Unifone: Designing for Auxiliary Finger Input in One-Handed Mobile Interactions

David Holman[1], Andreas Hollatz[1], Amartya Banerjee[1,2], Roel Vertegaal[1]

[1] Human Media Lab
School of Computing, Queen's University
Kingston, Ontario
Canada, K7L 3N6

[2] TIDAL Lab
McCormick School of Engineering,
Northwestern University
Evanston, IL 60208

{holman, andreas, roel}@cs.queensu.ca, amartyabanerjee2012@u.northwestern.edu

ABSTRACT

We present Unifone, a prototype mobile device that explores the use of auxiliary finger input in one-handed mobile interaction. Using force-distributed pressure sensing along the side of device, we examine how squeeze-based gestures impact four common mobile interactions: scrolling, map navigating, text formatting, and application switching. We evaluated the use of Unifone in these tasks using one-handed interactions by the non-dominant hand. Our user study shows that one-handed isometric gestures perform best when they augment rather than restrict or alter the primary pointing action of the thumb and, generally, are suitable for coarse isometric pressure input.

Author Keywords

Mobile Interaction, One-handed input.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI).

General Terms

Human Factors; Design.

INTRODUCTION

In this paper, we explore how auxiliary touch input impacts the usability of mobile interaction. Although gestures that use tilt, acceleration, spatial location, and even deformation have been actively researched in one-handed scenarios [2,4,7,6,19,20] a user's additional fingers are often overlooked as input channels that support or extend the thumb's primary pointing behavior.

As an initial step in this space, we focus on one-handed interactions that rely on a user's non-dominant grasp. Users often adopt one-handed strategies when interacting with mobile devices; this leaves a hand free to manage the demands of the real world (Figure 1). The thumb, stabilized by the hand's supporting fingers, acts as the primary pointing device in these scenarios. These fingers are often delegated to controlling hardware buttons for settings like volume or power. More often, they are unused. Though poorly suited for precise pointing, their movement is not completely inhibited. Even when the thumb is active, the individual fingers of a user's non-dominant grasp are capable of coarse isometric manipulations; the fingertips protrude and wiggle around the edge of the device. When grasping a mobile phone this way, gestures like squeezing the edges of a device are feasible.

Figure 1. In mobile scenarios, a user's hand is often occupied. Unifone gestures can be operated using the non-dominant hand, while still pointing with the thumb.

Leveraging this auxiliary finger input also influences the design tradeoff between screen size and interface complexity. Modern mobile devices, such as the iPhone or the Google Nexus S, have adopted high-resolution multi-touch displays that make it easier to interact with rich content. With greater demands on screen real estate, some applications, like Google Earth, limit the functionality of their mobile version. Others leave their functionality intact and distribute workflows across numerous screens and repetitive interface button presses. Instead, using auxiliary input supports transferring interface control elements off the display; for example, auxiliary input gestures can be mapped to general navigational controls, leaving the mobile free to render more content.

Although dedicated hardware buttons, such as the trumpet-like buttons in Weiser's Tab [23], can theoretically achieve this same benefit, an industrial design that is ergonomic for

TEI 2013, Feb 10-13, 2013, Barcelona, Spain.
Copyright 2013 ACM 978-1-4503-1898-3/13/02....$15.00.

a range of hand and finger sizes is challenging. To address this problem and to explore the use of auxiliary finger input, we designed Unifone, a prototype that senses isometric manipulations using a pressure-distributing accessory placed along its outer edge (see Figure 2 and 4). Using this hardware sensor, Unifone affords *coarse* targeting: instead of a precisely located hardware button, users squeeze the phone *near* its middle or corners, an ergonomic improvement that can adjust sensor location for each user and enhance the pointing behavior of the thumb (see Discussion section). We report on the evaluation of Unifone's three squeeze-based gestures—a middle squeeze, top corner squeeze, and bottom corner squeeze—and compare them against thumb-only interaction in a set of common mobile tasks. When tightly coupled with the movement of the thumb, Unifone's squeeze gesture improves the performance of these common mobile tasks.

RELATED WORK

Unifone relates closely to one-handed mobile interaction techniques. Yet, it differs in its emphasis on coarse auxiliary manipulation. To describe this active research space, we first examine one-handed mobile usage and interaction techniques related to grasp. We follow with a discussion of mobile research that extends one-handed interactions through spatial sensing, surface deformation, and examples that leverage pressure-based input for one-handed and even bimanual interaction.

One-Handed Mobile Interaction

Karlson et al. surveyed 228 mobile users to capture detailed information about mobile usage patterns [9]. Of the 18 common mobile activities defined, 9 were performed more often with one hand, 6 more often with two hands, and 3 with either. Overall, 45% of users recorded they used one hand for most interactions as compared to only 19% for two-handed users. Task type often dictated handedness: 14% of users used one hand for simple tasks and 63% reported they used two hands when it was the only way to complete a task.

