Tactile Feedback for Above-Device Gesture Interfaces: Adding Touch to Touchless Interactions

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ABSTRACT

Above-device gesture interfaces let people interact in the space above mobile devices using hand and finger movements. For example, users could gesture over a mobile phone or wearable without having to use the touchscreen. We look at how above-device interfaces can also give feedback in the space over the device. Recent haptic and wearable technologies give new ways to provide tactile feedback while gesturing, letting touchless gesture interfaces give touch feedback. In this paper we take a first detailed look at how tactile feedback can be given during above-device interaction. We compare approaches for giving feedback (ultrasound haptics, wearables and direct feedback) and also look at feedback design. Our findings show that tactile feedback can enhance above-device gesture interfaces.

Author Keywords

Above-Device Interaction; Distal Tactile Feedback;
Gestures; Tactile Feedback; Ultrasound Haptics; Wearables.

ACM Classification Keywords

H.5.2. User Interfaces: Interaction styles.

INTRODUCTION

Above-device gesture interfaces let people interact with mobile devices using mid-air hand gestures in the space above them. Users can gesture in a larger space above the device, overcoming issues with small touchscreen interaction and letting users interact more expressively; for example, users could provide more precise input on small wearables like smart-watches or could gesture imprecisely at their mobile phones while focusing on another task. Gestures also let users interact when touching a device would be inconvenient; for example, people could gesture over the display while cooking, to navigate a recipe without touching their tablet with messy hands.

Effective feedback is needed to help users overcome uncertainty about gesture performance and the complex sensing requirements of gesture interfaces. While visual feedback could be given about gestures, this takes already limited display space away from content. We think feedback should be given in the same space as users gesture, in this case the space above the device. We think that tactile feedback in particular could be given, helping users overcome uncertainty. Providing tactile cues while users gesture in mid-air is a challenge; vibration from a distal device would go unnoticed and users receive no physical cues from touching something.

New haptic technologies and wearable devices can overcome this challenge, letting gesture interfaces provide tactile feedback remotely. Technologies such as ultrasound haptics [11] or air vortex generation [18] would let users experience tactile sensations in mid-air as they gesture. Users could also receive tactile feedback from a wearable device such as a smart-watch or item of jewellery. Future gesture interfaces could use wearables for tactile feedback, even combining or selecting from multiple accessories (e.g. rings and watches) for feedback.

In this paper we focus on tactile feedback for above-device interaction with mobile phones. Mobile phones are small devices which could benefit from tactile feedback when gesturing and recent phones, such as the Samsung Galaxy S4 and Google Project Tango, show an interest in giving phones sensors capable of detecting gestures away from the touchscreen. Our studies focus on selection gestures as selection is often used in above-device interfaces [5, 9, 1, 8, 19]. Selection gestures are also focused interactions so will benefit from having another feedback modality to assist users.

We discuss the design and delivery of tactile feedback for above-device interfaces using two approaches: ultrasound haptics and wearable devices. We present the design of a gesture interface for mobile phones and discuss two experiments exploring different aspects of remote tactile feedback. Our findings show that tactile feedback can improve gesture interfaces and make it easier for users to gesture. We present recommendations for gesture interface designers to help them make the most of tactile feedback.

RELATED WORK

Researchers have developed a variety of ways of detecting mid-air gestures above or near devices, leading to a wide range of interaction techniques. Gesture interactions include simple hand movements over a device [13, 14], precise selection techniques based on finger movements [5, 9, 19] and more subtle gestures with wearables [1]. These interfaces give users feedback in a variety of ways. We now discuss some above-device interfaces with a focus on feedback.

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Visual Feedback

Most above-device gesture interfaces rely on visual feedback, although this is often just functional feedback showing the outcome of a gesture. In *HoverFlow* [13], for example, users could browse a colour palette with hand movements above a mobile device. Only functional visual feedback is given, when the colour palette updates in response to gestures. Interfaces with pointing gestures, such as *SideSight* [5] and *Abracadabra* [9], give continuous feedback about finger position using a cursor. Users see how their finger movements are tracked through updates in cursor position.

While functional feedback can help users interact, it provides little insight into how sensing works. Jones *et al.* [12] suggested that visualising sensor information could help guide users. Kratz *et al.* [13] proposed a technique for *HoverFlow* to show sensor readings, although users might not see this visual feedback as they gesture over the display. Niikura *et al.* [15] created a mid-air keyboard for mobile phones which showed a silhouette of users' fingertips as they typed, showing them how they were being tracked.

