Touchscreen Haptic Augmentation Effects on Tapping, Drag and Drop, and Path Following

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ABSTRACT

We study the effects of haptic augmentation on tapping, path following, and drag & drop tasks based on a recent flagship smartphone with refined touch sensing and haptic actuator technologies. Results show actuated haptic confirmation on tapping targets was subjectively appreciated by some users but did not improve tapping speed or accuracy. For drag & drop, a clear performance improvement was measured when haptic feedback is applied to target boundary crossing, particularly when the targets are small. For path following tasks, virtual haptic feedback improved accuracy at a reduced speed in a sitting condition. Stronger results were achieved in a physical haptic mock-up. Overall, we found actuated touchscreen haptic feedback particularly effective when the touched object was visually interfered by the finger. Participants subjective experience of haptic feedback in all tasks tended to be more positive than their time or accuracy performance suggests. We compare and discuss these findings with previous results on early generations of devices. The paper provides an empirical foundation to product design and future research of touch input and haptic systems.

CCS CONCEPTS

• **Human-centered computing** → *User studies*; *Touch screens*; *Haptic devices*; *Smartphones*; *Empirical studies in ubiquitous and mobile computing*.

KEYWORDS

Mobile Devices: Phones/Tablets; Haptics; Empirical study

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1 INTRODUCTION

Haptic actuators are embedded in most if not all touchscreen smartphones, totalling an estimated 2.5 billion in active use worldwide. Haptics on modern smartphones has two distinct types of use: attentional haptics (alarms, ringtones, notifications) and touchscreen haptic feedback. The first type is initiated by software and services through the haptic modality in order to attract the user's attention. The second type, the subject of the current study, is feedback in response to the user's manual input.

There is a body of HCI literature on mapping haptic feedback to computer input, mostly based on desktop and older generation of touchscreen and actuator technologies (see Related Work below). The goal of this investigation is to verify, update and add to that body of literature in the current touchscreen mobile phone context. On the current generation of smartphones, haptic feedback is used in select types of touch interfaces, such as long press (on both Android and iOS devices), "3D Touch" (some iPhone models), system navigation buttons (Android), keyboards (such as Gboard on Android, with on-off setting options). On the recent Google Pixel 2 phones, one can also move a cursor over text through the spacebar of Gboard and feel the "texture" of the text though haptic feedback.

It should not be overlooked that when the finger makes a contact with a touch screen, there is a passive (or "real" touch sensation to the finger that could be sufficient as confirmation for many touch input actions. The benefit of any additional *active* actuated "virtual" haptic augmentation needs to be beyond what this "free" haptic feedback provides, be it subjective or objective.

We study haptic feedback in three basic and general touch input tasks: tapping, drag & drop, and path following. They are some of the most commonly studied input tasks in HCI because they represent the elements or essence of more specific or complex interaction methods [1, 25].

We find that haptic feedback is most effective when the task is otherwise visually obscured by the finger, such as drag & drop for small targets. Across all three experiments, user's subjective experience with haptic feedback tended to be more positive than actual speed or accuracy improvements.

2 BACKGROUND AND RELATED WORK

Mclean [29] provides a broad overview of the human factors of haptics and their design implications in everyday user interfaces. In this brief review we focus on a few that are closely related to the current study.

Desktop Haptics

Akamatsu *et al.* [4] and Cockburn & Brewster [16] studied two tactile mice in target acquisition tasks. Akamatsu *et al.* [4] used a solenoid-driven pin that stimulates the index finger on the mouse button. Later they also added an electromagnet in the mouse chassis that could create drag between the mouse and an iron mousepad for force feedback effects. Their findings regarding mouse control performance were mixed. The additional feedback in haptics and force feedback tended to reduce overall movement times (and particularly the stopping phase) after the mouse cursor is inside of the target [4] but also increased error rate [3]. Cockburn and Brewster (2005) used a commercial ERM-based tactile mouse, the Logitech iFeel mouse, for tactile feedback and also used a cursor C:D gain manipulation for stickiness effect [16]. Their findings show the stickiness and tactile appear to help in Fitts' law tasks but could also "damage interaction though 'noise' that interferes with the acquisition of neighbouring targets".

Campbell *et al.* [12] studied an isometric joystick with vibration abilities in a semi-circle steering task, and showed the importance of "What you feel must be what you see" in the sense the haptic feedback should correspond to the visual texture displayed. Our trail following task uses the same shape as theirs and provides one visual dot per haptic bump, given their conclusion that haptic feedback only helps when visuals are presented in concert.

Dennerlein *et al.* [17] used a force feedback mouse to complete steering tasks, finding that it improved both speed and accuracy. Levesque *et al.* [14, 26] used variable friction displays to complete various steering and target acquisition tasks, again finding that the introduction of haptic feedback improved both speed and accuracy. MacKenzie & Oniszczak [28] studied haptic replacement of mechanical buttons on touchpads.

A fundamental difference between these desktop techniques and our study of touchscreen input with haptic feedback lies in the presence of a cursor. Today's touchscreen interaction does not use a cursor as a mediator, therefore haptic feedback cannot be designed according to the cursor location. Instead, haptic feedback is limited to the moment of finger contact with the screen.

For making untra-thin laptop computers, it is desirable to make the physical keyboard a flat touch-sensitive surface rather than movable keys. Active haptics should be and indeed has shown to be helpful in giving such keyboard a click feel [15, 22, 27].

Mobile Haptics

Device vibration for the purpose of attentional haptics can be traced to feature phones and pagers, to the degree that phantom vibration was a common illusion [18].