User preference results, however, suggested that users overwhelmingly wanted to use one hand exclusively. Overall, 66% stated they would prefer primarily one-handed interaction, 9% preferred two-handed, and 23% did not have a preference. Also, many of the users who preferred one-handed interaction only adopted two-handed usage patterns if the application absolutely required it. These findings indicate that one-handed mobile operation is common, is preferred, and should be appropriately supported.

Grasp-based Interaction

Taylor et al. [12] examined how mobile devices can implicitly infer the user's intention from grasp. They presented Graspables, a hardware and software platform that detects how a user is holding a device. Orientation and hand position is implicitly sensed and the most relevant interface representation is displayed. If the user holds the mobile like a camera, the photo capture software is displayed. Graspables senses the structure of the grasp and infers the user's most likely activity. Unifone, on the other hand, uses individual finger input instead of grasp-based sensing.

Similarly, Song et al.'s MTPen prototype wraps a capacitance multi-touch sensor around a pen to detect gripping gestures during drawing tasks [20]. Unlike Unifone, the grip is used implicitly to initiate different drawing modalities and an interaction vocabulary that varies by grasp.

Augmented Mobile Interfaces

Rekimoto's use of tilt [16] in handheld interaction is an early example of augmenting devices with spatial sensors. With one hand, a user can express inclination in three degrees of freedom. This allowed users to use tilt input to navigate menus, browse large maps, and select targets in pie menus. Informal evaluation showed that users could use tilt input very accurately if appropriate visual feedback was available.

Similarly, Harrison et al. [6] explored more general embodied mobile interactions. They designed three handheld prototypes that mimicked real world metaphors by sensing tilt, corner touches (to simulate page turns), and handedness. With these prototypes, users were able to scroll lists using tilt, turn virtual pages like a book, and automatically pad annotation margins depending on which hand they used. Although no evaluation of these interactions was discussed, feedback from user explorations suggested users were able to easily transfer existing knowledge of real world manipulations to an augmented handheld device.

Hinckley et al. [7] showed how multiple sensors (e.g. proximity, touch, tilt) could infer a user's context. In many ways, this work outlines common interactions available in modern mobile devices: using orientation to rotate between portrait and landscape, using proximity to modulate screen power, and recognizing when the device is shaken. Hinckley et al. also show how sensor fusion enables rich embodied gestures. In the Voice Memo application, multiple sensors determine when the user is holding a mobile like a stage microphone. Tilt sensors, in combination with knowledge of the user's grasp, trigger a recording when the mobile is tilted toward the user's face. Informal user studies suggested completing this embodied interaction required less cognitive and visual effort than on screen controls.

Although Hinckley et al.'s sensors enable rich interactions, it does not register input on the mobile's back surface. Baudisch et al. [1] explored how pointing can be supported on tiny screens using the back of the device. Small screens, like watch-sized displays, are often difficult to operate as

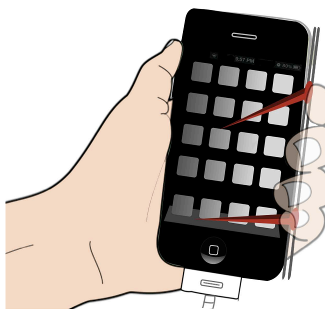

Figure 2. In this Unifone concept, the middle, top, and bottom areas of the right most edge have pressure-sensing areas that yield a target region (sensors indicated in red). The auxiliary fingers wrap around and generate isometric pressure input.

the pointing finger occludes screen content. Evaluations showed that front side target selection failed for screens under 1 inch. However, back-side interaction performed well, independently of display size. Baudisch argues how this generalizes to other types of target selection techniques, like back-of-device interactions that rely on two-handed interactions [24]. The non-dominant hand stabilizes the devices using a minimal grasp and the dominant-hand points on the back-side. This is difficult to support in one-handed usage scenarios.

In most of the previous work, interaction rarely takes place beyond the mobile's surface. Although Hinckley et al. [7] sample proximity to an object, they do so to make implicit assumptions about the mobile's context of use, a result alternatively achieved by Strachan et al.'s use of muscle tremor to determine grasp [21].

Butler et al. [3], however, embed infrared proximity sensors along both edges of a mobile. Detecting presence and position of fingers on both sides, they supported common mobile gestures like pointing, panning, and zooming. They also explored multi-modal gestures that leverage the non-dominant hand: in an annotation task, the user pans right and left with the non-dominant hand while marking with the dominant. Although this approach is conceptually similar to Unifone's emphasis on non-dominant interaction, it differs in two ways: (1) the mobile phone must be placed on a flat surface to work and is, by design, less generalizable and (2) the input device does not distinguish unique fingers.