Visualising sensor information could be helpful as it gives users insight into how their gestures are being sensed. Users can then adapt their gestures to ease sensing and can gesture confidently knowing their movements are being recognised as intended. However, mobile devices have small displays. Designers must choose between emphasising visual content and sensor visualisations. Audio and tactile feedback can be used to present information non-visually, reducing the amount of visual content on display and making certain information more salient. These modalities may also be noticeable from a distance; visual feedback would be difficult to see when gesturing from an arm length away. Visual feedback may also be occluded as users gesture over the display.

Audio Feedback

Audio is mostly used in gesture interfaces to overcome a lack of visual feedback. *Nenya* [1], a wearable smart-ring, lets users make selections by rotating the ring around their finger. The name of the selected item is spoken as users make selections. A similar type of feedback is used in *Imaginary Phone* [8]; as users make selections by tapping on the palm of their hand, the name of the selected item is read aloud. These examples of functional feedback give no insight into how users are being sensed, however. Users only receive feedback *after* input. Continuous audio feedback would be needed during interaction to help users, although this could be socially unacceptable if it annoys other people nearby.

Tactile Feedback

Tactile feedback has been used by some above-device interfaces to acknowledge gestures, similar to how smartphones vibrate to acknowledge touch input. Niikura *et al.* [15] gave tactile feedback from their mid-air keyboard, using the vibration motor in a phone to deliver feedback to the hand holding the device. A limitation of this approach is that users had to be holding the phone to feel the vibrations. This is a problem because users would first have to pick up the device; one of the advantages of above-device gesture interaction is that it is touchless, letting users interact when touch input is unavailable or inconvenient.

This modality has also been used to give continuous sensor information during interaction. Users interacted with *AirTouch* [14] with hand movements over wrist-worn sensors. Each of its four sensors was paired with an actuator, giving spatial vibrotactile feedback to show which sensors detected input. Users did not perceive this, however, instead saying feedback only let them know when their hand was being detected. More work is needed to explore the design space of tactile feedback for above-device gesture interfaces, to see how more sophisticated feedback may help users gesture.

Giving tactile feedback in a gesture interface is challenging because users may not be touching the device they are interacting with. Vibration directly from a device (e.g. [15]) would only be noticed when holding it. We now discuss two alternatives for delivering tactile feedback in a gesture interface: non-contact feedback and distal feedback from wearables.

Non-Contact Tactile Feedback

Ultrasound haptics uses acoustic radiation pressure to create tactile sensations using sound. Iwamoto *et al.* [11] used an array of ultrasound transducers to focus sound upon a fixed point which could be felt as ultrasound reflected off skin. Later work [10] allowed the focal point to be moved in 3D space above the transducers. Carter *et al.* [6] built on this work and created an ultrasound tactile display which could produce many focal points of feedback at the same time. Wilson *et al.* [20] considered wearable ultrasound displays, finding ultrasound haptics from a smaller array to be effective.

Air pressure is an alternative to acoustic radiation pressure for creating non-contact tactile sensations. *AIREAL* [18] used air vortex generation to create mid-air tactile feedback which could be perceived several metres away. This approach creates feedback with a resolution of around 85mm, almost ten times lower than ultrasound haptics [20]. We think ultrasound haptics is more appropriate for above-device interfaces because of its high resolution. Precise tactile feedback can be created for subtle movements relative to small devices.

Distal Tactile Feedback

Gesture interfaces could alternatively use wearables to give distal tactile feedback. Some wearables already have vibrotactile actuators for giving notifications (e.g. *haptic wristwatch* [16])- we think these could also be used for feedback while gesturing. Distal tactile feedback has already been used with large interactive surfaces and can be as effective as direct feedback, even when given on the inactive arm [17].

Summary

Above-device interfaces mostly rely on visual feedback during interaction, giving users a combination of functional feedback and sensor information. Giving some of this information with other modalities, such as audio or tactile, can free up space for visual content on small displays and make feedback more noticeable when interacting from a distance. We have chosen to focus on tactile feedback as it is personal and may help users overcome the lack of tactile cues when gesturing.

Tactile feedback directly from a device may not be noticed so novel ways of delivering tactile feedback from a distance are needed, as well as a better understanding of how to use this modality during gesture interaction.