Poupyrev and Maruyama [32] presented one of the first implementations of haptics for touchscreen feedback by attaching an actuator to a PDA. Many researchers have since explored using haptic feedback in mobile applications.

Brewster *et al.* [10] attached an external actuator on the back of an iPAQ PDA to provide haptic feedback to its stylus operated resistive touchscreen keyboard, with significant performance improvement. Hoggan *et al.* [20] also showed keyboard performance improvement by using the embedded actuator on a Samsung SGH-i718 PDA which also had a resistive touchscreen keyboard.

Lee and Zhai [25] did multiple experiments to study soft button performance with and without haptic or audio feedback. In their Experiment 1 on a resistive screen, they found performance improvement with either audio or haptic augmentation, but the combination of the two did not offer further improvement (See Figure 1 and 2 in [25]). Lee and Zhai explicitly distinguish *contact* and *force* based touch. The former can be activated by a bare finger contact whereas the latter is activated by exerting force greater than a set threshold. The "real" haptic perception from the instantaneous skin contact with the screen may be sufficient for contact-based touch, but not for force-based touch sensing. Force-based *press* has to reach a force threshold. Resistive touch screens, particularly those in the PDA era, were force-based and more responsive to pointed stylus than to soft fingers. The difference between contact-based and force-based touch sensing is particularly pronounced when it comes to fling (momentum scrolling) actions. Buxton [11] gives a very detailed analysis on "inking" on a pressure-sensitive touch tablet.

Zhang and Harrison studied a touchscreen finger dragging task and found user performance improvements when the target was augmented by electrostatic haptic feedback [38].

3 GENERAL EXPERIMENTAL DESIGN AND APPARATUS

The purpose of this study was to identify where active haptics is likely to benefit user performance or user's subjective experience on contact-based capacitive touchscreens augmented with electromagnetic haptic motors. Such a device combination is broadly available on the current generation of smartphones. We used three common elemental tasks in three separate experiments: tapping, drag & drop, and path following. In each task we choose to make the task parameters challenging and difficult. Easy tasks are already well performed on today's very responsive and contact-based touchscreen devices. We did not focus our study on functions where active haptic feedback is widely adopted or "obvious": long press (press and hold), the Active Edge squeeze gesture on Pixel 2, or the Home button on iPhone 7 and iPhone 8.

The type and degree of haptic feedback benefit may depend on both the fundamental properties of human haptic perception [19, 24] and the characteristics of the enabling haptic actuation technologies. We choose Google's Pixel 2 [37] as our testing platform. Powered by Android 8.0 Oreo operating system, Pixel 2 has a 5-inch (130 mm) capacitive touchscreen with 1920×1080 pixels (resolution 441 ppi). Each pixel was approximately 0.057 mm. Pixel 2 haptics was well received by its users ("The new haptic feedback motor = Tears of Joy") [34, 35].

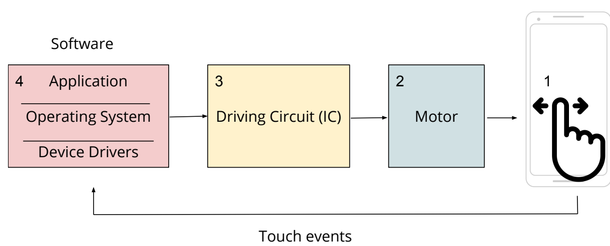


Figure 1: Main components of a smartphone haptic system.

The Pixel 2 haptics system consisted of both software and hardware components (Figure 1). Its touchscreen is rigidly attached to the phone's frame. In this type of phone design, which currently dominates the smartphone market, the vibrotactile effects come from the actuator mounted inside of the phone's body on the same rigid frame. Haptics are felt both on the finger touching the screen and the hand holding the phone. Such effects are fundamentally not localized, but often subjectively felt local due to the visual affordance from the screen and the user's expectation of the feedback coming from the specific object being touched.

As in other currently popular smartphones, Pixel 2's motor is an electromagnetic linear resonance actuator (LRA), instead of eccentric rotating mass (ERM) in early generations of phones, piezoelectric [15, 33], or programmable friction surfaces [7, 26] that are not (yet) seen in mass-produced smartphones. Pixel 2's LRA measures $8 \times 15 \times 3.8$ mm in volume. This is much smaller than the Taptic Engine in recent iPhone models, but larger than some other leading smartphone models such as the Samsung Galaxy S8. The Pixel 2 LRA's resonant frequency is 155 Hz and its maximum peak acceleration 1.67 G.

Our experiment application ran on Android 8.0 whose framework includes a list of Haptic Feedback Constants [5] implemented in Pixel 2' haptics Hardware Abstraction Layer (HAL). We applied Pixel 2's VIRTUAL_KEY haptic constant [5] in this study. The Pixel 2 embeds a Texas Instruments DRV 2624 IC driver which has various driving features such as Over Drive and Braking[21]. Through these features the VIRTUAL_KEY constant on Pixel 2 was tuned to be a crisp and pleasant haptic impulse. A sample recording of the acceleration waveform of this is shown in the lower half of Figure 2. It is known in the literature that click effects can be tuned toward a pleasant feeling [23].