More recently, Saponas et al.'s [19] PocketTouch enables interactions through fabric layers. Using a flexible capacitive multi-touch sensor, finger strokes are detected through a textile, affording more graceful management of notifications when a mobile is stowed.

Deformable Mobile Interactions

Although augmented and embodied interaction has been actively explored, mobile deformation is increasingly receiving attention [8, 11, 15]. Gummi [17] is a design concept that envisions deformable interaction techniques contained in a thin, bendable, credit card sized display. Gummi explores these bendable interactions using a physical prototype that mimics the feel of a flexible display.

PaperPhone [10] uses a flexible electrophoretic ink display to afford a gesture vocabulary centered on the deformation of a mobile's shape. A user scrolls through a list of contacts, for example, by bending a corner of the display. Unlike Unifone's focus on unimanual grasp, both Gummi and PaperPhone require either a symmetric or asymmetric bimanual grasp to operate their respective prototypes. Although Unifone's style of auxiliary input might be useful for bending the perimeter of a deformable display, understanding the design implications for rigid versus flexible interaction requires further research.

Pressure-Based Interaction

For a larger form factor, Ramos et al.'s [13] investigated the use of continuously sensing pressure input to operate multi-state interface widgets on a tablet device. Although they present a taxonomy for the design of pressure sensing widgets, it is focuses only on the use of a stylus for fine-grained input manipulations.

For mobile form factors, Wobbrock et al. [26] show the benefit of isometric pressure input; using two isometric joysticks, one on the front and one on the back of a device, a gestural text entry method is designed that achieves comparable words-per-minute to Multitap and T9. In a similar space, Shi et al. [18] examine discretization functions that map continuous pressure levels to discrete input events. Using a pressure sensor placed along the side of a mouse, they found fisheye-based mappings [18] can discretize continuous pressure input while increasing accuracy without compromising speed. This approach, however, assumes a fine-grained sensor manipulation by the thumb. The coarser and more limited movement of the auxiliary input of the fingers might not be able to operate a fisheye-based mapping with the same performance.

Blaskó et al. [2] leverage fine-grained manipulations of four pressure-sensitive strips on a small pad, ones that are mapped to a large number of interactions. Although effective for direct manipulation, it is uncertain whether the same effectiveness can be achieved by the non-dominant hand while grasping a mobile device. As well, Watanbe et al.'s "Bookishsheet" [22] interface, although effective at using pressure input to simulate a book like interaction metaphor, does not clearly translate to a one-handed scenario.

UNIFONE CONCEPT

We envision Unifone as a typical mobile device, one that is augmented with points along its edge that that are capable of sensing isometric pressure input (Figure 2). Although we imagine this sensing directly integrated into its industrial

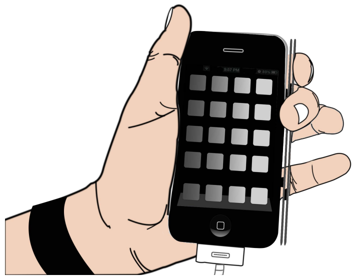

Figure 3a. Top Squeeze Gesture: The user positions the index and middle fingers near the top corner of the mobile. Typically, the other fingers are not raised (the pinky is shown extended for clarity).

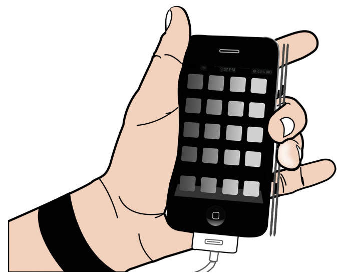

Figure 3b. Middle Squeeze Gesture. The middle and ring finger are positioned around the middle of the device and push inwards.

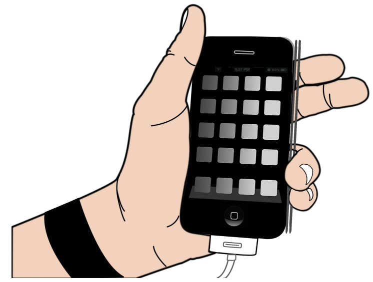

Figure 3c. The ring and pinky finger squeeze the bottom corner inwards.

design, we prototype it using a force-distributed pressure sensing metal attachment made of two separated aluminum planks. These planks house two pressure sensors at each end that, when compressed, allow three areas—top, middle, and bottom—to sense input. This transitions a precisely located button into a target *zone*, a shift that enables *coarse* input controls that are (1) ergonomically calibrated for the expressiveness of each user's auxiliary fingers and (2) afford imprecise targeting within each calibrated zone.