SELECTION GESTURES AND FEEDBACK DESIGN

Our research has three aims: (1) to evaluate ultrasound haptics and wearables for giving tactile cues during above-device interaction; (2) to understand what information users find useful when encoded tactually; and (3) to see how tactile feedback affects gesture performance. We chose to focus on above-device interaction with mobile phones as this is an emerging area of technology and well-designed tactile feedback can improve it.

In particular we focus on selection gestures. Selection is a continuous interaction, often requiring an active and focused engagement. Continuous interactions will benefit from multimodal feedback because users' movements are being sensed constantly so appropriate cues can keep them "in the loop" and help them gesture more effectively. Selection is also a common interaction in many above-device gesture interfaces [5, 9, 1, 8] so our work could help improve these interfaces. In this section of the paper we will discuss the design of two selection gestures, as well as the design of visual and tactile feedback given during interaction.

Selection Gesture Design

We chose two selection gestures, *Point* and *Count*, from an earlier gesture design study [7]. We were interested to see if tactile feedback could benefit both precise and imprecise gestures, so we choose a gesture requiring precise positional control (Point) and one which does not (Count). The Point gesture is used in a similar way to other around-device selection gestures (e.g. selection with *Abracadabra* [9]); users control an on-screen cursor which is mapped to their finger movements (Figure 1).

Users can make selections with Point by keeping the cursor over a target for 1000 ms. We chose this selection technique because it worked equally well for Point and Count, and because it let users see the effect of their actions, giving them a chance to correct their selection. We informally evaluated different dwell times and found that users were most comfortable with 1000 ms; shorter times were too fast for inexperienced users and longer times slowed the interaction too much. Rather than gesture above the display where occlusion may be a problem, we used the space beside the phone (as in other around-device interfaces [12]).

Our Count gesture is like the Finger-Count gesture described by Bailly *et al.* [2]. Users select from numbered targets by extending the required number of fingers; to select the second target, for example, the user extends two fingers (as in Figure 2, right). As with the Point gesture, a selection requires a dwell of 1000 ms. Users can navigate back through the user interface by swiping quickly from right to left with one or more fingers. An obvious limitation of Count is that users can only select from up to five targets. To allow a greater number of targets, we partition targets into groups of five or less. Depending on hand position relative to the device, users

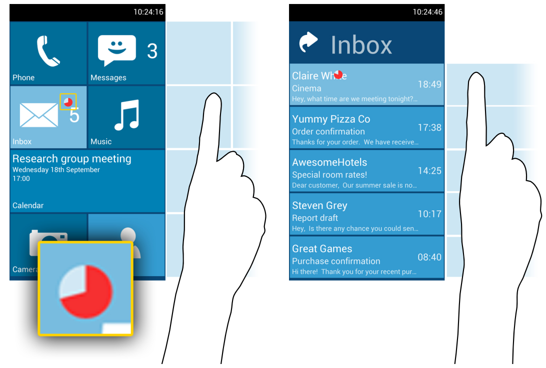

Figure 1. *Point*. A circular cursor (close-up shown in call-out on left) is mapped to finger position in the space beside the device. These images visualise how the space is divided between selection targets.

Figure 2. *Count*. Users can select from numbered targets by extending an appropriate number of fingers. The left image shows how palm position determines which group of targets is active.

can select from within a group of targets. In Figure 2, for example, the hand is towards the bottom half of the screen on the left so the bottom three targets can be selected; the top four icons are darkened to show that they are inactive.

Feedback Design

Visual Feedback

As Point requires precise position control, we wanted to make the selection targets large in order to make them easier to select. Our user interface (shown in Figures 1 and 2) featured large buttons in grid and list layouts. For the Point gesture, a white circular cursor showed finger position. As the cursor entered a target the button was highlighted and the cursor filled radially to show dwell progress (see callout in Figure 1). We used the cursor to show dwell progress for Point as users were likely to focus on the cursor during interaction.

When using Count, each selection target had a number associated with it, drawn in the bottom corner of the button. When making selections, the selected button was highlighted, as was the number in the corner. The target background filled from left-to-right to show selection progress (Figure 2). We initially filled the target background for the Point gesture as well, but early prototyping revealed that this distracted users when focusing on the cursor position. When users were presented with multiple target groups, inactive groups were faded out to make the active group more visible (Figure 2).

