Enhancing Physicality in Touch Interaction with Programmable Friction

ABSTRACT

Touch interactions have refreshed some of the 'glowing enthusiasm' of thirty years ago for direct manipulation interfaces. However, today's touch technologies, whose interactions are supported by graphics, sound or crude clicks, have a tactile sameness and gaps in usability. We use a Large Area Tactile Pattern Display (LATPaD) to examine design possibilities and outcomes when touch interactions are enhanced with variable surface friction, allowing users to feel interface controls. In a series of four studies, we first empirically confirm that variable friction gives significant performance advantages in a range of low-level targeting activities. We then explore the design space of variable friction interface controls, and assess user reactions. Most importantly, we demonstrate that variable friction can have a positive impact on the enjoyment, engagement and sense of realism experienced by users of touch interfaces.

Author Keywords

Variable friction, haptics, tactile feedback.

ACM Classification Keywords

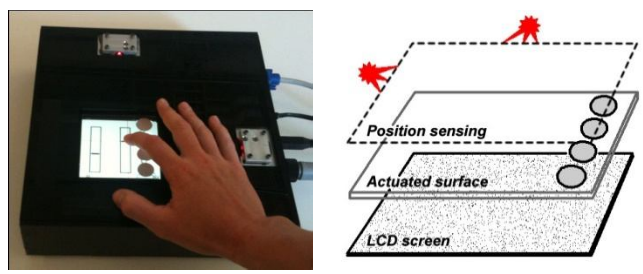
H5.2. [User Interfaces]: Interaction Styles, Haptic I/O.

INTRODUCTION

As recognition of the impact of emotion on design grows [16], designers seek natural, realistic and organic [22] means of interaction. In 1987, Shneiderman [26] observed the 'glowing enthusiasm' resulting from graphical user interfaces that allowed users to directly manipulate objects. The iPhone's successful exploitation of touch suggests a similar role of engagement and delight, presumably through the directness and realism of this modality; and this is driving renewed research interest in interaction metaphors using touch (e.g. [3, 10]).

However, touch interactions with most current devices are 'flat' – all interface objects still *feel* like the same plastic or glass, so any physical realism of underlying objects must be communicated through visual and auditory illusions. Tactile effects are generally limited to clicks and buzzes produced by low-frequency vibrotactile pulses. These can convey a great deal of information [13] but lack realism.

This paper examines design possibilities and outcomes when touch interactions are enhanced with variable surface friction. For our studies we use a Large Area Tactile Pattern Display (LATPaD) [14, 29] developed at Northwestern University. The LATPaD uses piezoelectric actuators bonded to a touch sensitive display to produce high-frequency vibrations, creating a friction-reducing 'squeeze film' of air (Figure 1). Our prototype consists of an actuated glass plate atop an LCD screen; with laser-based fingertip position measurement, we have a 57x76 mm touchscreen. A broad range of friction effects are produced by varying the high-frequency vibrations in response to finger movements.



(a) (b)

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

The ability to vary friction raises many interaction possibilities which are interesting from both performance and emotional standpoints. Activities such as pointing and dragging may become more efficient: high friction objects might 'grab' the finger, reducing overshoot and errors, while low friction surfaces should ease sliding movements and reduce finger judder. Emotionally, variable friction may increase perceived realism and subjective satisfaction.

In this paper, we report experiments measuring both effects. The specific contributions of our work are as follows:

1. Performance data showing that variable friction can improve performance in touch interaction;
2. Qualitative and quantitative evidence that friction enhanced widgets can positively impact users' emotional response to touch interactions;
3. An exploration of friction-enhanced interface design.

After providing background, we describe two studies (S1-S2) that examine how variable friction effects impact target

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selection performance, without and with surrounding distracters; S3 characterizes the biomechanical control effects of friction. We then present a series of design concepts exploiting variable friction effects and report results of an examination of users' subjective response (S4). Finally, we discuss our findings and conclude.

BACKGROUND

Issues grounding our approach range from past work to our own hypotheses on the value of variable friction.

Touch Interaction Without Tactile Feedback

Buxton et al's 1985 analysis of touchscreen interaction limitations still holds: pressure is needed to signal while pointing, or both move the cursor and select, and virtual widgets need haptics [4]. More recent systems have exploited non-feedback touching to address issues like 'fat finger' occlusion, accuracy and the need to feel edges. Roudaut et al identified all of these as concerns for target acquisition on small touchscreens and proposed new zoom techniques for thumb-based selection [23]. Physical metaphors have inspired new and more fluid gestures [21]. Others have elaborated strategies for particular control actions: Potter et al attributed high accuracy of 'lift-off' selection to its continuous nature [19]. We posit that increasing the tactile information available during this contact stream could be even more beneficial.

Tactility in Mobile Devices and Touchscreens

There are now many examples of interaction design for tactile feedback in small touch-surface devices, e.g. [12, 20], as well as research and commercial instantiations based on technologies such as piezo- or solenoid-actuated screens. Nearly all rely on vibration; a recent alternative is electrotactile [25]. None physically resist sliding.

Generally, speed and accuracy have improved when forces are included in pointing tasks [1, 5, 6]. This result is nuanced, however: in absence of knowledge of user's destination, feedback may also be encountered for non-target elements, which can introduce obstructions and slowdowns ([5]; and in particular, [18]). Furthermore, user preference does not always follow targeting utility [28].

While most efforts have layered tactile feedback atop a normal GUI (e.g. tactile overlays on soft keyboards that indicate key proximity and presses [11]), it is arguable that greater benefits are possible for interactions designed *around* taction. Pokespace relies on forces for its gesture set, and found reduced visual demand in augmented widgets tested in a similar manner to our Study 4 [27].

Theoretical Arguments for Variable Friction

Illusions can be exploited to improve performance or immediacy of a passive touch interaction. Synchronous sound and graphics can suggest absent tactile feedback. Users "feel" auditory clicks [7]; Apple's iPod took this illusion mainstream. But it fails when the earbuds are out, and lacks the useful physical constraint of a real click. Likewise, visuo-haptic effects such as 'sticky widgets', a manipulation of mouse control-display gain, can improve selection performance by curtailing overshoot in the closed-loop phase of motion and enlarging the motor space [2]. Variable friction may further improve performance, by making the finger *actually* stick to the target.

