Quantifying the Targeting Performance Benefit of Electrostatic Haptic Feedback on Touchscreens

Yang Zhang **Chris Harrison**
Carnegie Mellon University, Human-Computer Interaction Institute
5000 Forbes Avenue, Pittsburgh, PA 15213
{yang.zhang, chris.harrison}@cs.cmu.edu

ABSTRACT
Touchscreens with dynamic electrostatic friction are a compelling, low-latency and solid-state haptic feedback technology. Work to date has focused on minimum perceptual difference, texture rendering, and fingertip-surface models. However, no work to date has quantified how electrostatic feedback can be used to improve user performance, in particular targeting, where virtual objects rendered on touchscreens can offer tactile feedback. Our results show that electrostatic haptic feedback can improve targeting speed by 7.5% compared to conventional flat touchscreens.

Author Keywords
Electro-vibration; Friction; Haptic; Touch; Targeting.

ACM Classification Keywords
H.5.2. [User Interfaces]: Input devices and strategies.

INTRODUCTION
Owning to their intuitive direct manipulation interactions and general interface flexibility, touchscreens have become pervasive. However, their flat surfaces offer no programmable haptic feedback. Of course, touch is one of our most fundamental senses and plays a crucial role in our interactions with the physical world [22]. As a consequence, there is a significant literature on haptic feedback technologies and their performance impact on interactive experiences.

One such haptic technology is electrostatic feedback, first discovered in 1954 by Mallinckrodt [13] (then described as "electro-vibration"). Put simply, by oscillating an electric charge behind a thin insulator, a capacitive object (e.g., a fleshy finger) can be attracted to the surface, though only at very close distances. By controlling the oscillations, one can control the friction between a finger and the surface (see [2] for an extended discussion). More recently, electrostatic has been adapted for use on touchscreens. These initial efforts have chiefly explored the technology for interactive, assistive, and entertainment purposes [2,9,19,21].

ITS '15, November 15-18, 2015, Funchal, Portugal
© 2015 ACM. ISBN 978-1-4503-3899-8/15/11…$15.00
DOI: http://dx.doi.org/10.1145/2817721.2817730

In this work, for the first time, we quantitatively evaluate how electrostatic force feedback can be used to enhance targeting performance on touchscreens. This directly complements prior experimental work that has studied other haptic feedback means (see e.g., [3,4,12,16,18]). More specifically, we evaluated a series of haptic approaches in a head-to-head experiment. In addition to electrostatic feedback, we also tested designs with *actual* physical features, which serve as a gold standard. As a baseline control, we also included a plain (i.e., flat) touchscreen condition. Our main hypothesis was that electrostatic feedback would yield performance somewhere between no feedback and true physical feedback. The question was: where did electrostatic feedback lie within this spectrum?

RELATED WORK
Haptic Feedback on Touchscreens
Haptic feedback has been shown to make interactive experience more efficient and enjoyable [6,10]. The most common technique for providing haptic feedback is to use mechanical moving parts (i.e. vibration motor, piezo buzzer or solenoid). For example, many smartphones and Apple's "Force Touch" trackpads pulse or vibrate for certain events (e.g., key pressed). Lee et al. [11] created a pen instrumented with a solenoid that could, among many behaviors, simulate clicking, although the pen tip in actuality did not deform. Haptic pens of this nature have been evaluated in Fitts-style experiments previously (see e.g., [4,18]).

Another option is to overlay *physical* features onto a touchscreen, as seen in e.g., Touchplates [8] and SLAP Widgets [20]. However, this precludes dynamic button layouts and prevents the full screen space from being utilized. Thus research has also looked at transient physical elements, driven by pneumatics or hydraulics [6]. Harrison and Hudson evaluated such a "shape changing" display for targeting in an attention-saturated task [6]. There are also efforts to create texture "pixels" using micro-motor matrices [17], though these are challenging to scale.

There is also a class of ultrasonically-actuated haptic touch surfaces that modify friction through the squeeze film effect [1,3,5,12,15,16]. Interestingly, this effect *reduces* friction, which is opposite to electrostatic feedback. Studies similar to our own have been conducted on ultrasonic-based touchscreens [3,12], with results indicating that dynamic friction-reduction can be leveraged to improve users' pointing performance. Unfortunately, this result is not portable to electrostatic feedback, as the operating principle and sensation is rather different; hence this work directly compliments this prior work, filling a gap in the literature.