Figure 3. Sensor setup and vibrotactile ring prototype.

Tactile Feedback
We created two types of tactile feedback for our selection gestures: *Continuous* and *Discrete*. Continuous feedback was a constant stimulus presented while the user interacted with the device. When targeting a button, users felt smooth vibrotactile feedback (a 175 Hz sine wave); when not over a button, users experienced a rougher sensation (a 175 Hz sine wave modulated with a 20 Hz sine wave, as in [4]). No feedback was given if a hand was not being tracked. The aim of Continuous feedback was to let users know their hand was being recognised by the device. Change in feedback aimed to let users know when they: (1) started making a selection (e.g. when moving over a button using Point, feedback felt smoother); (2) finished making a selection (e.g. after selection, feedback returned to feeling rough); and (3) were gesturing incorrectly, or were not being tracked (e.g. feedback stopped entirely when the hand was not recognised).

Discrete feedback used short Tactons [3], mapping feedback to the same user interface events that Continuous feedback identified. The selection start and selection complete Tactons were 150 ms and 300 ms duration smooth vibrotactile pulses, respectively (both 175 Hz sine waves). The tracking error Tacton was a 300 ms long rough vibrotactile pulse (a 175 Hz sine wave modulated with a 20 Hz sine wave).

We supported four types of tactile feedback (Figure 4): (1) ultrasound haptics; (2) distal feedback from a ring (worn on the pointing finger for Point); (3) distal feedback from a watch worn on the wrist of the gesturing hand; and (4) feedback directly from the phone (when held). Although direct feedback will be inappropriate in some situations, we included this to see if it made sense to users to feel feedback at their inactive hand. Watch and ring form factors were chosen for wearables as wearing objects on the wrist and finger is widely accepted and products already exist that can do this. Smart wearable accessories could give users options for how they get feedback; for some interactions it may make more sense to get feedback from a ring than a bracelet, for example.

Apparatus
We used a Leap Motion sensor to track hands and fingers for input. The field of view is 150 degrees, offering a large space through which to track the hand. We created a gesture detector which ran on a desktop computer using Leap Motion's C# library. Information was sent to a mobile phone via a wireless network, allowing the phone to provide visual feedback during interaction (Figure 3).

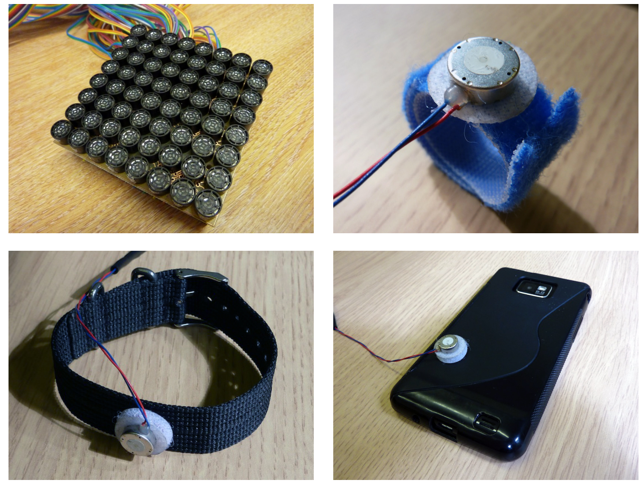

Figure 4. Hardware prototypes used to deliver tactile feedback: ultrasound array, ring, watch, mobile phone.

A prototype ultrasound tactile display was used to provide non-contact tactile feedback. This device (Figure 4, top left) has sixty-four 40 kHz transducers arranged in an 8 x 8 grid. Each transducer has a diameter of 10 mm; at 80 x 80 mm, the device is slightly wider than a smartphone. Focal points could be created on a flat plane 100 mm above the display (a limitation of our experimental prototype; ideally feedback could be positioned anywhere in 3D space). As the human hand cannot detect vibration at ultrasound frequencies, ultrasound was modulated at 200 Hz to create a perceivable sensation (as explained by Carter *et al.* [6]). Modulation frequency was fixed in our prototype so we were unable to create different textures (e.g. to distinguish between targeting and not targeting a button for Continuous feedback). Instead, a focal point of constant feedback followed the user's fingertip for Continuous feedback. After prototype evaluation we decided to only use the ultrasound display for Continuous feedback; ultrasound haptics produces a subtle sensation which some users were unable to perceive in the short durations of the Tactons used by the Discrete feedback design.

