navigation with rate control, and (e) numeric entry with slider.

tick marks and mode changes, or between different marked elements. The purpose of the detents varies from marking discrete locations to indicating a continuous flow-rate or density. The interaction style takes the form of either a linear or circular gesture, or a linear gesture against a rate controller. Circular gestures afford fast scrolling, while linear scrolling is likely to be slower. Some scenarios require some perception of scrolling rate, while others require stopping precisely on a specific detent.

4 EXPERIMENTS

Based on the observations of the previous section, we designed a set of experiments that provide basic information relevant to the implementation of these scenarios with PSF feedback. Our aim was to broadly sample the elements necessary for the design of haptically augmented scrolling interactions. These five experiments were designed to investigate, respectively: the identifiability of a set of six tactile detents (E1); the factors affecting the counting of detent sequences (E2); the comparability of detent densities (E3); the synchronization of tactile feedback to on-screen events (E4); and the most realistic rendering for a spring-like resistance (E5).

Participants carried out all five experiments in a single 1.5 hour session. Sound-blocking earphones playing white noise were worn to block audible feedback from the touchscreen. Of 18 volunteers (P1-18; 7 male, mean age 23.6, s.d. 4.1), one was ambidextrous, and all others right-handed. Nine frequently used touchpads and five frequently used smartphones; all were familiar with touchscreens. Nine were familiar with haptic feedback on cell phones and game controllers and six had participated in a previous experiment with the LATPaD. Due to a variety of technical issues, some participants did not complete all the experiments.

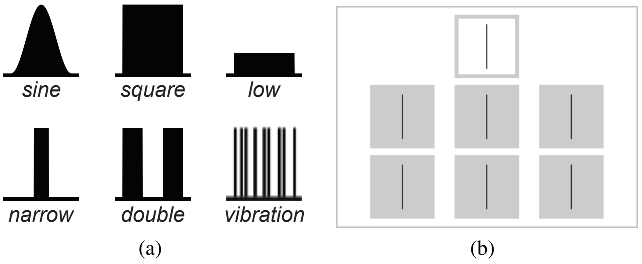
4.1 Experiment 1 – Detent Identification

4.1.1 E1 – Motivation and Tactile Feedback Design

Detents are a core element of scrolling, and many of our scenarios could benefit from distinguishable or identifiable tactile detents. E1 therefore aims to determine whether multiple detents can be reliably identified (hence distinguished), and the best friction patterns to produce detent-like haptic icons.

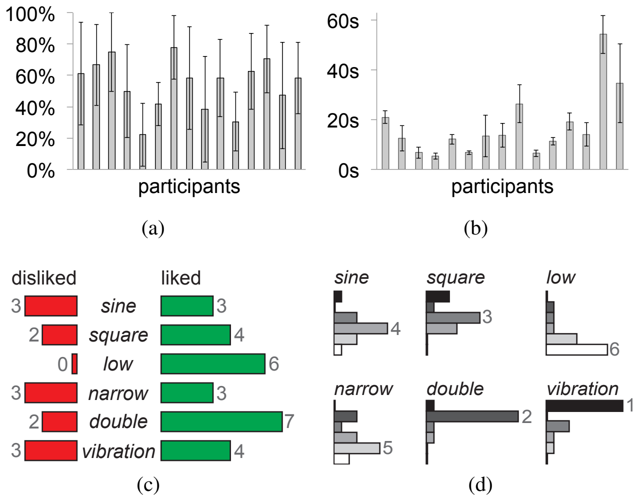
PSF detent rendering has a number of key parameters. A detent is generally produced by increasing friction when sliding over a marked location. The sensation can be altered by changing the friction pattern's width, amplitude, and shape (sinusoidal, triangular or square), and through repetition. A detent can also be produced by rapidly oscillating friction while within the marked location, irrespective of finger motion, for a sensation similar to vibration.

We designed a set of six detents (Figure 3a) to sample these parameters with what we hypothesized to be identifiable sensations. The *sine* and *square* detents are 4-mm patterns with smooth and sharp friction profiles. *low* is identical to *square* but reaches only 30% of its friction, while *narrow* reduces width to 1 mm. *double* is a 4-mm pattern formed by two narrow peaks. *vibration* is a 4-mm time-varying pattern with friction oscillating at 75 Hz.



(a) (b)

Figure 3: E1 design – (a) detent friction profiles, (b) visual interface.



(a) (b)

(c) (d)

Figure 4: E1 results – (a) detent identification rate and (b) mean trial durations (s.d. across detents); (c) distribution of liked/disliked detents and (d) strength rankings with median (1 is highest).

4.1.2 E1 – Experiment Design

In a trial, participants matched a test detent to one of six samples, shown visually as abstract spatial icons (Figure 3b), with spatial arrangement fixed within the session but randomized by participant, facilitating rapid (learned) task execution. Participants selected the matching sample by touching it on-screen and tapping on a keyboard with their other hand.

Participants were briefly trained by feeling the six samples, and instructed to try fast and slow sliding to find the most appropriate speed. They then performed 36 trials, in random order: 6 test detents $\{$*sine*, *square*, *low*, *narrow*, *double*, *vibration*$\} \times 6$ iterations. Finally, participants were asked to describe or draw the six detents, rank them by strength, and indicate liked and disliked detents.