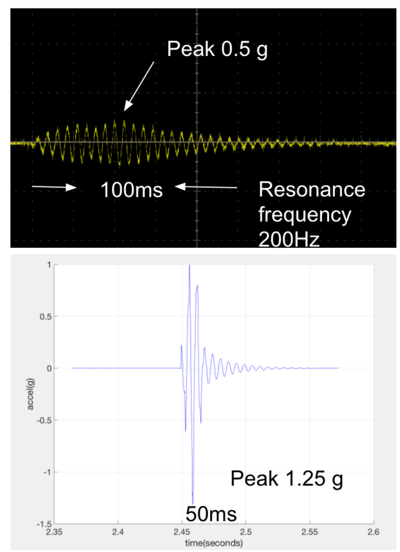


Figure 2: Recorded sample waveforms of Virtual_Key effect on the 2016 Pixel (top) and the 2017 Pixel 2 (bottom) phones.

4 EXPERIMENT 1: TAPPING

Akin to mouse-cursor based pointing, tapping on soft buttons is the most common input action on touchscreen smartphones today. We used a target tapping task similar to Fitts' law studies on desktop pointing [13] and finger Fitts' law studies on touchscreens [8].

As discussed earlier, tapping on contact-based touch sensing surface has "real" haptic feedback from the moment of skin contact. Augmenting it with virtual haptics may strengthen the feel of successfully landing on the target. Whether such augmentation brings any performance or subjective experience benefit was to be discovered in the experiment. Given the quality of today's very responsive touchscreens, such augmentation to tapping was unlikely to bring time or accuracy performance improvement but subjective experience improvement was possible.

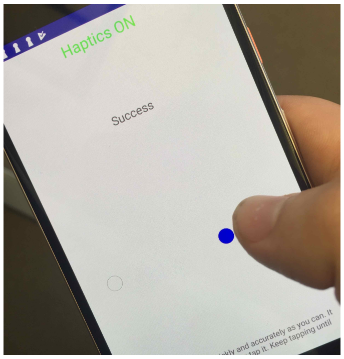


Figure 3: In the tapping task, a small 40px circle was displayed on each side of the phone, with the next dot to press colored blue.

Figure 4: The figure of eight course used in our walking condition aimed to simulate distracted / mobile usage of the phone.

Experimental Design

The task was tapping alternately two circles with a radius of 40 pixels placed 550 pixels apart horizontally. The target circle to be tapped next was solid blue, the other white. Upon landing anywhere on the screen, the blue circle turned back to white, and the other circle turned blue. Depending on if the finger touch point (centroid) landed inside or outside the target, a "success" or "fail" message was displayed above the circles.

There are two feedback conditions in the experiment, Visual only and Virtual haptics. In the virtual haptics condition, a "click" was enabled *inside* the blue target. In each condition, participants were required to do a total of 30 taps.

A secondary independent variable of this experiment was mobility: *walking vs sitting*. Participants did all the task/feedback conditions twice: once sitting on a couch, and once walking around a room in a figure eight pattern in a approximately 15 foot x 10 foot room (Figure 4). The figure eight was enforced by two desks placed near the front center and rear center of the room, marking the top center and bottom center of the two loops which make up an eight. Multiple furniture obstacles were scattered around the perimeter of the figure eight course, enforcing the that users stay on path while also making it more difficult to "learn" the course due to how the obstacles made the path width inconsistent. Walking tasks are frequently deployed in mobile input research [30]. On one hand, performing the simultaneous walking task may reduce the visual attention on the manual input task hence making haptic feedback more important. On the other hand, the additional instability from body movement in walking may overwhelm the haptic perception of the finger touch.

The experiment used a within-subject design with two independent variables: *feedback type* (Virtual Haptics vs. Visual Only) and *mobile condition* (Sitting vs. Walking). The order of these conditions were balanced in a Latin Square pattern.

The task was deliberately chosen to be on the difficult side, with small targets and a walking condition, based on the hypothesis that haptics is more helpful when the visual feedback is limited. The visual feedback could be distracted by walking or obscured by the finger before landing on the target. Note that the feedback of success or failure was too late for the current tapping trial, but the knowledge of result may help the user to adjust the pace and strategy for the subsequent trials.

Seventeen employees of an IT company participated in the experiment. Their mean age was 33, and 1/3 were female. Participants received an incentive worth $25 for their time.

In total, there were 2 *feedback types* x 2 *walking vs sitting* x 30 taps x 17 participants = 2040 taps. At the end of each study session, participants were asked questions about their thoughts and their subjective preferences.

Results

We report two metrics for this task's performance: distance and time. Distance is calculated as the distance from the tap to the center of the target. Time is the amount of time, in milliseconds, between taps. We removed 104 taps greater than three sigma away from the mean for either distance or time to prevent counting mis-taps or mis-trials. We also removed the first 10 trials to account for a learning effect. Figure 5 and Table 1 summarize the results.

Although the average time per tap was longer in the Virtual Haptics condition (Figure 5B), the impact of *feedback type* was not statistically significant on time ($F_{1,16} = 2.36, p = 0.144$) nor on distance ($F_{1,16} = 0.25, p = 0.622$).

As one would expect, tapping was significantly less precise (greater distance to the target center) in the Walking condition then in the Sitting condition $F_{1,16)} = 17.02, p < 0.001$.