Our wearable prototypes for distal feedback used a Precision Microdrives C10-100 Linear Resonant Actuator[1]. This actuator was chosen as its small size (10 mm diameter) and light weight meant it could be comfortably worn on the finger. We used an adhesive pad so that this actuator could be attached to a variety of prototype devices, including an adjustable velcro ring, a fabric watch strap and the rear of a mobile phone (shown in Figure 4; ring also in Figure 3). We attached an actuator to a phone (for direct feedback) for consistency, rather than use the rotational motor in the phone. Feedback was synthesised in real-time using Pure Data. Our tactile feedback designs (discussed previously) used 175 Hz sine waves as this is the optimal resonant frequency of the actuator.

[1] `http://www.precisionmicrodrives.com`

STUDY 1

Our first study was a preliminary evaluation of our feedback designs and the ways we delivered feedback. We wanted to understand what users liked and disliked about ultrasound haptics and distal tactile feedback so that we can identify how best to use them in above-device gesture interfaces. We also wanted to evaluate our initial feedback designs to see how effective they are and to get insight into what types of information users find helpful when presented tactually.

We chose to use only the Point gesture in this study to minimise the number of study conditions. Using just Point also meant we could restrict gesturing to the space above the ultrasound array, making ultrasound feedback perceivable during input. We look at Count in our second study.

Design

We asked participants to complete selection tasks using our Point gesture. Each task required selecting a menu item from the third level of the user interface hierarchy, requiring three selections per task. Tasks were based on typical mobile phone operations: selecting an action to perform on a contact list entry or an inbox item. Task order was randomised.

Participants completed a block of 14 tasks for each of eight conditions, representing combinations of our feedback designs (*Continuous*, *Discrete*, *None*) and delivery methods (*Phone*, *Finger*, *Wrist*, *Ultrasound*). These conditions are: *None (N)*; *Phone-Continuous (PC)*; *Phone-Discrete (PD)*; *Finger-Continuous (FC)*; *Finger-Discrete (FD)*; *Wrist-Continuous (WC)*; *Wrist-Discrete (WD)*; and *Ultrasound-Continuous (UC)*. There was no discrete ultrasound feedback as discussed previously. Participants experienced all conditions and condition order was balanced using a Latin square.

Sixteen people participated in this study (five female, three left-handed). Participants were recruited through mailing lists and social media websites, and were mostly undergraduate university students. Each participant was paid £6.

Procedure

Participants received a brief tutorial at the start of the study which demonstrated how to use the Point gesture. No tactile feedback was presented during the tutorial. After the tutorial, participants received a demonstration of the prototype feedback devices. We asked participants to hold the mobile phone in their non-dominant hand, beside the ultrasound array. As participants would have to hold the phone for conditions where feedback came directly from the device, this ensured that holding the phone was not a confounding factor for these conditions.

We interviewed participants at the end of the study to find out what they liked and disliked about tactile feedback while gesturing. During the interview we asked them to complete two card-sorting activities. The two sets of cards contained locations of tactile feedback (*Phone*, *Finger*, *Wrist*, *None*) and feedback designs (*Continuous*, *Discrete*, *None*). Participants were asked to sort the cards in order of preference. These activities gave us preference data and encouraged participants to focus on tactile feedback during the interview. When collecting location preferences, we asked participants to focus on the location of feedback rather than the device used: e.g. *Finger* could be vibrotactile or ultrasound feedback. We did this so we could better understand preference for location, rather than preference for a particular device.

Results

Table 1 shows median rankings for feedback locations and designs. Scores were assigned for each set of cards so that the highest ranked card received a score of 1 and the lowest ranked received a score of 4 (for location) or 3 (for design). Friedman's test found a significant difference in preference for location: $\chi^2(3) = 14.62$, $p = 0.002$. A *post hoc* Nemenyi test revealed significant differences between *None* and all other locations; no other pairwise differences were significant. There was no significant difference in ranks for tactile feedback design: $\chi^2(2) = 2.95$, $p = 0.23$.

Location				Design		
Phone	Finger	Wrist	None	Continuous	Discrete	None
1.75	2	2.5	4	1.5	2.5	2.0

Table 1. Median ranks for location and design (lower ranks are better).