4.1.3 E1 – Results

E1 was completed by 15 participants (P1-15; 5 male, mean age 23.5, s.d. 4.2). P16-18 did not complete the experiment due to technical issues. Trial conditions were slightly unbalanced for five participants, accounted for in analysis.

The identification rate varied from 22.2% (P5) to 77.8%, (P7), with a mean of 54.6% (s.d. 16.1%; Figure 4a). All participants did better than chance (20%) on average. The mean trial duration similarly varied from 5.2 s (P4) to 54.3 s (P14), with a mean of 17.2 s (s.d. 13.0 s; Figure 4b); seven trials with null duration were assumed to be mismeasurements and discarded.

Table 1 shows the confusion matrix for detent selection, with confusion rates above 10% marked with a star. The identification rate varied across detents from 34.4% with *sine* to 70.0%

Table 1: E1 results – confusion matrix showing percentage of selections (rows) for each test detent (columns), with confusions above 10% marked with a star (*); last column shows mean trial duration.

	sine	*square*	*low*	*narrow*	*double*	*vibration*	duration
sine	**34.4**	26.7*	10.0*	23.3*	3.3	2.2	18.9 s
square	7.5	**54.9**	5.1	3.0	15.6*	4.0	18.2 s
low	5.6	8.0	**59.1**	2.4	4.9	0.0	15.7 s
narrow	12.9*	4.9	6.7	**46.7**	6.7	2.2	18.5 s
double	1.1	5.6	4.4	6.7	**62.2**	10.0*	17.6 s
vibration	0.0	6.9	1.1	3.6	18.4*	**70.0**	14.0 s

with *vibration*. A repeated-measures ANOVA shows a significant effect, $F(5,70) = 4.21$, $p < .01$, attributable to differences between *sine* and *vibration* ($p < .05$). Trial duration also varied across detents, with shorter durations for *vibration* (14.0 s) and *low* (15.7 s), but a repeated-measures ANOVA found no significant effect, $F(2.39,33.42) = 1.53$, $p = .23$.

Participants slightly preferred *low* and *double*, consistently disliked none, and often did not dislike any (7/15, Figure 4c). By median, *vibration* was highest rated on strength, followed by *double*, *square*, *sine*, *narrow* and *low* (Figure 4d). Participants' illustrated or written descriptions of the detents referred to terms such as: friction, resistance, roughness/smoothness, hardness/softness, gap size, thickness, bounciness, stickiness, lightness and strength/weakness. Individual detents generated their own terms: buzzing/vibrating, rough/dirty (*vibration*); "2 clicks" or bumps (*double*), noted as similar (sometimes weaker) than *vibration*; stronger, stickier and thicker (*square*); fine, mild, weak, thin or smooth (*low*, *narrow* and *sine*). Several participants noted that some pairs of detents were difficult to distinguish, e.g. *low*/*square* and *narrow*/*square*.

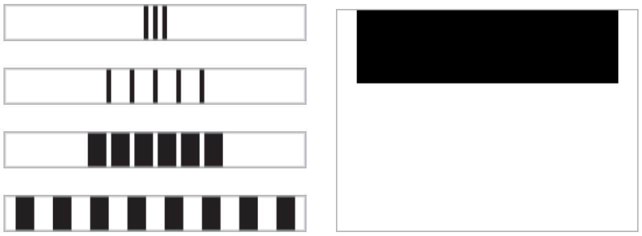
These results suggest that identifying detents within this set of six is error-prone and slow (mean 17.2 s), but provide guidance for the design of a smaller set of identifiable detents. *sine* fared poorly. *vibration* and *double* did best but were sometimes confused; since *double* was also confused with *square*, *vibration* is preferred. *low* and *narrow* both introduced errors but *narrow* was more often confused with *square*. We therefore recommend a set of three detents for further investigation: a strong detent (*square*), a weak detent (*low*), and a rough detent (*vibration*).

4.2 Experiment 2 – Detent Counting

4.2.1 E2 – Motivation and Tactile Feedback Design

Precision is an important aspect of some of our scenarios, in particular *Scenario 5 – Numeric entry with slider*. E2 investigates parameters that affect counting sequences of detents, and hence ability to select a specific item in a list.

Assuming a goal of maximizing detent density with sufficient strength and separation for counting, we investigated 1- and 4-mm square detents (E1's *square* and *narrow*) with 1- or 4-mm spacings (Figure 5a). The largest configuration allowed eight detents to be shown.



(a) (b)

Figure 5: E2 design – (a) detents for counts of 3, 5, 6 and 8, and patterns of 1-1, 1-4, 4-1 and 4-4 mm, and (b) visual interface.