Even though the prototype could be built to support bimanual gestures, we have designed the interactions for one-handed use. User feedback from early design iterations were in line with Karlson et. al's [8] observation that most user's adopt (and prefer) one-handed strategies whenever possible. Looking beyond convenience as an explanation, this behavior fits with Guiard's Kinematic Chain (KC) theory [5]. Guiard saw the hands as links in a serially assembled kinematic chain, with the non-dominant hand as an anchor and the dominant hand as the terminal link. The non-dominant hand executes coarser manipulation and provides the context for the action of the dominant hand. The sequence of motion during bimanual manipulation is non-dominant followed by dominant. For mobile interaction, this suggests the following behaviors: (1) users will reach for the phone with their non-dominant hand and (2) a task will terminate at the non-dominant hand if it can be achieved with a coarse level of control (in unifone's case, the thumb). Karlson's finding that users often employ two-handed strategies when a corresponding one-handed solution does not exist supports these observations.

In early design iterations, we explored a range of subtle and complex gestures that could be controlled with coarse manipulations. We created a keyboard application that discretized the squeeze gesture into three levels that trigger either a space, period, or uppercase letter. The top two corners were used to move the cursor forward or backward. Although users could, after training, type with little error, most complained that this interaction felt unnatural. We suspect that users lacked an appropriate metaphor to describe complex auxiliary interaction and had to recall the gestures. There is a risk in a gesture language that is prohibitively complex for mobile scenarios.

Motivated by this, we moved away from modal gestures. Instead of overloading a gesture, like the squeeze in our early typing task mentioned, Unifone treats deformations as quasimodes [10]. A quasimode is a mode change that is maintained by some persistent action of the user, like capitalizing a letter using the Shift Key of a keyboard. In Unifone's case, the manipulation of isometric input yields analog information that is more expressive than a button press.

Auxiliary Touch Gestures

To support quasimodal auxiliary finger gestures, we focus on three key gestures.

- *Top Squeeze*. Unlike the squeeze, this corner push is focused 2cm around the top right corner of the device and performed by the index finger (see Figure 3a).
- *Middle Squeeze*. The enclosure of the user's grasp is used to press the mobile's edge inward along its vertical axis. This gesture is easiest to complete when the mobile is placed squarely in the user's hand. However, squeezes 3cm *around* the middle axis are supported (see Figure 3b).
- *Bottom Squeeze*. A bottom corner squeeze is performed by the ring and pinky finger, or both, 2cm around the corner. (see Figure 3c).

Each of these gestures has the natural position of a user's grasp in mind. They can also be chorded: it is theoretically possible that a user might squeeze the middle and top corner at the same time. Chording, however, is particularly difficult for users to complete as some gestures generate sensor crosstalk (and that is why they are avoided in this design).

INTERACTIONS

Our set of interaction techniques are motivated by those commonly found in mobile interaction. We designed four interaction techniques that augment the thumb's action:

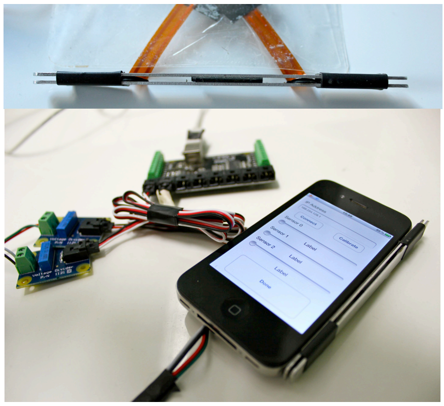

Figure 4. The Unifone prototype: two aluminum planks house two pressure sensors attached to an iPhone 4S. A Phidgets Interface Kit, attached to a Desktop computer, acquires the pressure data. The pressure data is streamed to Unifone over a dedicated wireless network connection.

1. *Scroll*. In thumb-only scrolling, the thumb is used to scroll a viewport and select targets. In Unifone, the *middle squeeze* gesture is used to augment the thumb by dampening and, if squeezed firmly enough, halting the scrolling. In a physics-based scrolling interaction, like that of the iPhone, this affords a larger range of motion in the thumb and, ultimately, a wider scroll extent; using a middle squeeze to halt scrolling means that the thumb does not have to touch the device's display as frequently.

2. *Navigate*. When using a map application in a one-handed scenario, navigating zoom levels is typically achieved by overloading taps (i.e. double taps zooms in). Using Unifone, a user zooms in using a *bottom squeeze* and zooms out using *a top squeeze*. This allows the thumb to focus exclusively on panning and targeting.

3. Context Menu. A *middle squeeze* is well suited for contextual quasimodal gestures. Depending on what item the thumb has selected, squeezing the device transitions the interface to a contextual menu. For example, if a piece of text is selected while composing an email, a middle squeeze could curl up the bottom right corner of the interface screen to reveal font settings (e.g. bold, italics, and underline). This is achieved with thumb-only input by using a dedicated interface button, something that takes up additional screen real estate.