Touch interfaces are also subject to the biomechanics of finger sliding on glass, which produces asymmetric stick-slip [15]. Given constant friction, there is greatest unpleasant, destabilizing 'judder' in the direction the finger points ('north') where friction acts to bend the finger while extensor muscles oppose this. Bending reduces contact angle, increasing the force required to maintain movement ('stick'), then the finger springs forward ('slip'). 'South' or sideways dragging is resisted skeletally with a relatively constant contact angle. Lowering friction should reduce the point of judder for even north movements.

Variable Friction Devices: the LATPad

The LATPaD's tactile feedback varies the friction experienced by the fingertip at the touch surface. Its operating principle, a squeeze film of air produced by 26 kHz piezo-actuated vibrations, lowers the friction coefficient of a glass surface from ~1.0 to ~0.15. Unpublished experiments indicate that the just-noticeable-difference in friction is about 30-40%; thus the LATPaD's dynamic range provides several distinguishable friction levels. Other models demonstrate this effect on larger and smaller plates of arbitrary shape and a range of materials.

Still in early development, our prototype has several limitations. The piezo actuation is compact, but the laser finger position sensing uses a larger housing. The piezos produce some audible noise when active. The vibrational mode that is used produces nodes where friction reduction is weaker, which applications must avoid (in this model, 2 narrow strips parallel to longer axis of screen). Development continues, focusing on these issues. Within two to three years, programmable friction is expected to be deployable in a form factor similar to current touchscreens with uniform feedback and no audible noise.

A DESIGN SPACE FOR VARIABLE-FRICTION TOUCH

These and other works (e.g. [24]) demonstrate that while entrancing, current touch technology leaves usability gaps: it is hard to accurately point, select and drag, to select text, achieve basic drag/drop functions, and enter text. The illusion of physicality, with both its utility and aesthetic, disappears with the withdrawal of image or sound.

In ongoing work, we are defining the design space where variable friction should offer value by filling these gaps. This space is structured around dimensions of (1) basic effects that can be rendered (e.g. impact, edges, stiffness) versus (2) information that can be communicated (e.g. selection support and confirmation, functional availability or attribute, spatial navigation). It has guided the choice of Study 4 design examples, by indicating both the extent of the space to be sampled and opportunities within it.

STUDIES 1-3: FRICTION PSYCHOPHYSICS

S1-S3 were conducted in one session and studied the effect of variable friction on target selection and finger motion.

Study 1: Target Selection Without Distracters

S1 concerns the speed and accuracy of target acquisition with and without variable friction. Based on the theoretical ability of variable friction to make the finger stick on the target, we hypothesize:

H1. Variable friction across the surface, with high friction over the target, will improve selection speed and accuracy.

A secondary consideration is the overall level of friction during targeting. It is possible that any benefit of varying friction could be explained solely by faster inter-target movement caused by the more slippery surface, rather than by differential friction at the target edge. The study controls for this effect, leading to the second hypothesis:

H2. There will be no significant difference between selection speed and accuracy when using a constant low level of friction and a constant high level.

Selection modality: lift-off. Friction only matters during sliding surface contact. Thus traditional Fitts' Law [8] 'tapping tasks', where most or all movement occurs above the surface, are unlikely to be influenced by friction effects; we therefore analyzed drag-based selections that are issued when the finger lifts off the surface. This is a common modality on touch devices, particularly when targets are small (e.g., sliding text entry on the iPhone). Furthermore, a lift-off selection modality has been seen to be more accurate than others for touch input in some contexts [19].

Direction. We controlled for movement direction (north, south, east and west), with the aim of revealing movement dynamics rather than testing a specific hypothesis.

Procedure

Participants were given written instructions on how to interact with the LATPad. They were then invited to try the device for approximately one minute by rubbing a finger across a checkerboard pattern with high and low friction. They were given the exact procedure for each of the target acquisition trials, which consists of the following steps:

1. *Initial state.* A thin blue 'control' line and a red 'target' line appear on the display.
2. *Acquire control line* by touching and remaining stationary on it. For any movement off the control line or off the surface, the trial is repeated.
3. *Free control line and begin.* After the finger pauses on the control line for 0.2 second, there is an audible beep and the control line is unlocked (can be dragged). The clock starts on movement.
4. *Drag control line over target*. The target turns green to confirm the over-target state, and in some conditions friction changes over the target.
5. *Lift-off to select by* raising your finger off the target. The target turns back to red briefly and the control line disappears until the next trial.

Participants completed 30 familiarization selections with a 36 pixel (5.62 mm) wide target (data discarded). Ten were completed with each interface condition with the same order of exposure as for the experimental trials (below). To reduce any possible influence of the LATPaD's audible sound, participants listened to white noise through Direct Sound Extreme Isolation EX-29 headphones throughout.

Each participant then completed 336 experimental trials (96 discarded) covering three factors: *interface*, *direction*, and *target width*. The three levels of *interface* were constant high friction (*HF*), constant low friction (*LF*) and variable friction (*VF*). In *HF* and *LF*, LATPad oscillations were always turned off or maximally on, respectively. In *VF*, friction was high (LATPad off) over the target, but low (maximally on) everywhere else. We did not test inverse variable friction (low over the target and high elsewhere) as it does not offer the psychophysical advantages of 'finger trapping' promised by *VF*. The four levels of direction were north (*n*), south (*s*), east (*e*), and west (*w*); and the four levels of width were 6, 12, 24, and 48 pixels (0.94, 1.87, 3.74 and 7.49 mm). The device was physically rotated when changing direction axis (*n*/*s*, *e*/*w*) so that movement remained within an optimal friction region. Movement amplitude was always 225 pixels (35.1 mm). The control and target lines were shifted slightly towards the *n* or *w* side of the screen to avoid interference from the raised screen rim. Figure 2 shows our interface for north-direction selections for the four widths.