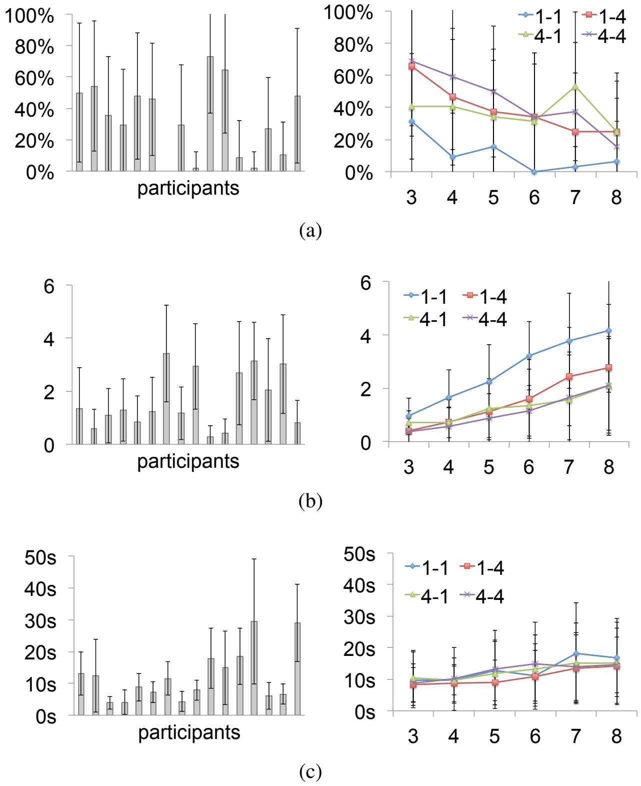
4.2.2 E2 – Experimental Design

Participants counted tactile detents displayed within a black rectangle shown on-screen (Figure 5b). Detents were rendered by varying configuration (two widths and two spacings) and six counts for a total of 24 variants (Figure 5a). Participants were first trained to count 3-detent sequences displayed with each of the four configurations, then performed a total of 48 randomized counting trials: 4 configurations {1-1, 1-4, 4-1, 4-4 mm} × 6 counts {3, 4, 5, 6, 7, 8} × 2 iterations. They were instructed to inform the experimenter of their answer after lifting their finger off the screen, which stopped a timer. They were asked to explain their strategy and what they felt helped or hindered counting.

4.2.3 E2 – Results

E2 was completed by 16 participants (P1-6, P9-18; 6 male, mean age 23.7, s.d. 4.4). P7-8 did not complete it due to technical issues.

Detents were correctly counted in 0.0% (P9) to 72.9% (P12) of trials, with a mean of 32.9% (s.d. 23.3%, Figure 6a). A repeated-measures 2-way ANOVA found significant main effects for detent configuration, $F(3,45) = 11.70$, $p < .001$, and count, $F(5,75) = 10.93$, $p < .001$, as well as a significant interaction, $F(15,225) = 2.41$, $p < .05$. Figure 6a suggests worse performance of the dense 1-1 mm configuration, which an analysis of simple main effects confirmed for half of the differences.



(a)

(b)

(c)

Figure 6: E2 results – (a) percentage of correct counts, (b) mean error and (c) mean trial duration across participants (left; s.d. across conditions) and conditions (right; s.d. across participants).

Mean counting errors ranged from 0.29 (P12) to 3.42 (P9), with a mean of 1.65 (s.d. 1.03, Figure 6b). Significant main effects were found for detent configuration, $F(3,45) = 29.59$, $p < .001$, and count, $F(1.57,23.47) = 28.62$, $p < .001$, as well as a significant interaction, $F(6.3,94.5) = 5.18$, $p < .001$. Figure 6b suggests once again a worse performance of the 1-1 mm configuration, which an analysis of simple main effects confirmed for 17 of 18 differences.

Mean trial durations varied from 3.9 s (P3) to 29.5 s (P15), with a mean of 12.2 s (s.d. 8.1 s, Figure 6c). A single trial of null duration was discarded. There was a significant main effect for count, $F(2.13,31.99) = 7.57$, $p < .05$, but not for detent configuration, $F(1.71,25.59) = 1.30$, $p = .29$.

Most participants felt that tightly spaced detents were more difficult to count (12/16). Some expressed a preference for thicker detents or greater resistance (3/16), while others preferred to reduce "finger catching" with lower friction or thinner detents (2/16). Several participants mentioned reducing or controlling their speed or applied pressure (8/16), some adapting their strategy to detent density (2/16). Other strategies included closing their eyes (2/16), switching fingers (2/16), pausing after detents (1/16), making multiple passes (2/16), and visually observing grease deposits on the screen (2/16).

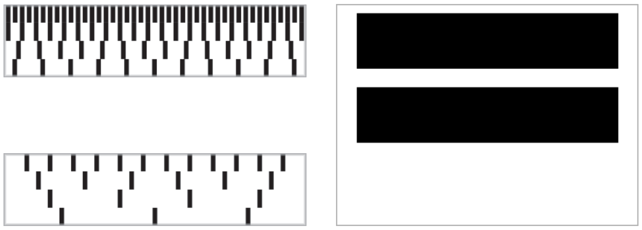
These results suggest that counting is easier with widely spaced detents, and increases in difficulty with the number of detents to be counted. The denser 1-1 mm detent configuration, in particular, was found to be significantly more difficult to count than others. Counting was also found to be inaccurate for most participants, even at slow speed. Interfaces should be designed to minimize the need for precise counting when used without multi-modal feedback.