Discussion

Feedback Location

All feedback locations were ranked significantly higher than None, although there were no other significant differences. We wanted to see if direct tactile feedback from the phone made sense to users, despite them gesturing with their other hand. Participants liked direct feedback because it was familiar; most who liked it said they were already used to their phone vibrating in response to touch input. Some participants suggested that direct feedback let them know when the phone was doing something, but other locations make more sense for gesture feedback. For example, interfaces could give feedback relating to hand movements to that hand or wrist.

Direct tactile feedback would be inappropriate in many gesture situations as users will not be holding the device they gesture at. In these situations, feedback from a ring or watch would let users experience tactile feedback. Participants gave feedback on the wrist and finger similar rankings. This shows the importance of supporting different wearable accessories and giving users choice of feedback location. In some situations it may even make sense to give feedback at several locations.

Participants liked tactile feedback on their finger because it was close to the point of interaction; fingertip position controlled the cursor so it made sense to receive feedback at this point. Ultrasound haptics was especially useful for this because feedback was given at the point of the finger tracked by the sensor. Although ultrasound feedback was not as noticeable as vibrotactile feedback on the finger, participants liked that they could experience it without having to wear anything.

Feedback on the wrist was further from the gesturing finger, yet people still found it helpful. We asked participants to wear the watch prototype on their dominant wrist, the opposite wrist from where most participants wore their own watch. Participants said they would be willing to wear their watch on the other wrist if it provided some purpose, such as feedback while gesturing. However, distal feedback from the opposite wrist may also be effective [17], letting users wear accessories on whichever wrist they prefer.

Feedback Design

There were no significant differences in feedback design rankings. We noticed that participants who preferred *Continuous* feedback generally ranked *None* ahead of *Discrete*, and *vice versa*. People who liked *Continuous* feedback felt it made them aware of how the gesture interface was responding to their actions. The presence of continuous feedback assured them that they were being sensed and subtle changes in feedback reflected changes in interface state. *Discrete* feedback did not provide much insight into sensor state as feedback was only given in response to certain events. However, some participants preferred this because it was less obtrusive than constant vibration.

Ultrasound haptics was more acceptable for continuous feedback because it produced a more subtle sensation. Feedback could be given from a combination of ultrasound haptics and wearable devices, using ultrasound haptics for constant feedback while wearables give more concise feedback. Some participants suggested that a mixture of the feedback designs would be more appropriate, as they found that feedback all the time was too much, but discrete feedback did not tell them enough about the interaction.

We created new feedback designs which combined popular aspects of Continuous and Discrete feedback: continuous feedback was only provided during gestures; at all other times there was no feedback. We used a 175 Hz sine wave as before. This design aimed to make users aware of when the interface was tracking their gestures and making a selection, without being obtrusive. We used short Tactons to acknowledge when tracking started or stopped. Visual feedback let users know when their gestures were sensed, with tactile feedback complementing it and making some information more salient.

We also wanted to see if we could use vibrotactile feedback to encode information about selection progress. Some participants found subtle changes in Continuous feedback helpful for knowing when selection started, so we wondered if we could encode other information this way. Encoding information tactually could reinforce visual feedback and reduce the need for visual attention because the same information is given multimodally.

We created two more feedback designs which provided a dynamically changing stimulus during selection. Each used a different vibrotactile parameter to encode selection progress: amplitude and roughness. Amplitude increased from 0 to 100% so that as selection progress increased, stimulus from a 175 Hz sine wave became more intense. Amplitude increased exponentially as a linear increase proved more difficult to notice during pilot tests. For roughness we modulated a 175 Hz sine wave with another sine wave, whose frequency increased from 0 Hz to 75 Hz. As selection progressed, the tactile stimulus felt smoother. We considered using frequency as a dynamic feedback parameter as well, although the response range of the actuator limits frequency use.

STUDY 2

Our second study evaluated our refined tactile feedback designs and looked at the effects of tactile feedback on gesture performance. Two of our new feedback designs used vibrotactile parameters (amplitude and roughness) to communicate selection progress. Although this information was also given visually, we wanted to see if tactile presentation would benefit users. For this study we chose to deliver feedback to users' wrists as this location was widely accepted and may make more sense for the *Count* gesture. In this study we also compared a precise position-based gesture (*Point*) to a less precise gesture (*Count*), although our focus was on tactile feedback.