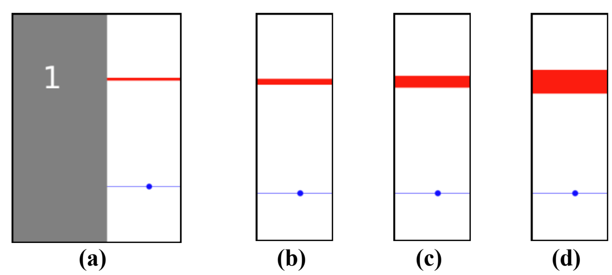

Figure 2. Target acquisition task for S1 in the *North* direction: (a) entire screen for first interface with width of 6 pixels, and partial screen with widths of (b) 12, (c) 24 and (d) 48 pixels.

The experimental trials (target acquisitions) were administered as blocks of 14 trials, each block sharing a direction axis (*n*/*s*, *e*/w), interface level (*LF*, *HF*, *VF*) and target size (6, 12, 24, 48). The first 4 trials of each block were discarded to allow for strategy adaptation. Initial direction was randomized for each block, then alternated on the direction axis. Blocks sharing a direction axis were administered consecutively to minimize physical device rotation; then grouped by interface level to allow questionnaire assessment. Block sets were counterbalanced such that all combinations of 2!=2 direction axis orderings and 3!=6 interface level orderings were used for one participant. Finally, block target size was randomized within same-interface sets. A total of 24 blocks (2 direction axis × 3 interface levels × 4 target sizes) were administered.

After each of the 6 sets, participants were asked to comment on the interface used and to respond to the Likert-scale questions (1 / 5 = strongly disagree / strongly agree): "I performed well/needed to concentrate to accomplish the task/felt confident in my ability to hit the target/felt frustrated/enjoyed interacting with the touchscreen."

After completing all trials, participants were asked to rank the interfaces ('ties' permitted) and for final comments. Interface was referred to by order of appearance, reinforced with a numerical label on the side of the display during use.

Participants

Twelve participants (6 female) were recruited from a local university: aged 19-48 (mean 29.4), all right-handed.

Design and Analysis

Dependent measures are analyzed using a 3×4×5 repeated measures analysis of variance for the factors *interface* ∈ {*HF, LF, VF*}, *direction* ∈ {*n, s, e, w*}, and *target width* ∈ {6, 12, 24, 48 pixels}. The dependent measures are selection time, number of errors, time between entering the target and lifting off it, and number of overshoots. We also analyze the goodness of fit to Fitts' Law models (coefficient of determination) and subjective responses.

Results

In summary: variable friction (*VF*) improved targeting performance over *HF* without compromising accuracy, thus we accept *H1*. The constant low friction conditions (*LF*) produced similar results as *HF*, so we also accept *H2.*

Acquisition time. There was a significant effect of *interface* ($F_{2,22}$=6.89, p<.01), with *VF* fastest (mean 921 msec, s.d. 324), then *HF* (mean 990, s.d. 344) and *LF* (mean 1002, s.d. 341); see Figure 3. Posthoc comparison using Bonferroni correction confirms differences between *VF* and both *HF* and *LF* (p<.05), but not between *HF* and *LF*.

As anticipated, there was a significant main effect of *width* ($F_{3,33}$=82.2, p<.001); but there was also a significant *interface*×*width* interaction ($F_{6,66}$=3.85, p<.01). Figure 3 suggests that *VF* performance deteriorated less rapidly across increasing Index of Difficulty than the other conditions. This explanation is supported by the Fitts' Law analysis, which showed strong models for all conditions

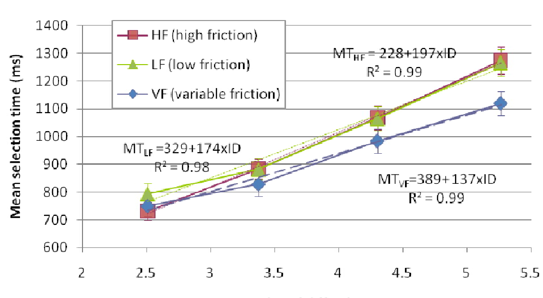

Figure 3. Results and Fitts' law models for interfaces (S1).

(R^2>0.98). The lower slope for *VF* corresponds to an Index of Performance (reciprocal of the slope) of 7.26 bits/second, which is higher than either *HF* (5.07 bits/second) or *LF* (5.74 bits/second).

There was no significant main effect of *direction* ($F_{3,33}$=1.8, p=.17), with means of 943, 960, 996 and 984 msec for *n, s, e* and *w* movement respectively.

Accuracy. Analysis of count of trials per block containing an error shows no significant effect of *interface* ($F_{2,22}$=0.74, p=0.49), with similar means of 0.82 errors with *VF*, and 0.7 and 0.81 for *HF* and *LF* respectively. The relatively high error rate is due to the use of small targets, and as expected, there is a significant effect of *width* ($F_{3,33}$=53.9, p<0.001), with errors increasing from a mean of 0.14 errors per block with 48-pixel targets to 1.8 errors per block with 6-pixel targets. There was a significant effect of *direction* ($F_{3,33}$=10.0, p<.01) with the *s* movement being the most error prone (1.2 errors per block) and *n* being the least (0.4 errors per block). Importantly, however, there was no *interface*×*width* ($F_{6,66}$=1.13, p=0.36) or *interface*×*direction* interaction ($F_{6,66}$=1.16, p=0.34).

Source of VF performance advantage. There are several possible explanations for the performance advantage with variable friction: users may move more quickly, resulting in a shorter target approach; they may respond more quickly to the over-target state, resulting in a shorter dwell time over the target; or variable friction may 'trap' the finger on the target, reducing overshoot. To understand which of these are at play, we conducted three more one-way ANOVAs (one for each *interface* level, results in Figure 4) with dependent variables of approach time (from initiating movement to last target border entry), dwell time (from last target border entry to selection by lifting), and entry count (number of times the target border was entered).

(a) (b) (c)

Figure 4. (a) Approach time, (b) dwell time, and (c) number of target entries as a function of the *interface* condition (S1).