4.3 Experiment 3 – Detent Density Perception

4.3.1 E3 – Motivation and Tactile Feedback Design

Perception of a detent sequence's density is important for some of our envisioned scenarios, and in particular for the identification of the different scrolling rates in *Scenario 2 – Video navigation with multi-rate scrubbing*. E3 investigates the precision with which users are able to judge the relative density of detent sequences.

We use 1-mm square detents, corresponding to E1's *narrow*, to extend the range of scrolling rates. A minimal spacing of approximately 0.5 mm was found necessary to produce a sensation of flow. We therefore investigate the relative scale judgment between reference densities of one detent per 1.5, 2.0, 3.0 and 5.0 mm, and densities 1, 2, 3 and 4 times greater (Figure 7a).



(a) (b)

Figure 7: E3 design – (a) four scales (1x, 2x, 3x, 4x) for 1.5 and 5.0 mm reference wavelengths, and (b) visual interface.

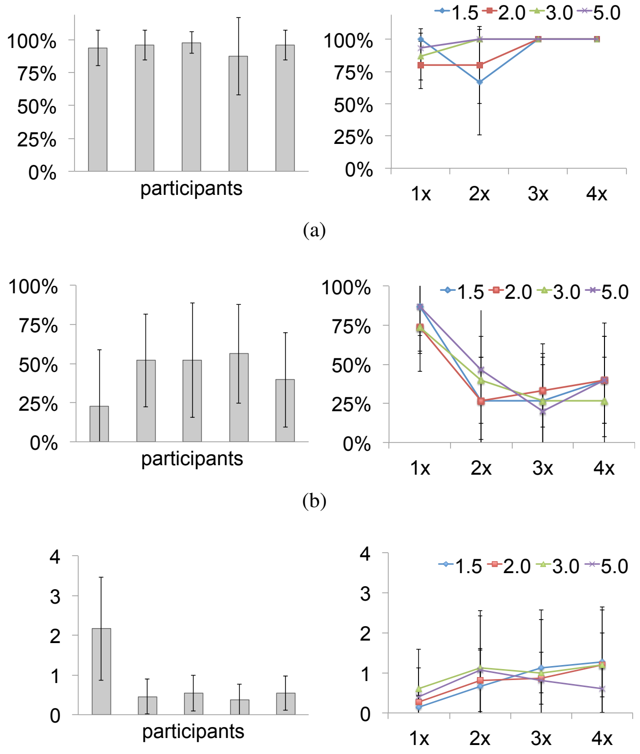
4.3.2 E3 – Experimental Design

Participants compared the density of two sets of detents shown on-screen as black rectangles (Figure 7b). The reference density was either one detent per 1.5, 2.0, 3.0 or 5.0 mm, and the comparison density was either 1, 2, 3 or 4 times larger (Figure 7a). The position of the reference density was randomized and participants were asked to specify which of the two densities was the greatest (if any) and the scaling factor (positive integer). Participants were briefly trained to perform the task with an example showing supporting visuals, and then performed a total of 48 randomly ordered comparison trials: 4 reference wavelengths $\{1.5, 2.0, 3.0, 5.0 \text{ mm}\} \times$ 4 comparison scales $\{1, 2, 3, 4\} \times 3$ iterations.

4.3.3 E3 – Results

This experiment was completed by 5 participants (P1-5; 2 male, mean age 24.6, s.d. 5.8). P15 and P18 could not complete the experiment due to lack of time, others due to technical issues. Due to the low participant number, statistical significance is not reported.

Mean trial duration varied from 4.3 s (P4) to 8.8 s (P1), with a mean of 7.3 s (s.d. 1.8 s), and was similar across reference densities and scales. Participants correctly identified the greater density, or lack thereof for 1x scale, between 87.5% and 97.9% of the time, with a mean of 94.2% (s.d. 4.0%; Figure 8a). The greater density was perfectly guessed at 3x and 4x. It was also guessed perfectly at 2x for references of 3.0 and 5.0 mm, but incorrectly on 20.0% and 33.3% of trials at at 2.0 and 1.5 mm. A difference was incorrectly found at 1x for 10% of trials. We tentatively conclude that the direction of density differences can be perceived when the relative scale or the wavelength are large (3-4x, 3-5 mm).



(a)

(b)

(c)

Figure 8: E3 results – (a) identification rate of greater density and (b) comparative scale, and (c) mean absolute error in scale judgment (for correctly identified greater density) across participants (left; s.d. across conditions) and conditions (right; s.d. across participants).

Scale of the density difference (how much, as well as which way) was judged correctly in 22.9% (P1) to 56.3% (P4) of trials, with a mean of 44.6% (s.d. 13.6%; Figure 8b). Scale was identified similarly across reference wavelengths and scales, but a lack of difference (1x) was perceived more accurately (80.0%). The mean absolute error on scale judgment, computed only when the greater density was identified correctly, varied from 0.38 (P4) to 2.17 (P1), with a mean of 0.82 (s.d. 0.76; Figure 8c). The mean error was once again similar across reference wavelengths and scales, although slightly lower in the absence of a scale difference (1x). Participants tended to overestimate scale, with mean perceived scales of 1.4 (1x), 2.8 (2x), 3.3 (3x) and 4.1 (4x). We tentatively conclude that the relative density of two detent sequences can be assessed with rough accuracy; perfect assessment is difficult.