Design

There were two factors in this experiment: Feedback (*None*, *Constant*, *Amplitude* and *Roughness*) and Gesture (*Point* and *Count*), resulting in eight conditions. Participants experienced all conditions and condition order was balanced using a Latin square. As in the previous study, participants completed a block of 14 tasks for each condition. Our dependent variables in this study were selection time and estimated workload. Selection time was measured for each task from when users started gesturing to when they completed their final selection. We measured workload with NASA-TLX questionnaires after each block of tasks. Sixteen people participated in this study (six female, three left-handed, five participated in the previous study). Participants were recruited through mailing lists and social media websites and were paid £6.

Procedure

Experimental procedure was the same as the previous study. We placed the phone on a table in front of participants, with the Leap Motion positioned so that their dominant hand gestured beside the display. Unlike the last experiment, participants did not hold the phone. Participants completed eight blocks of tasks (one for each condition).

We interviewed participants at the end of the experiment, using card-sorting activities to encourage discussion. We asked participants to sort two sets of cards: one for gestures (*Point* and *Count*) and the other for tactile feedback designs (*None*, *Constant* and *Dynamic*). We grouped *Amplitude* and *Roughness* under *Dynamic* feedback as we did not expect participants to identify each during the experiment. Also, we were more interested in what participants thought of using tactile feedback to encode other information.

Results

Mean selection time was 8529 ms (sd = 1729ms); see Figure 5 (all error bars show 95% CIs). This includes at least 3000 ms dwelling for each task and overheads for updating the UI. Performance was analysed using repeated-measures regression, with maximum likelihood estimation used to fit model parameters. Gesture was a significant predictor of selection time: $\chi^2(1) = 15.79$, $p < 0.001$. A *post hoc* Tukey comparison found that Point had significantly lower selection times than Count: $z = 5.19$, $p < 0.001$. Feedback design was not a significant predictor of selection time: $\chi^2(3) = 1.28$, $p = 0.73$.

Mean workload was 36.2 (sd = 17.5); see Figure 6. Workload was analysed using repeated-measures regression, with maximum likelihood used to fit model parameters. Gesture was a significant predictor of workload: $\chi^2(1) = 8.36$, $p = 0.004$. A *post hoc* Tukey comparison revealed that Point had a significantly lower estimated workload than Count ($z = 3.31$, $p < 0.001$). Tactile feedback was also a significant predictor of workload: $\chi^2(3) = 16.19$, $p = 0.001$. *Post hoc* Tukey tests revealed that tactile feedback using amplitude and roughness had significantly lower workload than no tactile feedback ($z = -3.58$, $p = 0.002$; and $z = -3.30$, $p = 0.006$). There was no significant difference between constant and no tactile feedback ($z = -1.20$, $p = 0.63$), amplitude and constant ($z = -2.38$, $p = 0.08$), roughness and constant ($z = -2.10$, $p = 0.15$), and roughness and amplitude ($z = 0.28$, $p = 0.99$).

We analysed card-sorting rankings as in the previous study. Table 2 shows median ranks for Feedback and Gesture. Friedman's test found a significant difference in preference for tactile feedback design: $\chi^2(2) = 11.44$, $p = 0.003$. A *post hoc* Nemenyi test revealed significant differences between no tactile feedback and all tactile feedback; there was no significant difference between constant and dynamic feedback. Wilcoxon's signed-rank test found users significantly preferred Point: $Z = 3.00$, $p = 0.004$.

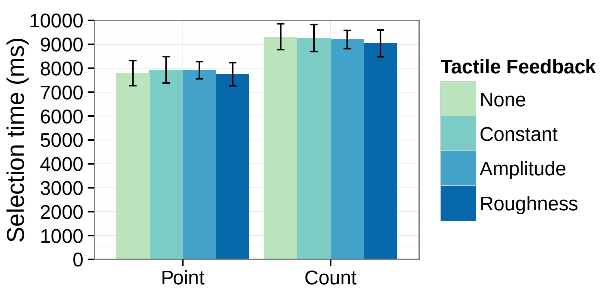

Figure 5. Mean selection times for each condition.