This revealed a significant effect for approach time ($F_{2,22}$=5.69, p<0.05) with *VF* faster (mean 634 msec, s.d. 268) than either *HF* (690, 283) or *LF* (706, 276). Neither dwell time ($F_{2,22}$=1.0, p=0.38) nor entry count ($F_{2,22}$=0.87, p=0.43) varied significantly, although *VF* had the lowest mean in both. Consequently, it seems that the largest effect of target acquisition with *VF* is that it increases users' confidence in moving towards the target, allowing them to approach more quickly without compromising ability to stop abruptly on the target and select it accurately.

Subjective results. Participants were asked to rank each interface condition after both *e/w* and *n/s* trial blocks. *VF* was ranked 1st 58.3% of the time, 2nd 29.2%, and 3rd 12.5%, producing a significant difference (Friedman χ^2=9.5, p<.01); mean rankings were 1.5, 2.0 and 2.1 for *VF, LF,* and *HF.* Questionnaire responses (Table 1) show that mean ratings for *VF* were most appreciative in all five questions, but only significantly so for enjoyment.

	VF	LF	HF	χ_r^2	Sig
Performance	3.9 (0.7)	3.7 (0.8)	3.5 (0.7)	2.3	=0.31
Concentration	3.2 (1.0)	3.7 (1.0)	3.5 (1.0)	3.4	=0.18
Confidence	4.0 (0.7)	3.5 (0.8)	3.7 (0.6)	2.8	=0.25
Frustration	1.8 (0.7)	2.0 (0.8)	2.2 (0.8)	2.3	=0.31
Enjoyment	4.2 (0.7)	3.8 (0.8)	3.6 (0.8)	5.8	=0.05

Table 1. Mean (st. dev.) questionnaire responses, with 1= strongly disagree, and 5 = strongly agree (S1).

Study 2: Target Selection With Distracters

Previous work with tactile feedback has demonstrated that it can negatively influence performance in the presence of distracter targets (as documented in [5]). This is a critical limitation, as most practical deployments will involve distracters. Therefore we tested the hypothesis that:

H3. Variable friction will not adversely affect targeting performance in the presence of distracter targets.

Procedure, Apparatus and Participants

The 12 participants from S1 proceeded immediately to S2. Selection was identical to S1, i.e. dragging the control line over the target and lifting off. Critically, however, the space between the control line and the target and beyond the target was populated with distracters of identical width to that of the target. All distracters produced the same visual and friction effects as the target, i.e. highlighted green to indicate the over-target state, and presence of friction effects. Distracters were otherwise displayed in black.

Distracter density is an important variable for *H3*, so S2 replaces S1's width with three levels of distracter separation: 5, 20, and 40 pixels (Figure 5). All targets and distracters were 24 pixels in width. The number of distracters placed before the real target varied from 1 to 3; there was always one distracter behind the target. We tested only the most extreme directions, *n* and *s*.

A block held twenty-two target selections (trials); three blocks were performed per interface condition. The direction (*n*,*s*) was initially randomized for each block and then alternated. The number of distracters and their spacing were selected randomly for the first four trials (discarded). To prevent memorization of the tactile pattern leading to the target and its use as an aid, the remaining 18 trials cycled randomly through all 3×3 combinations of distracter number and spacing in each direction (*n*,*s*). Interface order and subjective responses were controlled as for S1.

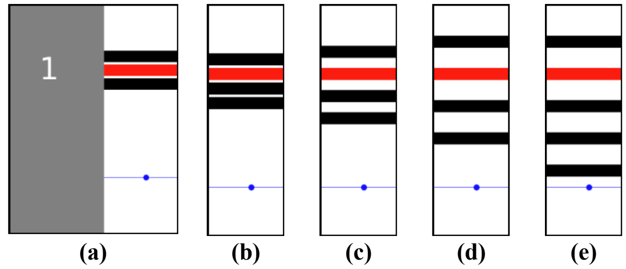

Figure 5. Target acquisition task for S2 in the *n* direction: (a) entire screen for first *interface* with 1 pre-target distracter and a *separation* of 5 pixels, and partial screen with 2 distracters and a *separation* of (b) 5, (c) 20 and (d) 40 pixels and (e) 3 distracters with a *separation* of 40 pixels.

Design

The same dependent measures as S1 are analyzed in a 3×2×3×3 repeated measures analysis of variance for *interface* ∈ {*HF, LF, VF*}, *direction* ∈ {*n,s*}, *distracter spacing* ∈ {5, 20, 40 pixels} and *number* ∈ {1, 2, 3}.

Results

In summary: the results show no effects of *interface* (main or interactions) for dependent measures of time or errors, thus we accept *H3*: variable friction does not harm performance in the presence of distracters.

Performance. Four-way ANOVA showed a significant effect of *distracter spacing* on acquisition time ($F_{2,22}$=13.3, p<.01), with mean of 908, 892 and 874 msec for 5, 20 and 40 pixel spacing respectively. There were no significant main effects or interactions involving interface for either task time or errors. Mean times were similar (900, 892, 882 msec for *VF*, *HF*, *LF*; $F_{2,22}$=0.26, p=0.78), as were per block error rates (0.16, 0.22, 0.19; $F_{2,22}$=0.71, p=0.5).

S1 trials (zero distracters) with *n/s* directions and 24-pixel targets were also compared to S2 (1, 2 or 3 distracters). A three-way ANOVA for factors *interface*, *direction* and *number of distracters* revealed no significant effects.

Subjective results. The participant's post-experiment interface ranking produced very similar results to S1: a significant ranking preference for *VF*, but non-significant responses to other questions.