4.4 Experiment 4 — Feedback Localization

4.4.1 E4 – Motivation and Tactile Feedback Design

Many of our scrolling scenarios produce haptic feedback as specific content scrolls through the screen. The specific event that should trigger friction feedback for moving (as opposed to fixed) content is however unclear. The marked headers and images of *Scenario 1 – Document navigation with vertical scrolling*, for example, could produce haptic effects as they pass the center of the screen or move past its edges. E4 investigates the most intuitive location for a haptic trigger in a scrolling window, or more generally how to synchronize tactile feedback with on-screen scrolling events.

We implemented six variations on the haptic trigger location (Figure 9). Augmented objects are drawn as 4-mm disks and produce an increase in friction on the whole surface as they pass over the trigger location, generating a 4-mm detent equivalent to E1's *square*. Additional visual feedback optionally indicates the location of the haptic trigger by drawing it as a dark gray pattern and by enlarging the disks as they activate the trigger.

The haptic trigger can be placed either at the center of the screen (*center*), at the left or right edges (*left*, *right*) or at both edges of the screen (*edges*). Alternatively, the trigger can shift to the left or right edge of the screen as a function of the scrolling direction, either ahead (*leading*) or behind (*trailing*) of the moving content. To prevent abrupt or confusing transitions, the trigger only shifts when a minimal distance is reached in the reverse direction, and triggers cross-fade over a short period of time (200 ms).

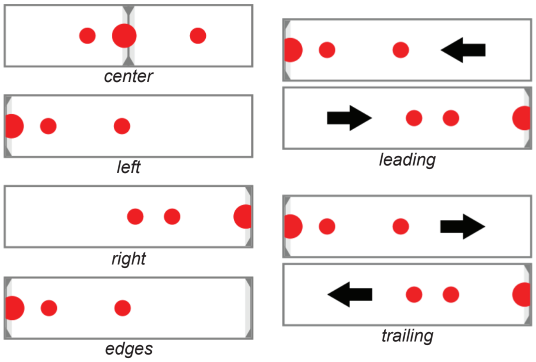
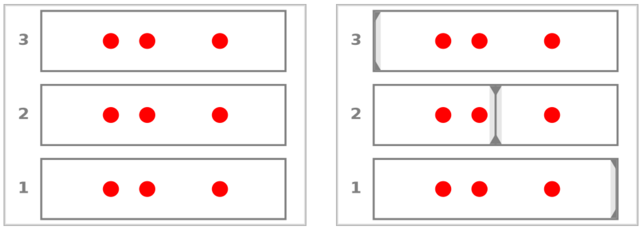


Figure 9: E4 design – illustration of haptic trigger locations.

4.4.2 E4 – Experimental Design

Participants interacted with the six variations of haptic trigger location and commented on the experience. The trigger locations were shown as two sets of numbered scrolled wheels. Scrolling was first experienced without visual feedback on the location of the triggers (Figure 10a) and participants asked to pick the wheels they most liked and disliked, as well as the ones they felt were most and least intuitive. The procedure was repeated a second time with visual feedback for the location of the triggers (Figure 10b).



(a) (b)

Figure 10: E4 design – visual interface for (a) first and (b) second iterations, without and with visualization of the haptic triggers.

4.4.3 E4 – Results

E4 was completed by all 18 participants (P1-18; 7 male, mean age 23.6, s.d. 4.1). Results with visual feedback, which represent outcomes once the trigger mechanism is understood and presumably long-term preferences, indicate a lack of consensus (Figure 11). The *edges* and *trailing* triggers were both liked and disliked equally, with 6 and 5 selections respectively. The *center* trigger scored similarly with 4 likes and 5 dislikes, as did the *leading* trigger with 3 likes and 2 dislikes. The *left* and *right* triggers were neither liked nor disliked. Comments suggest explanations for the dislike of some triggers. The *edges* trigger was said to provide too much feedback, while the *center* trigger was "weird" and often occluded. The *trailing* trigger provides feedback for element not yet visible. Personalization may therefore be required to select between *center*, *edges*, and *trailing* triggers according to individual preferences.

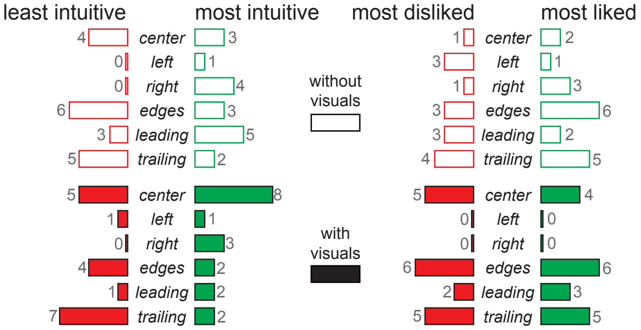


Figure 11: E4 results – distribution of trigger ratings, without and with visual feedback for trigger location; ties were permitted.