Experiments Using Electrostatic Force on Touchscreens

Most previous work on electrostatic force feedback touchscreens falls into one of two categories. First are efforts that attempt to model the fingertip-surface interface [5,14,15]. Special sensors were used for measuring the lateral frictional forces on a fingertip under well-controlled conditions. For example, Meyer et al. [14] modified the traditional ideal parallel plate model by considering the charge leakage through the *stratum corneum*. Such data can be used to better design and tune electrostatic feedback systems, for example, in generating more realistic textures.

A second significant body of literature studies how electrostatic forces can enable a variety of haptic feedback designs. For example, Bau et al. [2] investigated the perceptual characteristics of electro-vibration, in particular the minimum perception threshold and subjective evaluations of the electro-vibration by tuning the amplitude and frequency of the tactile signal. Later, electrostatic force feedback was explored for assistive technology for visually impaired users [21] and texture rendering [9]. Our work contributes to this literature by exploring and evaluating how electrostatic forces can aid users' targeting performance.

COMPARITIVE APPROACHES

At a high level, we wish to explore three *haptic modality* categories: *No Feedback, Physical,* and *Electrostatic* (see Figure 1). *No Feedback* is equivalent to most touchscreens today, and thus serves as our baseline. Achieving *Physical* feedback is considered by many to be the "holy grail" of touchscreen haptics. True physicality means zero latency and can stimulate our mechanoreceptors like real objects. However, achieving this in a manner that is as dynamic as a touchscreen display is to graphics remains elusive. Nonetheless, true physical feedback serves as a gold standard to which haptic technologies should aspire.

Once haptic feedback is introduced, either physically or electrostatically, there are different *haptic designs* that are possible. We include four designs in our evaluation, illustrated in Figure 1. *Line Leading Edge* places a haptic line at the leading edge of objects (relative to the direction of the incoming finger). This provides a cue that the finger has entered an object. *Line Center* is similar, but the haptic cue is provided in the middle of the object, conveying to the user that they are centered within an object. *Line Background* takes a different approach, and instead renders a line of feedback between objects, allowing for users to discern when they are crossing into a new object's area. And finally, we include a *Fill* design, where the whole object provides haptic feedback within its bounds.

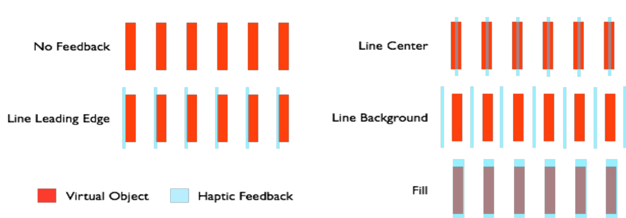

Figure 1. *No Feedback* and four haptic feedback designs. The latter designs can be physical or provided electrostatically.

Note that we provided haptic feedback on *all* objects in our experiment, instead of merely on the target for that trial. The reason is simple: in a real computing context, the users' destinations are not known *a priori*, and thus, haptic feedback must be equally applied to all applicable targets. These other, non-target objects are sometimes called "distractors" in the literature (see e.g., [12]).

USER STUDY

We used a Fitts-style dragging procedure [12], where each single trial had participants first select an object, drag the object to the target, and then lift their finger from the screen. This served as a metaphor for commonplace drag operations on touch devices – for example dragging a photo onto an email, selecting text, drag-and-dropping file and application icons, "swyping" over keyboard keys, scrolling a time selection widget, resizing an element with snapping points, etc. – all of which could be enhanced with haptic feedback.

Apparatus

We replicated the electrostatic setup described in Bau et al. [2]. Specifically, we used 3M MicroTouch capacitive panels mounted to a LCD screen (Figure 2). Our electrostatic feedback board used a 300 Hz signal to create haptic sensations and users were grounded using an antistatic wristband. A laptop, which ran the study and controlled the graphics on the LCD screen, sent commands to the board over USB.