Study 3: Constant Velocity Dragging

To characterize physical effects occurring at friction borders, we conducted a third shorter study with the same participants immediately after S1 and S2. Participants tried to achieve a target drag velocity in repeated bidirectional strokes across the display. Drag speed was specified by metronomic tempo beeps for hitting two fixed targets shown on the screen. We tested two speeds (50 / 100 mm/s, or 320.5 / 641.0 pixels/s), and both orientations (*n/s, e/w*). During these repeated strokes, friction patterns were produced in the middle of the screen (but not shown visually) including constant low or high levels, step increases or decreases, and single or sequential pulse increases or decreases with the same extent, number and separation as S1 and S2's targets and distracters. Each

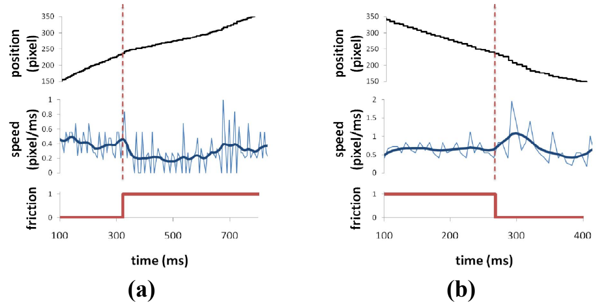

Figure 6. Selected S3 results: (a) deceleration after increase in friction (P2, *e*). (b) acceleration after step decrease (P4, *n*).

participant performed 168 trials in six blocks. The first six bidirectional trials of each block were discarded to allow subjects to adjust their speed (36 in total). The order of the different friction patterns was randomized within blocks and each friction pattern was shown once.

Results

Finger trajectory and surface states were recorded for 1584 trials in total; position and velocity trajectories for all trials were plotted and inspected visually. An effect of friction changes is clear in many of these trajectories. Figure 6 shows two of the best examples, where a step increase or decrease in friction is followed by a temporary deceleration or acceleration in the fingertip. This suggests that the velocity of the finger is affected at least under certain conditions, in a useful way: in effect, a sticky target is truly sticky with the variable friction effect. This effect may in other cases have been reduced by the stick-slip of the fingerpad or finger pressure, or masked by the relatively low spatio-temporal data. A quantitative analysis is beyond the scope of this paper, but currently underway.

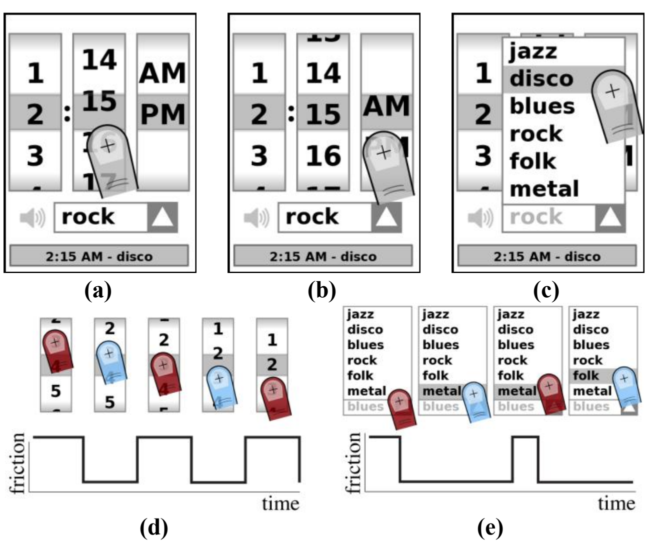

Figure 7. Alarm Clock: (a) hour and minute wheels, (b) AM/PM wheel, (c) sound combo box and friction patterns while selecting (d) hour and (e) sound. The finger color changes from light blue to dark red as friction increases.

STUDY 4: DESIGN EXAMPLES AND USER EXPERIENCE

We explored interface design for variable friction interfaces in an iterative process, beginning with glass etched prototypes, then exemplar designs, which finally led to a study to establish their emotional and subjective impact.

Demonstration Applications and Study Tasks

Four exemplar widgets were designed to provide good coverage of tactile sensations and of communication functions that variable friction might support.

Alarm Clock. Users set the alarm time using wheel widgets and the alarm sound using a combo box (Figure 7a-c). Variable friction provides two effects. The wheels produce strong ticks by abruptly increasing friction as items near their center (Figure 7d). The combo box produces similar ticks but with friction peaks between targets (Figure 7e). The *Alarm Clock* study tasks involved setting the time and sound to a value displayed at the bottom of the screen.

File Manager. File, folder and recycle bin icons are arranged in a 3×4 array (Figure 8a); recycle bin and folder icons enlarge 20% when a file hovers over them (Figure 8b-c). Variable friction produces two effects. Initially low, friction increases abruptly over folder icons and oscillates at 37.5Hz over the recycle bin, producing a bump and buzzing respectively (Figure 8d). The *File Manager* study task involved moving 8 files labeled from 1 to 3 into correspondingly labeled folders.

Game. In this arcade game, a ball bounces against a round cursor surrounding the finger and breaks bricks (Figure 9a-c). Some bricks require multiple hits to be broken; others produce special effects - releasing a second ball or making the cursor flicker and ball bounce erratically for 5 seconds. Compressing and releasing a spring initially launches the ball. Variable friction gives three types of effects. Friction

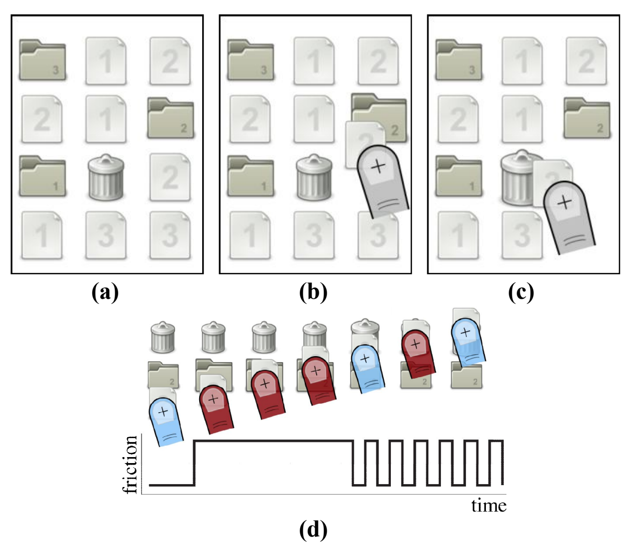

Figure 8. File Manager: (a) initial screen, moving a file into (b) a folder or (c) recycle bin, and (d) friction patterns while over a folder or bin. The finger color changes from light blue to dark red as friction increases.