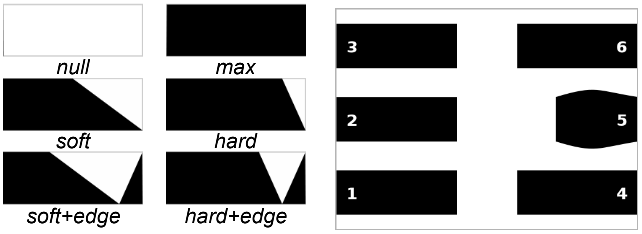
Results for intuitiveness are similar (Figure 11). The *center* trigger was judged most intuitive with 8 selections, but was also selected as least intuitive 5 times. The *edges* and trailing triggers were judged least intuitive 4 and 7 times and most intuitive only twice each. The *center* trigger may therefore be a more intuitive default when personalization is not possible.

A comparison of these results with initial judgments made without visual feedback on trigger locations shows that several participants changed their ratings once exposed to the triggering mechanism. This suggests that the source of the tactile events was not obvious in itself, as confirmed by some user comments, and that either training or visual reinforcement may be necessary to build the necessary mental model of the tactile interaction.

4.5 Experiment 5 — Resistance Perception

4.5.1 E5 – Motivation and Tactile Feedback Design

As exemplified by *Scenario 4 – List navigation with rate control*, scrolling can also be triggered by pushing against a spring-like controller. In E5, we investigate the most appropriate friction patterns for the rendering of a spring-like resistance.



(a) (b)

Figure 12: E5 design – (a) friction profiles showing variations in the friction level (black) as each of the six springs is compressed from right to left; (b) visual interface with fifth spring at 25% compression.

A realistic illusion of a stiff spring cannot be produced with our PSF touch screen, perhaps due to an insufficient range of friction, but the sensation can be approached by modulating friction and visuals together. We empirically designed six springs that produce slightly different feedback intended to be felt as a resistance (Figure 12a): spring *null* has no feedback while *max* has maximal friction whenever engaged. Springs *soft* and *hard* linearly increase the friction over distances of 15 and 5 mm respectively before maintaining maximum friction. Springs *soft+edge* and *hard+edge* similarly increase friction linearly, but impulsively increase then release friction when first engaged to create a sensation of impact. The spring names reflect the tactile effect that each friction profile was hypothesized to produce. All springs were represented visually as rectangles that bulged identically when compressed (Figure 12b).

4.5.2 E5 – Experimental Design

Participants interacted with six numbered and randomly positioned springs, shown as black rectangles (Figure 12), and commented on the experience. They were asked to select the springs with tactile feedback that most and least matched the visuals, and those stiffest and softest.

4.5.3 E5 – Results

E5 was completed by 16 participants (P1-14, P16-17; 5 male, mean age 23.1, s.d. 4.1); P15 and P18 did not have time. The *null* spring was judged the softest (14/16; Figure 13). Judgments varied on the stiffest spring. Springs with a rapid increase in friction were more often judged to be stiffer (*hard*, *hard+edge*; $n = 5,7$) than those with slower transition (*soft*, *soft+edge*; $n = 0,3$). The *max* spring was rated stiffest twice and softest once. These results suggest that the presence of friction can be associated with a sensation of stiffness, and that the stiffness is greater with a rapid increase in friction (initial impulse) rather than a slow or very abrupt increase.

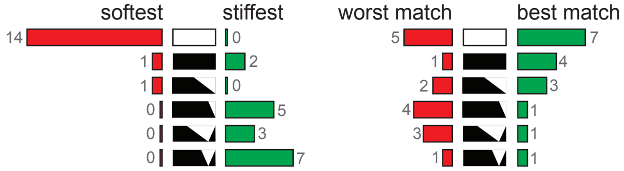


Figure 13: E5 results – distribution of spring selections for softness or stiffness and worst or best match to visuals; ties were permitted.

The best match to visuals is less consistent (Figure 13). Surprisingly, *null* was judged both the best ($n = 7$) and worst ($n = 5$) match despite having no haptic feedback. Comments suggest that visual feedback may have caused a pseudo-haptic effect, with *null* described as “soft and chewy”, “flexible, liquid, soft” or a “soft feel”. The *max* and *soft* springs were otherwise ranked best ($n = 4,3$) while *hard* and *soft+edge* were judged worst ($n = 4,3$). Comments suggest that different criteria may have been used to judge the quality of a match, with one participant preferring the bouncy feel of soft springs, another associating springs with a stiffer feel, and another ranking the springs based on comfort and naturalness. These differences may explain the lack of consensus between participants.