As described in the Comparative Approaches section, we studied three haptic modalities. The *No Feedback* condition and all of the *Electrostatic* designs used the same area of our touchscreen monitor (Figure 2, right monitor, upper half). To create *Physical* feedback, we used two methods. For the line-based designs, we used thin transparent stickers adhered to the screen's surface. To switch between *Physical Line Center*, *Physical Line Leading Edge*, and *Physical Line Background* designs, the virtual objects were simply rendered in with different horizontal offsets. For *Physical Fill*, we covered the corresponding area in a loose grid of con-

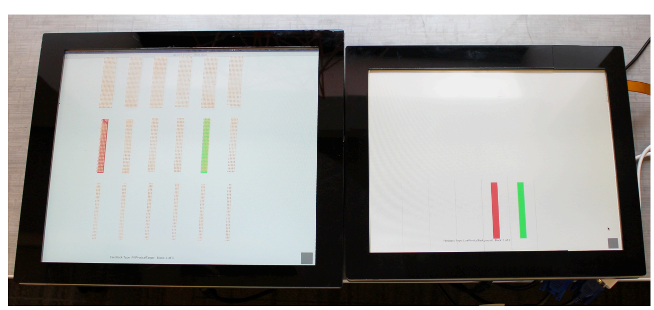

Figure 2. Two monitors were used for the study. The left monitor contained three widths of the *Physical Fill* design. The right monitor hosted line-based designs (bottom half) and also the *electrostatic* and *No Feedback* designs (top half).

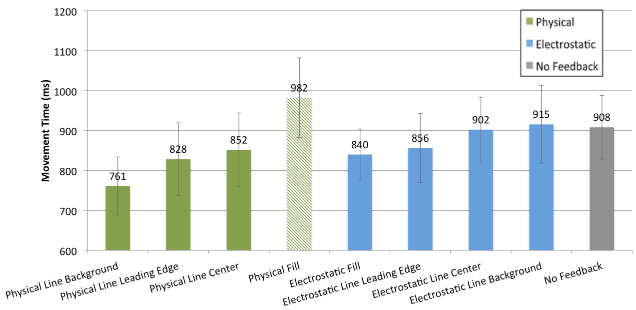

Figure 3. Average movement time cross feedback types. Error bars are standard error across participants.

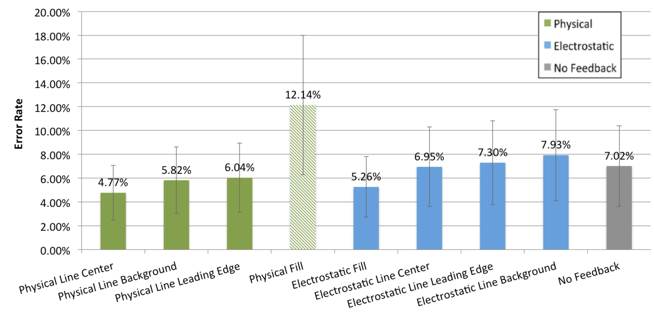

Figure 4. Average error rate cross feedback types. Error bars are standard error across participants.

ductive (copper-based) glue dots, which provided a slightly raised and matte texture, yet still passed touch events through to the 3M panel.

Participants

We recruited 20 participants (9 female), with a mean age of 24. All were regular computer users and right handed. The study took approximately 60 minutes and paid $10.

Design

The user study was a (2 × 4 + 1) × 3 × 5 within-subjects design. The independent variables and levels were:

Haptic Modality × *Haptic Design* + No Feedback baseline:

> *Physical Line Center, Physical Line Leading Edge, Physical Line Background, Physical Fill, Electrostatic Line Center, Electrostatic Line Leading Edge, Electrostatic Line Background, Electrostatic Fill, No Feedback.*

Target Width (W): *16, 32, 64 pixels (0.26mm per pixel).*

Target Distance (D): *128, 256, 384, 512, 640 pixels.*

Participant completed five trials for each W-D combination, resulting in 75 trials for each haptic modality/design, which constituted one block. The order of blocks was randomized.

Procedure

For each trial, participants first touched the red object to select it. Participants then slid their finger across the distance and dropped the red object on the target, highlighted in green. Participants had to successfully lift their finger anywhere within the target area to move to the next trial. Trials where participants did not successfully lift their finger on the target on the first attempt were marked as errors and disregarded from analysis (i.e., a "one chance" procedure). Additionally, following the procedure in [4], we dropped one participant's data, which was greater than three standard deviations from the mean user performance.

Trials were combined into blocks, which contained all widths and distances for a given haptic modality/design pair. Participants could take breaks before starting each trial block. Each block started with a brief warm up, where participants were allowed to practice trials until they were comfortable with the new feedback (max. 3 minutes). After participants finished all blocks, they were asked to qualitatively rank nine cards representing the eight haptic modalities crossed by haptic design, plus *No Feedback*.