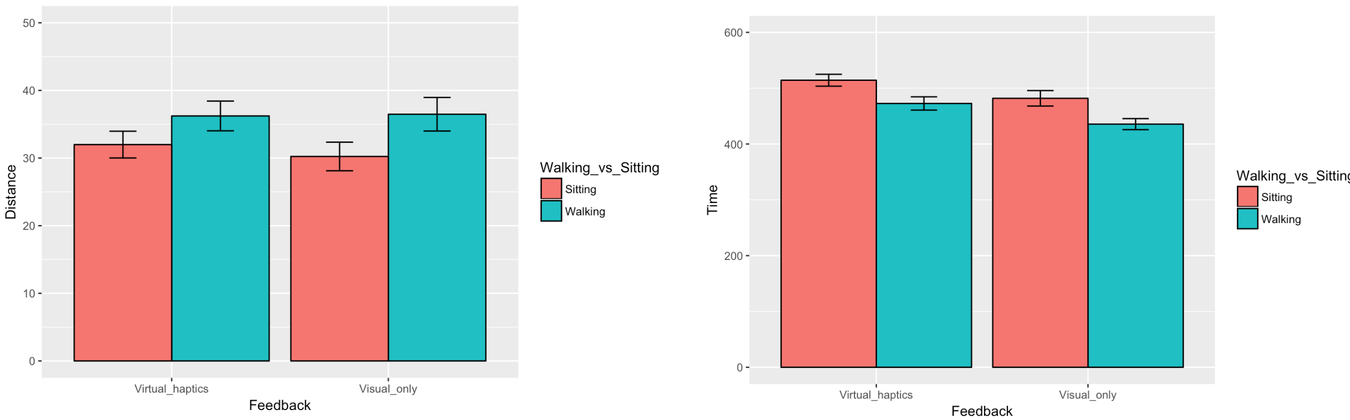


Figure 5: (A): Distance (in pixels) and (B): Time (in milliseconds) results for tapping. The effect of walking vs sitting was significant, but the effect of haptics type was not.

Feedback	Walk_v_Sit	Distance (SE)	Time (SE)
Virtual_haptics	Sitting	32.0 (1.0)	514.3 (5.4)
Virtual_haptics	Walking	36.2 (1.1)	472.6 (6.0)
Visual_only	Sitting	30.2 (1.1)	481.9 (7.0)
Visual_only	Walking	36.5 (1.3)	435.6 (5.0)

Table 1: Mean distance (in pixels) and time (in milliseconds) for all tapping conditions, with Standard Error.

Tapping in the Walking condition was faster than in the Sitting condition: $F_{1,16} = 5.41, p = 0.034$. Overall, people tended to be in a more hurried mode when splitting their attention between tapping on the screen and navigating their walking path, resulting in faster but more sloppy taps.

Importantly, there was no significant interaction between *feedback type* and *mobile condition* ($F_{1,16} = 0.47, p = 0.502$). Haptic feedback did not improve tapping performance in either Sitting or Walking conditions.

In sum, haptic augmentation of tapping targets on contact-based touchscreen did not improve tapping performance.

Follow-up study with varied target radius. To determine whether feedback type might have an effect with larger tap targets, we conducted a small follow-up study with 6 new participants. The procedure and design was identical to the initial tap study, except it featured targets with both a 35px radius and a 50px radius. While the larger width did result in a significant time reduction ($F_{1,5} = 21.61, p = 0.006$), it did not result in a significant distance change, nor were there any significant interaction effects.

Subjective Feedback. The subjective experience of the participants was nuanced. On one hand, many did not expect haptics to have increased their performance, as the feedback did not guide their finger landing. On the other hand, five participants said that they enjoyed the feel and the confirmation that they correctly hit the target: "I liked the confirmation, it made me feel confident" and "it just felt nice, I don't really know why."

Experiment 1 Discussion

Although subjectively preferred by some users, the virtual haptic feedback condition did not result in improvement in either tapping speed or tapping accuracy in the current experiment. This is in contrast to Brewster *et al.* [10], Hoggan *et al.* [20], and Lee and Zhai [25] which all found vibrotactile haptic feedback improved performance in some ways. There could be many reasons for this contrast. First the experimental tasks in these previous studies were different. Brewster *et al.* [10] used stylus keyboard text entry. Hoggan *et al.* [20] used finger keyboard entry. Lee and Zhai [25] used numeric keyboard tapping. Although these tasks all contained a tapping element, they were not simple reciprocal tapping as in the current experiment. There could be some aspects of the text or number entry tasks that could have benefited more from the active haptic feedback. Second the haptic feedback design and implementation were different, in particular Hoggan *et al.* [20] which used three different vibration patterns on their keyboard: a sharp 30ms vibration for key press (similar to this study's haptic effect), a 300ms vibration with a smooth rise and fall envelope for the F and J key, and a 500ms vibration with a three peak envelope when the fingertip slipped over the edge of any button on the screen. In the current project we informally tested giving haptic anchors on the F and J keys but did not find them effective. It is unknown whether it is useful on today's smartphones to implement the boundary crossing feedback. Today's common smart touch keyboards (STK) and smart gesture keyboards (SGK) [36] all use statistical decoding to correct spatial errors so users are expected to be fast and "sloppy". Portions of their finger touch points normally land outside the nominal key boundary [6]. In fact, dynamically resized keys [31] often do not show visual boundaries in, for example, Android Gboard.

A third plausible reason for the performance improvements in previous studies absent in the present tapping experiment lies in the force-based resistive touchscreens used in Palm Treo, Samsung i718, or the iPaq PDA employed in [10, 20, 25]. Unlike today's capacitive touchscreen that are tuned for registering input on skin contact which confirms tap completion to the user through "real" haptic feedback, older force-based resistive screens tuned for stylus use could only register input when a press passed a force threshold. An active haptic feedback confirming that the finger had pressed hard enough on such screens is conceivably more helpful than on today's contact-based touchscreens.