4. *Switching*. With limited display size, mobile interfaces often distribute applications across multiple screens, running in the background until switched to by the user. To move through running applications with Unifone, for example, the user performs a *middle squeeze* to reveal the running applications and then swipes to the necessary application, before releasing the squeeze to indicate a selection.

USER STUDY

The goal of the study was to measure Unifone's impact on task completion in frequently used one-handed thumb interactions. Users completed tasks with Unifone gestures and the thumb (thumb+unifone) or just the thumb. We measured the task completion time of five tasks that correspond to Unifone's use as a direct, supportive, continuous, and discrete input device:

1. *Direct Scroll* (Direct & Continuous). The user scrolls through a list of 100 ordered numbers in a single column. At the top of the screen, a text label specifies the target number. To shorten search times, the target number is highlighted red in both conditions. Upon finding the number, the user touches it with the thumb. In the thumb condition, the thumb scrolls the list up or down. In the thumb+unifone condition, the top squeeze gesture scrolls up and the bottom squeeze gesture scrolls down. In both conditions, acceleration is matched: the maximum acceleration using the thumb and the thumb+unifone's pressure base input are the same.

2. *Halted Scroll* (Supportive & Continuous). The previous scrolling task actually counters Unifone's design goal of supporting the thumb's primary behavior via coarse auxiliary finger input. For the purpose of comparing a direct and supportive interaction, Unifone's middle squeeze is used to slow down and halt scrolling. The thumb condition is the same as the previous task. The thumb+unifone condition is identical, yet the middle squeeze slows and, once fully pressed, halts altogether. In both tasks, the target number is also highlighted in red.

3. *Map Navigation* (Supportive & Discrete). In this task, users target on a two-dimensional map application by locating, translating and zooming until selecting a target city on a map. In the thumb+unifone condition, users zoom in one level using a bottom squeeze and zoom out one level using a top squeeze. The thumb translates and pans until the city full occupies the viewport and, by doing so, indicates a selection. In the thumb condition, the thumb also translates position. However, single finger input is overloaded; users zoom in one level by double tapping and zoom out one level by triple tapping. We chose not to deviate from Unifone's single-handed usage scenario, as early user tests affirmed overloading tapping was suitable for this task (instead of bimanual gesturing).

4. *Context Menu* (Supportive & Discrete). In this task, the user selects and formats a single word in a chunk of text. A text label asks users to "Set word to bold." To shorten search times, the target word and text on the formatting button is highlighted red in both conditions. In the thumb condition, the user touches the target word with the thumb, and then the 'formatting' button to reveal a context screen contains the formatting settings. The screen peels and reveals the bold, italics, and underline buttons in the bottom right corner. The user then touches the appropriate formatting button. In the thumb+unifone condition, the

screen peel is triggered by the middle squeeze gesture. This gesture is released to confirm the formatting selection.

5. *Switching* (Supportive & Discrete). In this task, users switch between a set of running applications. In the thumb condition, the user taps the screen to see a zoomed view of running applications. The user scrolls through the applications horizontally with their thumb. When the target application is found, the user touches the screen. In the thumb+unifone condition, the squeeze gesture triggers the zooms view. The user scrolls through the application using their thumb and lets go of the squeeze to select the target application.

Experimental Design

We used a within-subjects design, with two independent variables for each task: input type (thumb vs. thumb +unifone) and target distance. Target distance is a term that encompasses a target's configuration in each of the five tasks, e.g. for scrolling, target distance implies variable length of vertical scrolling, while for context switching (formatting), target distance implies different positions of the target word in a paragraph. There were five tasks that were repeated in five trials for each condition. The tasks were structured using a latin square and order of input type was balanced across subjects. Our dependent measure was task completion time. At the start of the study, users were familiarized with Unifone. While seated in a chair, they were presented with a screen that displayed each sensor's feedback and were asked to perform each gesture until they were comfortable with these interactions. All users were able to learn and perform Unifone's gesture easily. No high level details about Unifone's application to mobile interaction were provided. Before each task, users completed a training phase. On the mobile device, users were presented with a text instruction screen that instructed them how to complete the task. Verbal instructions were only provided if the users needed additional help understanding the text instructions. The training was repeated until subjects could complete five trials successfully. Also, as we are evaluating the Unifone interactions in one-handed mobile applications where the thumb performs the same target selection in all conditions, we define an error to be a trial that exceeds a practical time limit or where the user verbally states they do not want to finish the task. This is more inclusive to the thumb+unifone condition and measures how long it takes to complete each trial; overshooting or mis-selections are not considered errors.