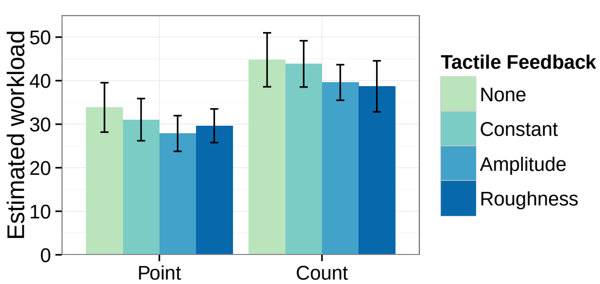

Figure 6. Mean estimated workloads for each condition.

Tactile Feedback			Gesture	
None	Constant	Dynamic	Point	Count
3	2	1	1	2

Table 2. Median ranks for feedback and gesture (lower ranks are better).

Discussion

Tactile feedback had no significant effect on selection time. We think this may have been because selection was too easy for feedback to impact performance. However, dynamic tactile feedback did significantly lower task workload. Participants also ranked all tactile feedback significantly higher, in terms of preference, than no tactile feedback. These results suggest that tactile feedback is beneficial while gesturing. As in the previous study, we found a variety of reasons that users liked getting tactile feedback.

Some participants said dynamic tactile feedback made them more aware of how the interface was responding to their gestures. Subtle changes in dynamic feedback told users that something new was happening, for example a new gesture was starting to be recognised. Frequent changes in feedback also suggested sensors were having difficulty sensing gestures. One participant explained that unexpected changes in feedback told him something was wrong, for example a gesture was being misrecognised or he accidentally changed target with *Point*. Changes in amplitude were more noticeable than changes in roughness. As a result, most participants found amplitude a more useful way of encoding information.

Dynamic feedback also created familiar touch metaphors. One participant said changes in roughness were similar to what he would feel when moving over a physical button, crossing from a noticeable edge to a smooth surface. Another said increasing vibration strength was like pushing harder against a button. Even though we gave tactile feedback on the wrist, participants were able to associate these (unintended) aspects of feedback design with physical sensations.

We think our findings will apply to other above- and around-device interactions. Multimodal feedback improved users' awareness of interface state and made it easier to interact; we think giving tactile feedback will have similar benefits for other gestures near small devices.

DESIGN RECOMMENDATIONS

Based on our findings, we suggest above-device designers:

1. Give tactile feedback during above-device gesture input as this shows system attention, can improve user experience and can make interaction easier;
2. Use dynamic tactile feedback as subtle changes in feedback make users more aware of how the interface is responding to their actions. Constant feedback was also helpful although it gave less insight about continuous sensing;
3. Encode information multimodally as tactile feedback reinforces visual feedback and creates useful tactile cues. For example, we encoded selection progress tactually which created subtle cues to users about interface behaviour;
4. Give feedback about gestures close to the point of interest. For example, give feedback on a finger if tracking finger movement and users are wearing an appropriate accessory;
5. Give "familiar" feedback about generic interface events directly from the device, if held or worn while gestured at. For example, feedback not relating to gesture sensing;

6. Present important information in many ways, if possible. For example, show gesture acceptance using multiple accessories and directly from the device, if being held;
7. Use ultrasound haptics for more subtle types of tactile cue. For example, give continuous ultrasound feedback under the fingertip so users feel like they are touching something, but use more salient tactile displays for gesture feedback;
8. Let users choose their preferred tactile feedback accessories as feedback is effective at different locations. For example, some of our participants were not willing to wear rings but found watches and bracelets more acceptable;

CONCLUSIONS

In this paper we looked at how above-device gesture interfaces can give tactile feedback. Our first study was a preliminary look at how feedback may be designed and given from a gesture interface for mobile phones. We compared ultrasound haptics, distal tactile feedback from wearables and tactile feedback direct from a phone. Our second study evaluated refined feedback designs and investigated the effect of tactile feedback on gesture performance. We found that although tactile feedback did not affect interaction time for our interface, certain designs did make it easier for users to gesture. Users also showed strong preference for tactile feedback.

We recommend that above-device interface designers, especially those creating interfaces for small devices like wearables or mobile phones, give tactile feedback. Tactile cues can improve gesture interfaces, making it easier for users to gesture by improving awareness of how the interface is responding to their gestures. As remote haptic technologies improve and wearable devices grow in popularity, gesture interfaces will have more options for giving tactile feedback. We contribute design recommendations based on our study findings. These recommendations will help others use tactile feedback effectively in above-device gesture interfaces.

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