5 EXPERIMENT 2: DRAG & DROP

Today's touch UI maximizes object size and visual feedback effects so they cannot be obscured by the finger whenever possible, at the cost of pushing many functions into deeper and less discoverable UI layers or multiple screens. They also impose high visual attention demand. In a pilot study we found that success rates under such conditions were near 100% regardless of haptics. One potential benefit of haptics, is to "reclaim" or expand the visual design space, hence the focus on smaller targets in the experiments. Further, drag and drop tasks with small targets can be necessary even in today's interfaces. For instance, moving app icons on an home screen is notoriously finicky and haptics could be helpful. Moving a text selection end point is another example of dragging to a small target. Interfaces on a smartwatch are even more space constrained. In this experiment, we test the impact of haptics on dragging and dropping small targets.

Experimental Design

Drag & drop is a common task on desktop computers. It is also used on touchscreen mobile devices for tasks such as changing app icon locations. In this experiment, participants were asked to drag a small black circle on the left side of the touchscreen, and drop it into a larger target circle on the right side of the touchscreen. The task was considered a success if the black circle was dropped at least halfway inside the target circle, which turned green to indicate this (though for most target sizes, this visual change was entirely occluded by the finger, as is typical in touchscreen mobile interaction). The task was finished when the user lifts their finger, regardless of where the movable circle was.

This experiment had two independent variables: *feedback type* and *target radius*. Feedback type could be either visuals only, or visual plus virtual haptics produced through the set-up described in the introduction. When virtual haptics was enabled, the participant received a single haptic click if at least half the moveable circle was moved inside the target circle, and another haptic click if the movable circle left the target circle.

The size of the movable circle remained constant, with a radius of 20 pixels. There were three radii sizes for the goal circle: 25, 30, and 35 pixels. For each target radius x feedback condition, participants repeated the task 4 times in a row.

To keep the number of independent variable combinations manageable, this experiment did not include the walking condition described in the earlier tapping experiment, as we deemed target radius a more informative independent variable.

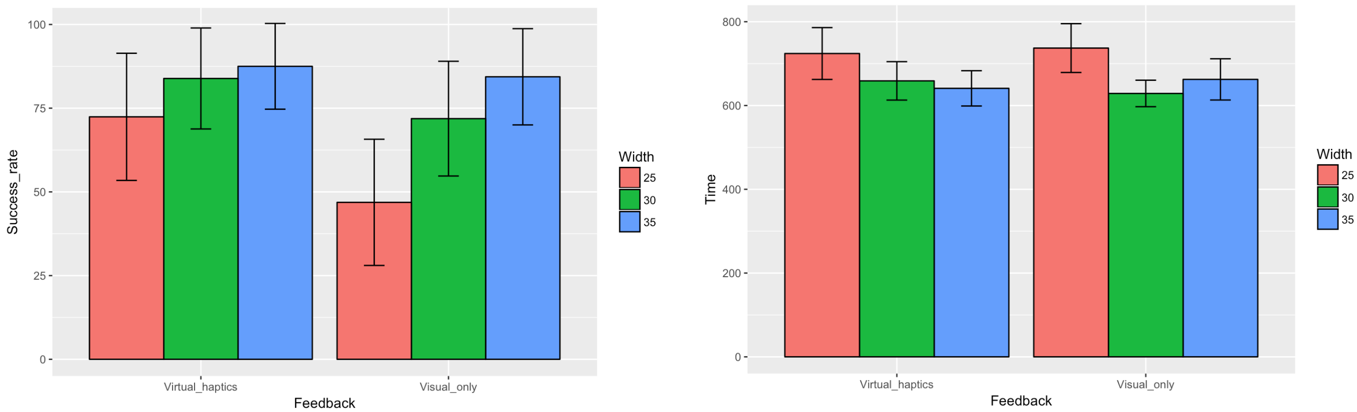
Participants. Eight employees of an IT company, with mean age of 31, participated in this experiment. Approximately 1/3 were female. Participants received an incentive worth $25 for their time.

Procedure. For this within-subjects study, order for the radius of the goal circle was random and order for the other variables was controlled via a latin-square design. In total there were 2 *haptics conditions* x 3 *target circle radii* x 8 participants x 4 repetitions = 192 drag & drop trials. At the end of each study session, participants were asked about their thoughts and subjective preferences.

Results

We report two metrics to measure this task's performance: success rate and time. Success rate was calculated as the percent of successful drag & drop trials, and time was the number of milliseconds from finger down to finger up. We removed 13 trials where the time or accuracy was greater than three sigma away from the mean to prevent counting mis-taps or mis-trials. Figure 6 and Table 2 shows the results for drag & drop success rate and time.

The impact of *feedback type* was statistically significant on success rate but not on time, with one way repeated measure ANOVAs reporting $F_{1,7} = 6.67, p = 0.036$ and $F_{1,7} = 0.01, p = 0.914$ respectively. Virtual Haptics resulted in a higher success rate without a significant difference in time. The impact of *target radius* was significant both on success rate ($F_{1,7} = 10.66, p = 0.002$) and on time ($F_{1,7} = 10.40, p = 0.002$). Smaller target radii generally resulted in lower success rates and slower times.



(A) (B)

Figure 6: (A): Success Rate (in percent) and (B): Time (in milliseconds) results for drag & drop.