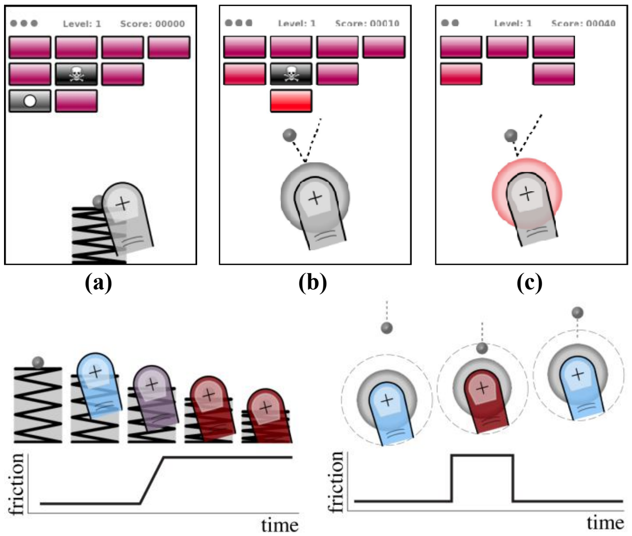

Figure 9. Game: (a) launch, (b) normal and (c) erratic bounce, and friction patterns during (d) launch and (e) bounce. Low friction shown as a blue finger, high friction red.

increases gradually to simulate a spring's resistance (Figure 9a,d). For ball impact (Figure 9b,e), friction abruptly increases as the ball approaches the finger. Erratic bouncing (Figure 9c) produces a friction oscillation identical to the *File Manager* recycle bin. The Game study task involved playing the game, with ten difficulty levels available.

Text Editor. Words are selected by dwelling for 0.3 second using a cursor that extends above the finger, reducing the 'fat finger' problem. While dragging a selected word, collisions are indicated by visual compression up to 30%, after which both words remain fixed while the cursor moves on (Figure 10a). The words then swap places when the cursor reaches a position where it can be relocated. Swiping left or right flips pages (Figure 10b). Variable friction provides three effects. When moving a word within a line, friction increases linearly as word compression increases from 20% to 30%, and drops abruptly after a word swap, creating a popping sensation as a word moves through a line (Figure 10c). When moving a word between lines, line-based friction effects fade in and out as lines are exited and entered, with a brief friction pulse between lines. Swapping pages triggers a tick via an abrupt increase in friction. The *Text Editor* study task consisted of 'fixing' sentences by reordering words within four pages of text – e.g. "the store grocery sells yellow tomatoes green bananas red lettuce and eggplants purple."

Experimental Procedure

Participants interacted with each of the four applications twice, with and without variable friction. Each interaction was limited to 2 minutes to provide exposure without boredom. Each application was presented first for ¼ of the participants, and the order of the others was randomized. Half of the participants experienced variable friction first for all applications, the other half without. Participants were instructed to focus on experience rather than performance.

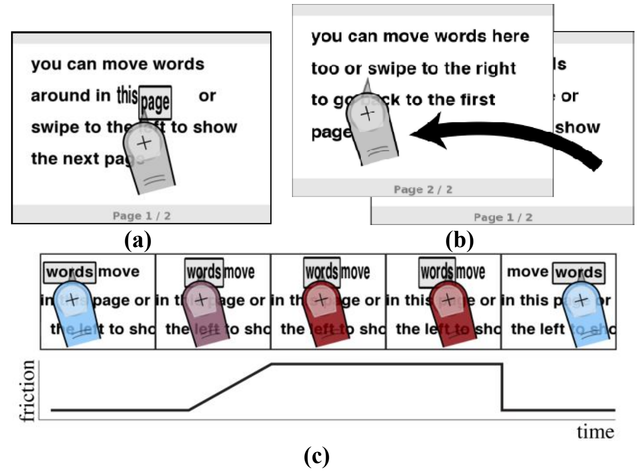

Figure 10. Text Editor: (a) word movement, (b) page swap and (c) friction patterns while moving a word. The finger color changes from light blue to dark red as friction increases.

A User Engagement Scale (UE1-10) was used after each condition (twice for each application; once with and once without friction). A tactile feedback questionnaire (TF1-7) was completed after each interaction with variable friction (once per application feature). Once both friction conditions were completed with an application, a comparison questionnaire (C1-5) was administered, followed by a short interview (I1-3). This procedure was repeated for all four applications, and followed by a final questionnaire (F1-2). The User Engagement Scale used a 7-point Likert scale and all others a 5-point scale (strongly disagree to strongly agree). Each questionnaire is further described below.

The User Engagement Scale (UE1-10) was adapted from a validated 31-question questionnaire developed to assess six aspects of engagement: Focused Attention, Perceived Usability, Aesthetics, Endurability, Novelty and Felt Involvement [17]. Ten of the 31 questions were adapted, spanning all aspects:

UE1. I was absorbed in my interaction task.
UE2. I felt in control of my interactive experience.
UE3. I found this application confusing to use.
UE4. I liked the visual and tactile effects used in this application.
UE5. This application appealed to my visual and tactile senses.
UE6. I would recommend this application to my friends and family.
UE7. I would have continued to interact with this app. out of curiosity.
UE8. I felt interested in my interaction task.
UE9. This interactive experience was fun.
UE10. I felt involved in this interaction task.

The tactile feedback questionnaire (TF1-7) was filled for the main tactile features of each application: hour/minute wheel, AM/PM wheel and sound combo box for *Alarm Clock*; folders and recycle bin for *File Manager*; launcher, normal and erratic bounce for *Game*; movement within or between lines and page swapping for *Text Editor*. Participants were asked if they noticed the feature, and if so rated whether the tactile feedback was (TF1) weak, (TF2) natural, (TF3) informative, (TF4) annoying, (TF5) matched the visuals, (TF6) felt good, and (TF7) was preferred.

The comparison questionnaire (C1-5) asked if tactile feedback (C1) was preferred, (C2) made the task easier to perform, (C3) the application more enjoyable, (C4) the interface more realistic and (C5) made them more confident.

Interview questions (I1-3) asked participants (I1) to describe the sensations, (I2) what they liked and didn't like about the tactile feedback, and (I3) how they would improve it.