5 DISCUSSION

Experiment 1 investigated the identifiability of a set of six tactile detents, and found that these detents can be distinguished above chance, but with some difficulty and error in identification. The number of distinct detents used in a single interface should therefore be minimized when precise identification is required, such as when using a device in-pocket with haptic feedback alone. E1’s confusion matrix suggests a potentially-optimal reduced set of three detents: a strong (*square*), a weak (*low*) and a rough detent (*vibration*). A larger set may be feasible when identification is beneficial but not required, or when distinguishability is sufficient. Feeling differences between marked items may for example be useful but not essential when scrolling a document with visual feedback. Identification was also performed slowly, which suggests that performance would deteriorate with more natural sliding gestures. Subtle differences in detents should for example be expected to be missed during the fast, ballistic phase of a scrolling task but may be more salient as slow, precise adjustments are made near the target. It may also be possible to extend the variety of tactile markings with textured areas larger than the 1- and 4-mm detents used here, as well as other feedback modalities such as vibrotactile feedback.

E2 investigated the countability of detent sequences. We found that counting is imprecise even when performed with care, and that difficulty increases with tightly spaced detents and large counts. Scrolling interactions that require counting without additional feedback should therefore be designed to accommodate imprecision, or should maximize precision with low counts and widely-spaced detents. E.g., parameter entry (*Scenario 5 – Numeric entry with slider*) may be difficult to perform accurately without visual feedback but possible when coarse adjustments are sufficient, like volume control. These results also suggest that fine adjustments of a few items may be possible in other scrolling interactions, such as *Scenario 3 – List navigation with circular scrolling*, when detents are appropriately spaced. E1 also suggests that rendering minor and major tick marks may be possible, potentially increasing the counting range by allowing chunking of minor detents.

E3 investigated the comparability of detent densities. Density differences can be detected and their direction felt accurately, and scaling factors can be judged with some accuracy. Scrolling interactions can therefore be designed to leverage the perception of detent densities to represent information such as scrolling rates or content flow. An interface as envisioned in *Scenario 2 – Video navigation with multi-rate scrubbing* could for example communicate the scrolling rate of control sliders with distinct detent densities. Other scrolling interactions, such as *Scenario 3 – List navigation with circular scrolling*, could similarly provide a better feel for instantaneous scrolling velocity through the flow of detents.

E4 investigated the optimal synchronization of haptic feedback to on-screen events. Producing feedback as an element scrolls through the center of the screen (*center*) may be slightly more intuitive, but producing feedback at both (*edges*) or at a trailing edge (*trailing*) may be preferred by some, suggesting value in personalization. Training or visual feedback may be needed to support a correct mental model of the tactile interactions. These results have implications for the design of scrolling scenarios that involve synchronizing friction feedback with sliding visual content.

Finally, E5 investigated the rendering of a spring-like resistance. A sensation of resistance can be produced with friction feedback, and perceived hardness can be controlled with alterations to the friction profile. Activating scrolling with a spring-like rate controller, as envisioned in *Scenario 4 – List navigation with rate control*, could therefore be possible. Our observations suggest, however, that feedback may be limited to activation and release of the spring, with only subtle feedback to communicate the extent of the compression and hence current scrolling rate or acceleration.

The results of these five experiments provide extensive information that will guide the design of usable scrolling interactions in future work. As described above, some of the scrolling scenarios envisioned in our design space exploration may have to be adjusted or simplified to account for the perceptual capabilities of users and limitations of current PSF technologies. The experiments nevertheless confirm the feasibility of many of the envisioned scrolling interactions and provide guidance for their implementation. The following guidelines summarize our conclusions:

- Use few distinct detents for precise or fast identification, and more when identification is beneficial but not required, distinguishability is sufficient, or slow movement is acceptable.
- Expect counting to be imprecise unless number is low and detents are well spaced.
- Leverage detent density perception to display scroll rate and content flow.
- Trigger friction feedback at the screen’s center, or both edges / trailing edge if personalized; reinforce with visual feedback.

- Indicate activation and release of a rate controller with spring-like resistance.

6 CONCLUSION

We first explored the design space of scrolling interactions and proposed five concrete scenarios that illustrate the range of interaction styles and tactile effects that programmable friction could support in this context. This exploration informed the design of five user experiments, each investigating a specific aspect of friction feedback of direct relevance to the envisioned usage scenarios. Their results provide extensive information about the use of distinct detents, countable detent sequences, comparable detent densities, friction feedback synchronization to on-screen events, and resistance in rate controllers. We have synthesized this information into guidelines that will be used to design usable scrolling interactions that leverage programmable friction for an improved user experience.

We believe that haptic feedback can improve the user experience of touch interactions by bringing back the tactile richness found in physical interfaces, from musical instruments to computer keyboards. In this work, we explored the potential of programmable surface friction, a promising tactile feedback modality that has yet to be deployed in commercial devices but may prove advantageous or complementary to more common vibrotactile feedback. We focused our attention on enabling functionality for scrolling interactions, an aspect of touch interfaces of particular importance on small devices with limited screen space. We intend to demonstrate in future work that programmable friction can improve the experience of scrolling interactions in various usage scenarios.

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REFERENCES

[1] M. Baglioni, S. Malacria, E. Lecolinet, and Y. Guiard. Flick-and-brake: finger control over inertial/sustained scroll motion. In *CHI EA'11*, pages 2281–2286, 2011.

[2] O. Bau, I. Poupyrev, A. Israr, and C. Harrison. Teslatouch: Electrovibration for touch surfaces. In *Proc. UIST'10*, 2010.