RESULTS AND DISCUSSION

Physical Fill

It became apparent during the study that *Physical Fill* was problematic, and indeed the condition was significantly worse in both movement time and errors than any other haptic modality/design (p<0.05). We believe this is not an effect of the design, but rather the physical implementation. More specifically, we suspect the copper glue dots interfered with the capacitive sensing of the 3M panel. Thus, we omit *Physical Fill* from subsequent analysis, though we include it in Figures 3 and 4 for reference.

Movement Time Analysis

Movement time (MT) is the time taken between when the object was selected and when it was successfully dropped on the target. The results in this section include only trials in which there were no errors. As illustrated in Figure 3, six techniques outperformed *No Feedback* (i.e., conventional touchscreens). A mixed-effects model ANOVA analysis showed a significant effect for modalities on movement time ($F(2,4.16)=69.7$ $p<0.05$). The average MT for the *Physical* modality was 813.7 (SD=38.5) ms, while the *Electrostatic* modality was 878.3 (SD=31.1) ms. This compares to 908 ms when *No Feedback* is provided. As expected, there were also significant effects on width ($F(2,38)=582.5$ $p<0.05$) and distance ($F(4,76)=301.6$ $p<0.05$).

The best haptic design provided by electrostatic force was *Electrostatic Fill*, which shortened the average movement time by 7.5% compared to *No Feedback*. The best haptic design within the physical modality was *Physical Line Background*, which shortened the average movement time by 16.2% compared with *No Feedback*. Post-hoc multiple means comparison tests showed that *Physical Line Background*, *Physical Line Leading Edge* and *Electrostatic Fill* were significantly better than *No Feedback* (p<0.05).

Error Rate Analysis

The result indicated no significant effect for modalities on error rate (see Figure 4). The factors which had significant effects on error rate were width ($F(2,38)=11.87$ $p<0.05$) and distance ($F(4,76)=4.69$ $p<0.05$). The best haptic design, with respect to errors, in the electrostatic modality was *Electrostatic Fill,* which lowered the mean error rate by 25.1%; and in the physical modality was *Physical Line Center*, which lowered the average error rate by 32.1% com-

Feedback Type	Model	R^2
Physical Line Background	MT = -13.42 + 216.89 ID	0.96
Physical Line Center	MT = 57.63 + 223.47 ID	0.97
Physical Line Leading Edge	MT = -57.71 + 245.44 ID	0.94
Electrostatic Fill	MT = -72.54 + 256.58 ID	0.96
Electrostatic Line Center	MT = -6.88 + 257.56 ID	0.97
Electrostatic Line Leading Edge	MT = -75.18 + 264.01 ID	0.96
Electrostatic Line Background	MT =-41.74 + 271.18 ID	0.97
No Feedback	MT = -81.93 + 277.82 ID	0.96

Table 1. Fitts' law models for all modality-design pairs.

pared with *No Feedback* (Figure 4). However, post-hoc multiple means comparison tests showed no significant differences between these three feedback types.

Fitts' Models
Although not a true Fitts' Law task, our study can be used to construct an approximate Fitts' model for each of our modality/designs as an additional means of comparison. Indeed, our data results in very good fits ($R^2 > 0.93$ in all cases; Table 1). Lower values of slope indicate that participants' performance deteriorates less rapidly across increasing Indexes of Difficulty (ID). There are two findings of particular note: Foremost, looking at the slope values of the feedback types shows that all haptic designs were superior to *No Feedback* (i.e., lower slope values). Secondly, haptic feedback provided by physical features consistently yielded lower slope values than feedback provided by electrostatics.

Qualitative Ranking
Following the experiment, we asked participants to rank the modality-designs pairs. We assigned the most preferred type with a score of nine, with one being least preferred. The result showed that the *Physical Line Leading Edge* was the most preferable feedback type with an average score of 6.42 (SD=2.09). Conversely, *Electrostatic Line Background* got the lowest average score of 4.26 (SD=2.12). Overall, there was little agreement among the participants, producing large standard deviations. Correlating mean preference rank against slope of the Fitts' regression and against mean movement time yielded no correlations of note (R^2 =0.12 and 0.04). Users had a slightly better sense of their performance with respect to error rate, with an R^2 value of 0.38 for mean preference rank plotted against mean error.

ACKNOWLEDGEMENTS
This research was generously supported by the David and Lucile Packard Foundation, Google and Qualcomm.