Apparatus

The Unifone prototype consists of three components: an iPhone 4S, a metal attachment, and two pressure sensors (see Figure 4). The pressure sensors (#IESF-R-5L from CUI Inc.) measure a maximum pressure of 1.5Pa that corresponds to 1024 unique levels at 5.0 Volts using a 10bit ADC. Two sensors are mounted at each corner and are suspended between two thinly spaced aluminum planks.

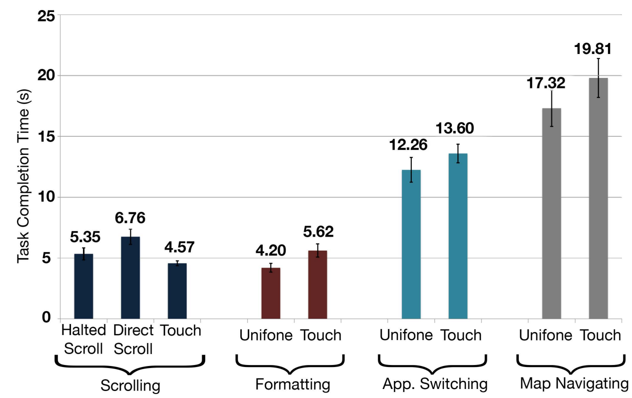

Figure 5. Task completion times (s) for scrolling, formatting, application switching and map navigating tasks with thumb+unifone and thumb-only input.

These planks extend the pressure sensors beyond a focused point and, using only two sensors, enable a middle squeeze gesture to be detected. Without this force-distributed design, it is difficult to achieve ergonomic comfort across a range of users.

Each sensor is connected to a Phidgets Interface Kit that is controlled using a Macbook Pro. Sensor values are pushed to the iPhone 4S over a local Phidget Server and a dedicated wireless network connection. When operating Unifone, there is no perceivable lag to the user. A one-time calibration controls the sensitivity of the pressure sensors: this is to prevent natural movements from falsely being recognized as a gesture and also setting the maximum sensor values for each squeeze gesture to be inline with the user's grasp.

The experiment software application was created in the Cocoa Touch development framework. It operates on the device as an iOS application. The testing software manages the operation, ordering of tasks, recording of data, and all other quantitative activities of the user study.

Participants

10 participants (6 male, 4 female) between the ages of 20 and 36 were recruited from a pool of friends and colleagues at Queens' University

Mean subject age was 24.67 years. All subjects owned one of an iPhone, iPod Touch, touched operated BlackBerry, or Android multi-touch phone. All subjects were right handed. Average hand size was 17.22 cm and measured across the top of the palm. Average time spent using computers was 14 hours per week. All subject had university or advanced degrees.

Results

To measure the performance of Unifone's interaction techniques, we selected four tasks commonly performed on a mobile device: scrolling, application switching, text formatting (revealing a contextual menu), and navigating a map. Overall, users completed all tasks within each practical time limit and did not withdraw from any task.

Scrolling task: We analyzed the measures collected by performing a two-way repeated measures factorial analysis of variance (ANOVA) using *input type* (3) and *target distance* (5) on task completion time. The three input types were: *halted scroll* and *direct scroll* for thumb+unifone design, and thumb input (i.e. touch) exclusively. For task completion time, the analysis showed that both *input type* ($F(2, 22)=6.11$, $p<0.05$) and *target distance* ($F(4, 44)=15.36$, $p<0.001$) were significant. Pairwise post-hoc tests with Bonferroni corrected comparisons between input types reveal that touch was significantly faster than both *direct scroll* and *halted scroll*. Mean task completion times for *direct scroll*, *halted scroll* and touch input were 5.35, 6.76 and 4.57 seconds respectively (Figure 5, scrolling).

Formatting task: Similar to the scrolling task, we performed an ANOVA using *input type* (2) and *target distance* (5) on task completion time. Unlike the scrolling task, the formatting task had one thumb+unifone condition that was compared to thumb (i.e. touch) input. The analysis showed a significant main effect for *input type* ($F(1, 9)=8.58$, $p<0.05$). Thumb+unifone condition was significantly faster than touch input, mean task completion times for thumb+unifone and touch input were 4.20 and 5.62 seconds respectively (Figure 5, formatting).

Application switching: An ANOVA using *input type* (2) and *target distance* (5) on task completion time. This task had one thumb+unifone condition that was compared to thumb (i.e. touch) input. We found that there was a significant effect of *input type* ($F(1, 9)=5.89$, $p<0.05$) and *target distance* ($F(4, 36)=156.26$, $p<0.001$). Thumb+unifone condition was significantly faster than touch input; mean task completion times for thumb+unifone and touch input were 12.25 and 13.6 seconds respectively (Figure 5, app. switching).