Feedback	Radius	Success_rate (SE)	Time (SE)
Virtual_haptics	25	72.4 (9.3)	724.1 (30.2)
Virtual_haptics	30	83.9 (7.4)	658.8 (22.5)
Virtual_haptics	35	87.5 (6.3)	640.9 (20.7)
Visual_only	25	46.9 (9.2)	737.1 (28.6)
Visual_only	30	71.9 (8.4)	628.8 (15.5)
Visual_only	35	84.4 (7.0)	662.3 (24.1)

Table 2: Mean success rate (in percent) and time (in milliseconds) for all drag & drop conditions, with Standard Error. Radius is measured in pixels and time in milliseconds.

The interaction effect between *feedback type* and *target width* was not significant on success rate ($F_{2,14} = 0.86, p = 0.433$) or on time ($F_{2,14} = 0.38, p = 0.689$). This indicated that the change in success rate brought by virtual haptics was not dependent upon target width. We see that virtual haptics improves the success rate for all radii, with the largest improvement for the smallest radius of 25 pixels, going from 46.9% to 72.4%. Success rate changed the least for the largest radius of 35 pixels, going from 84.4% to 87.5%. A Bonferroni-adjusted pairwise post-hoc t-test shows that this difference is significant ($p = 0.3$).

Subjective Feedback. All 8 participants expected virtual haptics had improved both their success rate and time (despite the fact that it we did not find the main effect of feedback type to be significant on time). Participants went so far as to say "I was definitely way faster with the haptics on" and "it just made everything much clearer and easier." They all commented that it improved their confidence, and that they enjoyed the feel.

Experiment 2 Discussion

In this 2D drag & drop experiment the task performance was significantly improved with the LRA based haptic feedback. This result is consistent with Zhang and Harrison's study on a 1D dragging task augmented with electrostatic haptic feedback [38]. The biggest performance improvement in the current study was with the smallest sized targets where the success rate increased by 54.4%. Notably, time did not significantly change as a result of feedback type, indicating that there is not a speed/accuracy tradeoff for the increased accuracy that virtual haptics brought to the drag & drop task.

Drag & drop targets on touchscreens are often smaller than the finger width in practice too. Without haptic feedback, whether the dragged object under the finger has entered the drop target area is often a guess. With haptic feedback, the boundary of the target can be clearly felt when the finger slides across it, alleviating the "fat" finger occlusion problem significantly for this type target acquisition. This result also agrees with previous results with different methods of delivering haptic feedback. For example in their 1995 study of a haptic mouse, Akamatsu *et al.* found that known that multimodal feedback can be advantageous in situations where the target is difficult to see [4].

The finding in this experiment suggests that haptic feedback is particularly useful for target (boundary) crossing tasks [2] since the sliding finger tended to occlude the target visually. We believe there could be many practical UIs designed to take advantage of this finding in the future.

On the other hand, practical drag & drop tasks often involve passing distractors in order to drop an object on a target. All of these distractors would also need to present haptic feedback when crossed. Whether such distractions would reduce or diminish the performance improvement needs further research.

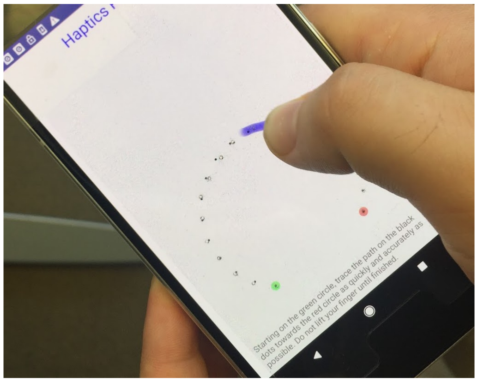


Figure 7: In the trail following task, the physical haptics condition used a plastic screen protector with small bumps pressed into it over the dots on the path.

6 EXPERIMENT 3: TRAIL FOLLOWING

Experimental Design

This experiment used a trail following task to study the impact of haptics on continuous finger movement on a touchscreen. This is a trajectory-based task similar but alternative to the steering task as introduced and modelled by Accot and Zhai [1] that requires subjects to move a cursor through a tunnel without hitting the tunnel's visual boundaries. Our task was inspired by the original visual steering task but without the visual borders that defined the path width in the Steering law. The task is very similar to force-feedback based path learning tasks in studies such as [9].

Currently steering tasks are not broadly used in touch interfaces possibly because they are difficult to use in a purely visual implementation. The appeal of physical sliders suggests that haptic feedback may improvement touchscreen steering tasks. One potential instance is touchscreen based volume control in cars, which is currently very difficult to do while driving.

In this experiment, participants were asked to trace 3/4 of a circle without lifting their finger. The 3/4 circle was displayed as a series of black dots beginning at 45 degrees and ending at 315 degrees, with a radius of 350 pixels. The black dots were consistently spaced around the perimeter at 15 degrees apart. The starting dot had a green outline, and the ending dot had a red outline. As users moved their finger across the screen, they left a 40 pixel wide blue trail behind them (which dissipated slowly with time) to show them their progress. For each dot hit by the user, they received a haptic bump at the moment their finger hit the dot.

For the purposes of delivering haptic feedback, their finger was considered to have successfully passed over a dot if the dot was inside the trail emitted by moving the finger. Users were required to start with their finger on the green starting dot, and the task ended once their finger went below the red end dot at any time during a trial. Figure 7 shows the physical haptics condition of this task.

The main independent variable was *feedback conditions*. Unlike the other two experiments, this experiment had three feedback conditions: visuals only, virtual haptics, and real / physical haptics. In the virtual haptics condition, users received a haptic click effect each time their finger passed over a black dot along the 3/4 circle. In the visuals only condition, the black dots had no haptic feedback.