REFERENCES

1. Amberg, M., Giraud, F., Semail, B., Olivo, P., Casiez, G. and Roussel, N. STIMTAC: a tactile input device with programmable friction. In *Proc. UIST '11 Adjunct*, 7-8.
2. Bau, O., Poupyrev, I., Israr, A. and Harrison, C. TeslaTouch: Electrovibration for Touch Surfaces. In *Proc. UIST '10,* 283-292.
3. Casiez, G., Roussel, N., Vanbelleghem, R. and Giraud, F. Surfpad: riding towards targets on a squeeze film effect. In *Proc. CHI '11,* 2491-2500.
4. Forlines, C., and Balakrishnan, R., Evaluating tactile feedback and direct vs. indirect stylus input in pointing and crossing selection tasks. In *Proc. CHI '08*, 1563-1572.
5. Giraud, F., Amberg, M., Lemaire-Semail, B., Merging two tactile stimulation principles: electrovibration and squeeze film effect. In *Proc. WHC '13*, 199(203), 14-17.
6. Harrison, C. & Hudson, S. Providing dynamically changeable physical buttons on a visual display. *Proc. CHI '09*, 299-308.
7. Hoggan, E., Brewster, S. and Johnston, J. Investigating the effectiveness of tactile feedback for mobile touchscreens. In *Proc. CHI '08*, 1573-1582.
8. Kane, S.K., Morris, M.R. and Wobbrock, J.O. Touchplates: low-cost tactile overlays for visually impaired touch screen users. In *Proc. ASSETS '13,* 8 pages.
9. Kim, S., Israr, A., and Poupyrev, I. Tactile rendering of 3D features on touch surfaces. In *Proc. UIST '13,* 531-538.
10. Koskinen, E., Kaaresoja, T. and Laitinen, P. Feel-good touch: finding the most pleasant tactile feedback for a mobile touch screen button. In *Proc. ICMI '08*, 297-304.
11. Lee, J., Dietz, P., Leigh, D., Yerazunis, W. and Hudson, S. Haptic Pen: A Tactile feedback stylus for touch screens. In *Proc. UIST '04*. 291-294
12. Lévesque, V., Oram, L., MacLean, K., Cockburn, A., Marchuk, N.D., Johnson, D., Colgate, J.E. and Peshkin, M.A. Enhancing physicality in touch interaction with programmable friction. In *Proc. CHI '11*, 2481-2490.
13. Mallinckrodt, E., Hughes, A. and Sleator, W. Perception by the Skin of Electrically Induced Vibrations. *Science*, 1953. 118(3062), 277-278.
14. Meyer, D.J., Peshkin, M.A. and Colgate, J.E. Fingertip friction modulation due to electrostatic attraction. *World Haptics Conference 2013*, 43(48), 14-17.
15. Meyer, D.J., Wiertlewski, M., Peshkin, M.A., and Colgate, J.E., Dynamics of ultrasonic and electrostatic friction modulation for rendering texture on haptic surfaces, *Haptics Symposium*, 2014. 63(67), 23-26.
16. Mullenbach, J., Shultz, C., Piper, A., Peshkin, M. and Colgate, E. Surface Haptic Interactions with a TPad Tablet. In *Proc. UIST '13 Adjunct*, 7-8.
17. Overholt, D., Pasztor, E., Mazalek, A. A Multipurpose Array of Tactile Rods for Interactive sXpression (Abstracts and Applications), In *Proc. SIGGRAPH '01*.
18. Poupyrev, I., Okabe, M. and Maruyama, S. Haptic feedback for pen computing: directions and strategies. In *CHI EA '04*, 1309-1312.
19. Senseg, Inc. http://senseg.com
20. Weiss, M., Wagner, J., Jansen, Y., Jennings, R., Khoshabeh, R., Hollan, J. and Borchers, J. SLAP widgets: bridging the gap between virtual and physical controls on tabletops. In *Proc. CHI '09*, 481-490.
21. Xu, C., Israr, A., Poupyrev, I., Bau, O., and Harrison, C., Tactile display for the visually impaired using TeslaTouch. *CHI EA '11*, 317-322.
22. Wolfe, J.M., Kluender, K.R., Levi, D. M., Bartoshuk, L. M, Herz, R.S., Klatzky, R.L. and Lederman, S.J. Sensation and Perception. Sinauer Associates, 2006.