Map navigation: Similar to the previous tasks, a two-way repeated measures factorial analysis of variance (ANOVA) was performed using *input type* (2) and *target distance* (5) on task completion time. The two input types were: thumb + unifone, and thumb input (i.e. touch) exclusively. For task completion time, the analysis showed that both *input type* ($F(1, 9)=5.47$, $p<0.05$) and *target distance* ($F(4, 44)=135.00$, $p<0.001$) were significant. Thumb+unifone condition was significantly faster than touch input; mean task completion times for thumb+unifone and touch input were 17.32 and 19.81 seconds respectively (Figure 5, map navigating).

DISCUSSION

The results suggest that auxiliary finger input, when used to control isometric gestures, can improve the performance of thumb-only interaction. Initially, the direct scrolling that was strictly controlled through top and bottom squeeze gestures performed 28% slower than thumb-only input. However, when the fingers were adjusted to dampen or halt the thumb's scrolling behavior, it performed only 17% slower than thumb-only scrolling. This result is likely due to users placing their thumb on the top left corner of the device to stabilize their grasp while performing a middle squeeze, a behavior frequently observed. Even though this level of stabilization is not actually required to perform a middle squeeze, we suspect the user's natural inclination towards minimizing even mild pressure between the fingers and hands produces this behavior. It is likely that users are not accustomed to the inward reciprocal pressure experienced in their palm during a squeeze gesture (a force that is counteracted by placing the thumb on the corner). This could also be complicated by a mental model that expects a mobile to be perfectly still while operating

Unlike thumb-only scrolling, regrettably, this places the thumb far away from the target and effectively decouples the synchronization between the thumb and auxiliary fingers. We argue that with a better industrial design, perhaps a pressure sensing apparatus that is directly integrated into a mobile's form, it is possible to minimize this thumb displacement device movement in the user's hand and, ultimately, see better results.

However, for the tasks that required displaced movement of the thumb (formatting, application switching, and map navigation), Unifone performed better than thumb-only tasks. The formatting task was 25% faster than thumb-only, application was 9.8% faster, and map navigation 12.5% faster. The performance gain is also from restricting the thumb to necessary movements only. When switching applications using Unifone, there is a seek time to find and press the button that initiates the application switching. By offloading these types of controls to auxiliary input and simplifying their operation using discretized pressure input, the thumb is free to position itself for more important, fine-grained tasks.

Design Guidelines

Motivated by these results, we provide the following design principles:

Principle 1: Auxiliary input is supportive. The thumb is naturally positioned as a mobile display's pointing device. Using the fingers to directly control interaction, on the other hand, adds a layer of indirection to this fine-grained input control. This also decouples the haptic and visual feedback that takes place when the thumb guides interaction. Therefore, the remaining fingers should act as secondary controls that extend the thumb's behavior.

Principle 2: Auxiliary input is coarse. The fingers are extremely poor at providing fine-grained input and even ergonomically targeting precise positions. In the scrolling task, many users had a slower performance using Unifone as a continuous input device, mainly because of the level of precision it required. The simpler manipulations, like performing a middle squeeze to trigger application switching, are more practical by the very fact that they require less precise targeting. Given the limited range of motion of the auxiliary fingers, designing for coarse interaction is preferred and supporting input *zones*—instead of exact target locations—is critical.

Principle 3: Auxiliary input is a quasimode. Early design iterations showed that chorded pressure-based gestures with multiple discretization levels [18] were frustrating to users. Although pressure as an input channel is expressive, a complex gesture requires training, dexterity, and memorization. Thus, the complexity of modal operations can be avoided by treating pressure as a simple quasimodal input state. If multiple levels are used, as it is in the halted scrolling task, it should be mapped across a continuum of the same dimension.

Principle 4: Couple auxiliary input. Although quasimodal deformations simplify interaction, they also cause tension in the user's grasp and limit the thumb's movement. In the map navigation task, the top and bottom squeeze gestures guided the thumb's position around the center of the display. In the halted scroll, users moved their thumb to the side of the display to stabilize the phone's movement. Therefore, quasimodal gestures should be brief, should pay close attention to their relationship with the thumb, and be carefully designed to conform to the user's mental model and expectation of physical motion as they grasp and manipulate a device. Of course, this relies on an appropriate industrial design, one that minimizes this potential tension between the thumb and fingers when performing Unifone's gestures.

CONCLUSION & FUTURE WORK

We present the design and evaluation of Unifone, a hardware prototype that investigates the use of squeezable gestures in a mobile device. Using an iPhone 4S and pressure sensors, we evaluated how one handed isometric gestures influence four common mobile interactions. Overall, Unifone shows that gestures that augment the behavior of the thumb perform best. In future work, we will integrate pressuring sensing directly into Unifone. Casting a pressure sensing silicon mold, one that is impregnated with carbon black, could reduce the force required to perform Unifone gestures.