We added a "real" / physical haptics condition to compare current generation virtual haptics to a "gold standard" mock-up: a plastic screen protector was overlaid on the screen with small bumps pressed into the plastic at precisely the location of the black dots. This is because we felt the type of haptic actuation in today's commercial products and our testing devices might not be rich enough to help the tracing task where the user could feel on or off the path only in a binary fashion. With the three dimensional and strongly localized real-physical screen overlay, the user's finger tip could potentially feel in an analog fashion the degree of tracking the path, hence giving us hits on the value of more complex haptic technologies in the future. Note that the screen overlay was a static mock-up and it had to be thin and transparent enough to not affect the touchscreen use. This limited how rigid the tactile bumps could be made.

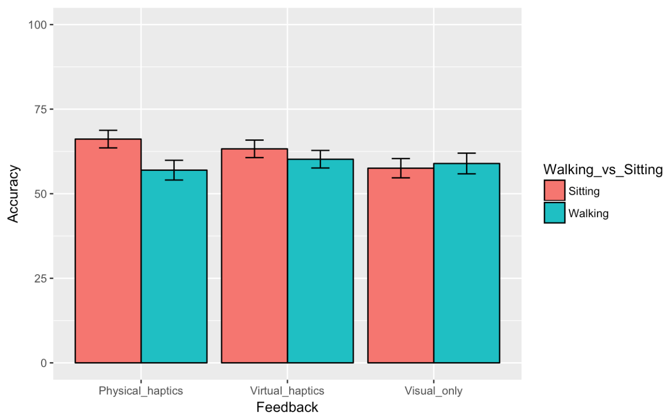
Like in Experiment 1, a second independent variable, *mobile condition* (Sitting vs. Walking), was included in the steering task experiment.

At the end of each steering attempt, participants were shown their time and a score for their accuracy (both discussed in further detail in the Results section). Participants completed this task 15 times in a row. Repetitions were relatively consistent and did not show a clear learning effect.

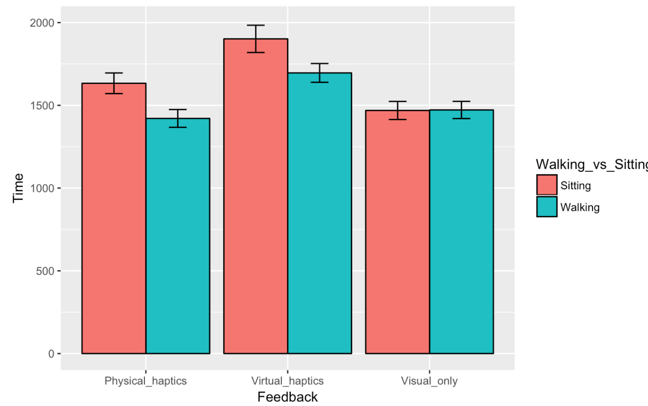
Participants. We recruited 11 participants for this experiment from a tech company. Their average age was 29, and approximately 1/3 were women. Participants were given an incentive worth $15 for their time.

Procedure. We conducted this study using the same type of phone described in the introduction and earlier sections. We used two phones: one with a modified plastic screen protectors mentioned above installed, and one without. Participants were given the relevant phone for the physical haptics condition they were completing. Participants were given the same instructions on how to hold the phones as Experiment 1, and were similarly shown a quick tutorial for each task. They were again instructed to be as fast and accurate as possible. The sitting vs walking condition was the same as described in Experiment 1.

Order for feedback type and sitting vs walking was controlled by a Latin Square design. At the end of each study



(A)



(B)

Figure 8: (A): Percent Accuracy and (B): Time in milliseconds results for steering. For accuracy, feedback type had a significant effect on accuracy but only while sitting. For time, the effect of feedback type on time was significant both while sitting and walking.

session, participants were verbally asked questions about their thoughts and preferences. In total there were 3 *feedback types* x 2 *walking vs sitting* x 15 repetitions x 11 subjects = 990 trials.

Results

In this task, steering accuracy was calculated as the percent of the user's path that is inside the goal path (computed by comparing the goal path with the edges of the 40px trail emitted by the user's finger). Task completion time was measured as milliseconds between finger down and finger up. We removed 64 trials with time or accuracy greater than three sigma away from the mean to prevent counting mis-taps or mis-trials.

Feedback	WalkvSit	Time (SE)	Accuracy (SE)
Physical_haptics	Sitting	1633.2 (31.5)	66.1 (1.3)
Physical_haptics	Walking	1420.8 (27.2)	57.0 (1.5)
Virtual_haptics	Sitting	1901.6 (41.7)	63.3 (1.3)
Virtual_haptics	Walking	1695.7 (28.8)	60.2 (1.3)
Visual_only	Sitting	1468.9 (27.8)	57.5 (1.4)
Visual_only	Walking	1471.9 (26.3)	58.9 (1.5)

Table 3: Mean percent accuracy and time in milliseconds for all steering conditions, with Standard Error.

As shown in Figure 8 (A), the impact of *feedback type* on accuracy depended on Walking vs. Sitting conditions. A two-way repeated measures ANOVA shows a significant interaction effect between *feedback type* and *walking vs sitting* ($F_{2,20} = 5.81, p = 0.010$). In the Walking condition this impact was very small and statistically insignificant in Bonferroni-adjusted pairwise post-hoc tests ($p = 1.0$) for all comparisons). In contrast, in the Sitting condition the mean accuracy with Virtual Haptics was higher than with Visual feedback alone ($p = 0.05$), and it was higher still with Physical Haptics ($p = 0.04$).