The final questionnaire (F1-10) asked (F1) if participants would turn this type of feedback off on their phone, and (F2) if tactile feedback improved their experience.

Participants

The data for eight participants were rejected due to protocol irregularities (2) and hardware (4) or software (2) complications that may have affected subjective responses. The remaining twelve participants (6 females) were aged from 19 to 38 (mean 24.3). Eleven were students, only four of them from engineering or computer science. Ten used touchscreen phones or music players once a week or more.

Results

The participants' comments and questionnaire responses demonstrate that variable friction can improve the emotional and subjective experience of touch interactions. They also provide some important insights into its potential negative effects, which need to be addressed through design. We begin with the interview responses and comments, and then report the questionnaire results.

Interview Responses

Several comments show that variable friction enhanced the participant's sense of realism: ***"When I was moving the words against something, I could feel something squeeze back."*** (P3, Text Editor); **"*I knew I was actually touching it.*"** (P2, File Manager); **"*It feels […] as if turning the wheels.*"** (P11, Alarm Clock).

Their comments also show that variable friction increased awareness of the system state, some suggesting a reduced dependence on vision: **"*I think it gives me accuracy, like even if I closed my eyes I would be able to predict the amount of scrolling that I do.*"** (P5, Alarm Clock); **"*Feel more informed ... when I am moving on the line I can feel each word.*"** (P11, Text Editor); ***"[F]or the garbage bin it's like oh ah don't do it."*** (P3, File Manager).

Importantly, several comments showed that participants liked the friction effects: **"*this is nice... it makes things a lot more interesting.*"** (P3, Game); ***"I liked the sensation while I am rolling*"** (P8, Alarm Clock).

Nine of the twelve participants were predominantly positive in their comments about variable friction for one (1), two (3), three (4) or four (1) of the applications. The remaining three were predominantly negative or neutral. Negative words used to describe variable friction included "*unpleasant*", "*weird*", "*creepy*", "*annoying*" and "*itchy*". The tactile feedback was often described more neutrally using physics-related terms such as *"resistance"*, *"friction"*, *"slippery"* and *"sticky"*. Negative comments were often aimed at the limitations of the applications but also suggested potential pitfalls of variable friction such as *"[getting] in the way of trying to move"* (P8, File Manager) or inducing fatigue through overuse (P3, Alarm Clock).

Interestingly, there was little cross-participant consistency in assessing which applications and friction effects were positive additions. Similarly, participants differed in their assessment of the feedback strength, with two stating that the stimuli were too weak and one too strong. These observations suggest a need for variable friction effects to be very carefully designed and customizable by end users, much like audio-visual feedback.

Finally, a majority of participants spontaneously discussed variable friction's potential integration in commercial devices and voluntarily shared their impressions for 5 to 15 minutes after completion of the experiment.

Questionnaire Responses

The questionnaire responses tend to amplify the overall positive response to variable friction effects.

User Engagement Scale (Table 2). Responses for variable friction were positive or neutral, except for control (UE2) in *Alarm Clock*, confusion (UE3) in *Alarm Clock* and *Game*, and liking (UE4) in *Game*; none statistically significant. Of forty comparisons (4 applications × 10 questions), variable friction received better scores in 30: χ^2=9.0, p<.005.

Tactile Feedback. The tactile feedback questionnaire showed marked differences in the noticeability of friction effects, with only 25% noticing the rapid pulse experienced during page swapping, but 100% noticing Alarm Clock wheel effects. Weak noticeability is explained by rare use (Recycle Bin, Page Swapping) or a brief, subtle sensation (Launcher, Page Swapping). Means for 67/77 contribution assessments of variable friction effects made by each participant reflected positive opinions (χ^2=40.7, p<.0001). Negative assessments were most common in *Game*.

	Clock		**Files**		**Game**		**Text**	
	HF	***VF***	***HF***	***VF***	***HF***	***VF***	***HF***	***VF***
UE1. Absorbed.	**4.7 (1.2)**	**4.9 (0.9)**	**4.8 (1.2)**	**5.4 (1.2)**	**5.6 (0.9)**	**5.8 (0.6)**	5.1 (0.8)	5.1 (1.2)
UE2. Control.	5.3 (0.8)	5.1 (1.3)	5.6 (0.7)	5.6 (0.9)	**4.9 (1.2)**	**5.3 (0.9)**	**4.0 (1.7)**	**4.8 (1.9)**
UE3. Confusion.	2.0 (1.2)	2.3 (1.3)	1.7 (0.8)	1.7 (0.9)	1.8 (0.9)	2.2 (1.2)	**2.5 (1.4)**	**2.3 (1.6)**
UE4. Liked.	**4.4 (1.3)**	**5.0 (1.3)**	**4.9 (0.9)**	**5.4 (1.4)**	4.7 (1.7)	4.5 (1.6)	**4.5 (1.7)**	**5.1 (1.5)**
UE5. Appeal.	**4.2 (1.3)**	**5.3 (1.1)**	**4.1 (1.5)**	**5.5 (1.0)**	**5.1 (1.1)**	**5.7 (0.8)**	**3.8 (1.5)**	**5.2 (1.3)**
UE6. Recommend.	**4.2 (1.4)**	**5.0 (1.4)**	**4.1 (1.4)**	**5.0 (1.6)**	5.0 (1.3)	5.0 (1.5)	**4.7 (1.7)**	**4.9 (1.8)**
UE7. Curious.	**4.0 (1.9)**	**4.9 (1.5)**	**3.6 (1.7)**	**4.6 (1.9)**	5.6 (1.5)	5.6 (1.6)	**4.2 (1.9)**	**4.9 (1.8)**
UE8. Interested.	**4.3 (1.7)**	**5.2 (1.5)**	**4.6 (1.5)**	**5.0 (1.5)**	**5.8 (1.0)**	**5.7 (1.0)**	**4.7 (1.5)**	**5.4 (1.6)**
UE9. Fun.	**4.2 (1.6)**	**5.0 (1.7)**	**4.2 (1.6)**	**4.7 (2.0)**	**5.6 (0.8)**	**5.7 (1.0)**	**4.4 (1.8)**	**5.0 (1.5)**
UE10. Involved.	**4.6 (1.6)**	**5.3 (0.8)**	**4.6 (1.4)**	**5.7 (1.0)**	**5.2 (1.2)**	**5.7 (0.7)**	**4.3 (1.8)**	**5.5 (0.8)**

Table 2. Mean (and s.d.) for the User Engagement Scale [1-7]. Rating pairs favorable to *VF* are bold.