REFERENCES

1. Baudisch, P., Chu, G. Back-of-Device Interactions Allows Creating Very Small Touch Devices. In Proc. of CHI 2009. Boston, Massachusetts: ACM Press, 2009.
2. Blasko, G., and Feiner, S. Single-Handed Interaction Techniques for Multiple Pressure Strips. In Extended Proc. of CHI 2004. 1461-1464.
3. Butler, A., Izadi, S., and Hodges, S. SideSight: multi-"touch" interaction around small device. In Proc. of UIST 2008. 201-202.
4. Fitzmaurice, G. Situated information spaces and spatially aware palmtop computers, Communications of the ACM, Special issue on Augmented Reality and UbiComp, July 1993, 36(7), p.38-49.
5. Guiard, Y. Asymmetric division of labor in human skilled bimanualaction: The kinematic chain as a model. Journal of Motor Behavior 19, 4,1987, pp. 486-517.
6. Harrison, B. L., Fishkin, K. P., Gujar, A., Mochon, C., and Want, R. Squeeze Me, Hold Me, Tilt Me! An Exploration of Manipulative User Interfaces. In Proc. of CHI 98. 17-24.
7. Hinckley, K., Pierce, J., Sinclair, M., Horvitz, E. Sensing Techniques for Mobile Interaction. In Proc. of UIST 2000. 91-100.
8. Holman, D., and Vertegaal, R. Organic User Interfaces: Designing Computers in Any Way, Shape or Form, Communications of the ACM, June 2008.
9. Karlson A., Bederson B., and Contreras-Vidal, J. Understanding One Handed Use of Mobile Devices. In Handbook of Research on User Interface Design and Evaluation for Mobile Technology. Information Science Reference, 2008, pp. 86-101.
10. Lahey, B., Girouard, A., Burleson, W. and R. Vertegaal. PaperPhone: Understanding the Use of Bend Gestures in Mobile Devices with Flexible Electronic Paper Displays. In Proc. of CHI 2011, ACM Press, 2011.
11. Lee, S. et al. How users manipulate deformable displays asinput devices. In Proc. CHI '10. 1647-1656.
12. Taylor, B., and Bove Jr., V. M. Graspables: Grasp-Recognition as a User Interface. In Proceeding of CHI 2008. Boston, Massachusetts: ACM Press, 2009, pp. 917-925.
13. Ramos, G., Boulus, M., and Balakrishnan, R. Pressure Widgets. In Proc. of CHI 2004. 487-494.
14. Raskin, J. The Humane Interface: New Directions for Designing Interactive Systems. Addison-Wesley Publishing. 2000.
15. Rasmussen, M., Pedersen, E., Petersen, M., Hornbæk, K. Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions, CHI'12, (2012), 735-744
16. Rekimoto, J. Tilting Operations for Small Screen Interfaces. In Proc, UIST 96. Seattle, ACM Press, 1996.
17. Schwesig, C., Poupyrev, I., and Mori, E. Gummi: A Bendable Computer. In Proc. of CHI 2004. 263-270.
18. Shi, K., and Irani, P., Gustafon, S., and Subramanian, S. PressureFish: A Method to Improve Control of Discrete-Pressure-based Input. In Extended Proc. of CHI 2008. 1295-1298.
19. Saponas, T. S., Harrison, C. and Benko, H. 2011. PocketTouch: Through-Pocket Capacitive Touch Input. In Proc. of UIST '11. 303-308.
20. Song, H., Benko, H., Guimbretière, Izadi, S., Cao,Xiang, Hinckley, K. Grips and Gestures on a Multi-Touch Pen. Proc CHI'11, 1323-1331.
21. Strachan, S., Murray-Smith, R. Muscle Tremor as an Input Mechanism. In Extended Proc. of UIST 2004.
22. Watanbe, J., Mochizuki, A., and Horry, Y., Bookissheet: Bendable Device for Browsing Content Using the Metaphor of Leafing Through the Pages. In Proc. of UbiComp 08'. 360-369.
23. Weiser, M. The Computer for the 21st Century.Scientific American, 1991, 265 (3), pp. 94- 104.
24. Wigdor, D., Forlines C., Baudisch, P., Barnwell, J., and Shen, C. LucidTouch: A See-Through Mobile Device. In Proc. of UIST 2007. Newport, Rhode Island, USA. ACM Press.
25. Wigdor, D., Balakrishnan, R. TiltText: Using Tilt for Text Input to Mobile Phones. In Proc. UIST'03. 81-90.
26. Wobbrock, J., Chau, D., and Myers, B. An Alternative to Push, Press, and Tap-tap-tap: Gesturing on an Isometric Joystick for Mobile Phone Text Entry. In Proc. of CHI 2007. 667-676.