Feedback type also impacted time ($F_{2,20} = 8.76, p = 0.002$). Comparing the red bars (Sitting condition) in Figure 8 (A) and (B), we see the improvement in accuracy due to haptic feedback was accompanied with increases in completion time, particularly in the Virtual Haptics condition which was statistically significantly higher than in the Visual Only condition in Bonferroni-adjusted pairwise post-hoc tests ($p = 0.01$).

Subjective Feedback. Ten of the eleven participants enthusiastically remarked that they expected both physical and virtual haptics to improve both speed and accuracy. For physical haptics, several participants commented that they felt they could trust it without visual confirmation. Multiple participants also commented that both virtual and physical haptics helped them to feel more engaged with the task. All participants commented that they felt both types of haptics helped them figure out when they made a mistake sooner than visuals only. Four commented that both haptic types made them feel particularly more confident in the walking condition.

Experiment 3 Discussion

In the this experiment, we see that feedback type significantly affected accuracy, but only in the sitting condition. This is somewhat in agreement with the findings from Brewster *et al.* that haptic feedback via an actuator glued to the back of a PDA did little to reduce text entry errors while on a subway, but did help while stationary [10]. While sitting, virtual haptics improved accuracy by 10% over the visuals only condition, while physical haptics improved it by 15%.

We expected haptic feedback could be more helpful to users while walking since their visual attention could be more distracted. However the results in this experiment did not show either tracing accuracy or tracing speed improvement with either type of haptic feedback while walking. This may be because the task was too demanding or the form of haptics implemented in the experiment did not match the demand and complexity of touch interaction while walking. It is also possible that with the added difficulty of the task, the participants already reached a touch interaction ceiling so no haptic feedback condition would help..

Feedback type also significantly affected task time, while sitting vs walking did not. Specifically, while the difference between visuals only and physical haptics was not significant, virtual haptics was significantly slower than both. From subject feedback and our own observations, this is not surprising. The task using virtual haptics seemed to cause subjects to slow down and "feel for" the bumps. This was not a problem with physical haptics due to their increased dimensionality, enabling the finger to feel it more broadly and before the center of the finger necessarily hits it. Combined with the accuracy results, this experiment shows that virtual haptics introduces a speed/accuracy tradeoff in trail following tasks, while its physical counterpart afforded even higher accuracy without significantly higher time cost.

7 DISCUSSION, CONCLUSIONS AND FUTURE WORK

Based on a current smartphone haptic technology, we set out to identify and estimate where haptic feedback could improve user performance and experience with touch interactions, beyond the most obvious applications such as press and hold. We tested haptic feedback in three types of elemental tasks: tapping, drag & drop, and trail path following. The task parameters were set with relatively high visual-manual accuracy demand.

The first general finding is that the users' subjective experience and preference with haptic feedback tended to be more positive than speed and accuracy type of performance measurements. Users generally found haptic feedback, at least the type of crisp effect we implemented, made their experience more confident and more engaged.

The most dramatic performance improvement with haptic feedback comes from situations where the task state change are visually obscured by the finger but are easily perceptible haptically. We see a more than 50 percent accuracy gain in drag & drop tasks for small targets.

On the other hand, the relationship between haptics to visual feedback is also complex. In two experiments we introduced a walking condition which demanded the participants visual attention away from the screen. Such a distraction degraded their performance overall, but the haptic feedback, at least at the level we implemented, was not able to fill the attention and feedback gap.

In one experiment we also explored a "future" version of haptic feedback through a physical screen overlay, which afforded more haptic dimensions and localization. We saw indeed more accuracy improvement with it, suggesting more user benefits that are not realizable in today's mainstream products.

There are many limitations to the current work and more research to be done in the future on touchscreen haptic feedback augmentation.

(1) We narrowly focused the scope and task parameters of this study and avoided systematic task modelling aspects of performance.
(2) We opted out of experimenting with "obvious" performance gains of haptics, including press and hold and force-sensing based gestures such as the Active Edge haptic feedback effect in the Pixel 2 phone we used. The design of these haptic effects could also benefit from formal empirical investigations.
(3) We investigated a basic tap effect for virtual keys. Android 8.0 APIs [5] include many more types haptic feedback. In particular, the recently introduced key release effects helped the pre-loaded Gboard on Pixel 2 phones to have paired press-and-release effects. While it might be felt more engaging, such pairing effect's performance impact on text input has yet to be formally studied.
(4) The mobile haptics literature can also benefit from a replication of Hoggan *et al.*'s study [20] on modern contact-based capacitive touchscreen phones with smart keyboard's statistical decoding capabilities.
(5) The tasks we studied all had strong visual dominance. Previous review has shown stronger haptic feedback effect to keying when a large flat keyboard with no moving keys were hidden from view [27].
(6) We focused this study on smartphones. The very different ergonomics on tablet or laptop computers with a flat keyboard could require very different haptics designs, such as those in [22, 27, 27].

Both touch sensing and haptic actuation have made remarkable progress on smartphones in the last decade. Based on one of the latest state-of-the-art smartphone models and three controlled experiments, our study produced a set of current assessments and analysis of the benefits and limitations of touchscreen actions augmented with active haptic feedback. It provides an empirical foundation to near future product decisions and future research advancements in input and haptic system design.

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