	Alarm Clock	File Manager	Game	Text Editor
C1. Preference	3.7	4.0	3.3	4.0
C2. Ease	3.5	3.1	2.8	3.3
C3. Enjoyment	3.4	3.8	3.6	3.9
C4. Realism	4.1	3.3	3.7	4.0
C5. Confidence	3.7	3.7	3.2	3.9

Table 3. Mean ratings [1-5] and distribution of answers (1 bottom - 5 top/black) for comparison questionnaire.

Comparison. Table 3 shows that all but one of the 20 direct comparisons favors variable friction: χ^2=14.4, p<.001. None of the participants expressed a strong preference for constant high friction in any of the questions. *Final Questionnaire.* Participants were asked if they would turn friction effects off (mean response 2.4, s.d. 1.0) and felt variable friction "improved experience" (mean 4.1, s.d. 0.5); 1 for strongly disagree to 5 for strongly agree.

DISCUSSION AND NEXT STEPS

We first investigated performance for variable friction effects. We found measurable benefits without harm, an unusual result for haptic targeting aids. S1 confirms that variable friction (high over target, low elsewhere) significantly improves targeting performance. S2 verifies that variable friction targeting is no worse than normal friction when distracters are present, crucial since pseudohaptic 'sticky' targets and vibrotactile (VT) targets can reduce performance in the presence of distracters. S3 indicates that friction variations cause actual, not only perceived, velocity changes: unlike pseudohaptic and VT aids, rendered stickiness does slow the fingertip. Yet overall movement time does not rise, even with distracters, because approach stages are faster (S1-S2).

We then focused on user *experience*, not performance [9] – engagement, enjoyment, directness, perceived utility – and found through our S4 application samples that variable friction can enhance the emotional aspect of using a touch interface. This approach freed us to explore many design concepts and highlight what may ultimately be the most crucial factor in improving upon passive touch interfaces.

In the following we reflect upon generalizing these results to real-world use and understanding their value.

Hardware Factors

The LATPaD is currently a bulky prototype. However, the critical components for producing variable friction are the small, thin piezoelectric actuators visible in Figure 1a and there are no major barriers to miniaturizing the technology to the scale of current mobile devices. Rendering non-uniformities are also expected to be resolved in the near future, and our S4 designs successfully avoided them.

Performance in real-world target acquisition

The LATPaD's variable friction effects are only felt when the finger is sliding against the display surface; S1-S2 therefore used dragging tasks to maximally expose participants to the effects of interest. The lift-off selection used here is common on mobile devices, including the iPhone's text entry keypad. However, when approach occurs in the air, e.g. targeting keypad letters, friction effects would only be felt during the final acquisition. We need to better understand how variable friction can benefit other selection modalities, but feel that this first analysis examined the most appropriate one, as the most effective interaction mode for a variable friction device.

Variable Friction Versus Vibrotactile Feedback

Variable friction produces sensations that are very different but complementary to those of vibrotactile (VT) actuators. Friction tends to feel more natural but is only perceivable during sliding; vibrations are ideal for discrete clicks and textures, including tapping confirmation. Variable friction can physically alter finger velocity, whereas VT can communicate a larger range of informative sensations, even without sliding. These two tactile modalities are complementary and in theory can be produced with the same actuators: variable friction can offer continuous feedback during sliding, while VT feedback augments tapping with clicks and other discrete haptic events.

Theoretical Design Space for Variable Friction

The exemplar applications and widgets examined in S4 were developed through an iterative design process, and they were successful in their purpose of generating subjective responses. We took guidance both from the beginnings of our design space and from our intuition and iterations. We will refine this beginning with a taxonomy of all variable friction haptic sensations and their mapping to current (and novel) interactive widgets. This will include examining how our current set of widgets can be generalized to other uses. For example, the *Alarm Clock* wheel widget was among the most popular, and we will examine how it can be deployed in support of other related uses, such as scrolling.

Towards Variable Friction Design Heuristics

In its infancy, the design of interactions with tactile feedback is prone to naive uses and excesses. We hope to launch a discussion of best practices for variable friction, extending a design space with heuristics such as these:

- *Sliding not tapping:* To be effective, friction-augmented interfaces must work around the notion of sliding, with different metaphors and visual representations. The *Text Editor*, for example, was based upon 'compressible words' so that friction could be associated with object deformations and give meaningful feedback during dragging.
- *Shaping friction to increase expressiveness:* To compensate for the limited human sensitivity to friction variations and the current display range, expressiveness can be enhanced by varying friction 'attack', modulating it to create textures and patterns, and tying sensations to visual representations.
- *Stop only for a purpose:* Some users felt that friction variations seemed occasionally to slow them down. Strong feedback should have an equally strong purpose.

• *Nice not strong:* We tend to maximize tactile signal strength to ensure feedback is felt and performance improvements are measurable; but this leads to unpleasant sensations – the analog of blinking text on a website.

CONCLUSION

Programmable friction displays can vary the friction felt at the fingertip while it moves across a touch sensitive display. Through a series of studies and design explorations we have demonstrated the strong potential of programmable friction displays. Most importantly, participants using our exemplar programmable friction designs felt that it increased their sense of engagement, they preferred using it to traditional constant friction touch interactions, and they reported a variety of positive effects, including a sense of realism and a reduced dependence on visual feedback. In addition, our examination of programmable friction psychophysics showed significant target acquisition advantages for discrete drag-based selections and no adverse effects when distracter targets are present.

This is the first analysis we are aware of for interaction with variable friction displays. These quantitative and qualitative results show exciting possibilities; the technology is on a development path 2-3 years from commercial realizability. There is great potential for more investigation: further performance analysis, design exploration and then deployment in mobile handhelds and laptop touchpads.

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