[3] W. Buxton, R. Hill, and P. Rowley. Issues and techniques in touch-sensitive tablet input. *Proc. SIGGRAPH'85*, 19(3):215–224, 1985.

[4] G. Casiez, N. Roussel, R. Vanbelleghem, and F. Giraud. Surfpad. In *Proc. CHI'11*, page 2491, Vancouver, BC, Canada, 2011.

[5] E. Hoggan, S. A. Brewster, and J. Johnston. Investigating the effectiveness of tactile feedback for mobile touchscreens. In *Proc. CHI'08*, pages 1573–1582, 2008.

[6] T. Igarashi and K. Hinckley. Speed-dependent automatic zooming for browsing large documents. In *Proc. UIST'00*, pages 139–148, 2000.

[7] B. L. M. Kaaresoja, T. and J. Linjama. Snap-crackle-pop: Tactile feedback for mobile touch screens. In *Proc. EuroHaptics'06*, pages 565 – 566, 2006.

[8] K. U. Kyung, J. Y. Lee, and M. A. Srinivasan. Precise manipulation of GUI on a touch screen with haptic cues. In *Proc. World Haptics Conference 2009*, pages 202–207, 2009.

[9] V. Levesque, L. Oram, K. MacLean, A. Cockburn, N. D. Marchuk, D. Johnson, J. E. Colgate, and M. A. Peshkin. Enhancing physicality in touch interaction with programmable friction. In *Proc. CHI'11*, pages 2481–2490, May 2011.

[10] J. Luk, J. Pasquero, S. Little, K. MacLean, V. Lévesque, and V. Hayward. A role for haptics in mobile interaction: initial design using a handheld tactile display prototype. In *Proc. CHI'06*, pages 171–180, 2006.

[11] K. MacLean and M. Enriquez. Perceptual Design of Haptic Icons. In *Proc. EuroHaptics'03*, 2003.

[12] S. Malacria, E. Lecolinet, and Y. Guiard. Clutch-free panning and integrated pan-zoom control on touch-sensitive surfaces: the cyclostar approach. In *Proc. CHI'10*, pages 2615–2624, 2010.

[13] N. D. Marchuk, J. E. Colgate, and M. A. Peshkin. Friction measurements on a large area TPaD. In *Proc. Haptics Symposium 2010*, pages 317 –320, 2010.

[14] I. Oakley, J. Angesleva, S. Hughes, and S. O'Modhrain. Tilt and feel: Scrolling with vibrotactile display. In *Proc. EuroHaptics'04*, 2004.

[15] I. Oakley and S. O'Modhrain. Tilt to scroll: evaluating a motion based vibrotactile mobile interface. In *Proc. World Haptics Conference 2005*, pages 40 – 49, 2005.

[16] J. Pasquero and V. Hayward. Tactile feedback can assist vision during mobile interactions. In *Proc. CHI'11*, page 3277, 2011.

[17] J. Pasquero, J. Luk, V. Lévesque, Q. Wang, V. Hayward, and K. E. MacLean. Haptically enabled handheld information display with distributed tactile transducer. *IEEE Transactions on Multimedia*, 9(4):746–753, 2007.

[18] I. Poupyrev and S. Maruyama. Tactile interfaces for small touch screens. In *Proc. UIST'03*, pages 217–220, 2003.

[19] I. Poupyrev, S. Maruyama, and J. Rekimoto. Ambient touch: designing tactile interfaces for handheld devices. In *UIST '02: Proceedings of the 15th annual ACM symposium on User interface software and technology*, pages 51–60, New York, NY, USA, 2002. ACM.

[20] B. Shneiderman. Direct manipulation: A step beyond programming languages. *Computer*, 16(8):57–69, 1983.

[21] G. M. Smith and m. c. schraefel. The radial scroll tool: scrolling support for stylus- or touch-based document navigation. In *Proc. UIST'04*, pages 53–56, 2004.

[22] S. S. Snibbe, K. E. MacLean, R. Shaw, J. Roderick, W. L. Verplank, and M. Scheeff. Haptic techniques for media control. In *Proc. UIST'01*, pages 199–208, 2001.

[23] B. A. Swerdfeger, J. Fernquist, T. W. Hazelton, and K. E. MacLean. Exploring melodic variance in rhythmic haptic stimulus design. In *Proc. GI'09*, pages 133–140, 2009.

[24] D. Wigdor, S. Williams, M. Cronin, R. Levy, K. White, M. Mazeev, and H. Benko. Ripples: utilizing per-contact visualizations to improve user interaction with touch displays. In *Proc. UIST'09*, pages 3–12, 2009.

[25] D. Wigdor and D. Wixon. *Brave NUI World: Designing Natural User Interfaces for Touch and Gesture*. Morgan Kaufmann, 2011.

[26] L. Winfield, J. Glassmire, J. Colgate, and M. Peshkin. T-PaD: Tactile Pattern Display through Variable Friction Reduction. In *Proc. World Haptics 2007*, pages 421–426, 2007.

[27] L. E. Winfield and J. E. Colgate. *Haptic Rendering: Foundations, Algorithms and Applications*, chapter Variable Friction Haptic Displays. A.K. Peters, 2008.