INVESTIGATING NEW FORMS OF SINGLE-HANDED PHYSICAL PHONE INTERACTION WITH FINGER DEXTERITY

by

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This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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STATEMENT OF CONTRIBUTIONS

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The following list serves as a declaration of the works included in this dissertation. This material is expanded and revised from the original publication.

Portions of Chapter 3:
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Portions of Chapter 4:
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1 https://authors.acm.org/author-resources/author-rights. Accessed on May 9th, 2023

ABSTRACT

With phones becoming more powerful and such an essential part of our lives, manufacturers are creating new device forms and interactions to better support even more diverse functions. A common goal is to enable a larger input space and expand the input vocabulary using new physical phone interactions other than touchscreen input. This thesis explores how utilizing our hand and finger dexterity can expand physical phone interactions. To understand how we can physically manipulate a phone using the fine motor skills of finger, we identify and evaluate single-handed "dexterous gestures". Four manipulations are defined: shift, spin (yaw axis), rotate (roll axis) and flip (pitch axis), with a formative survey showing all except flip have been performed for various reasons. A controlled experiment examines the speed, behaviour, and preference of manipulations in the form of dexterous gestures, by considering two directions and two movement magnitudes. Using a heuristic recognizer for spin, rotate, and flip, a one-week usability experiment finds increased practice and familiarity improve the speed and comfort of dexterous gestures. With the confirmation that users can loosen their grip and perform gestures with finger dexterity, we investigate the performance of one-handed touch input on the side of a mobile phone. An experiment examines grip change and subjective preference when reaching for side targets using different fingers. Two following experiments examine taps and flicks using the thumb and index finger in a new two-dimensional input space. We simulate a side-touch sensor with a combination of capacitive sensing and motion tracking to distinguish touches on the lower, middle, or upper edges. We further focus on physical phone interaction with a new phone form factor by exploring and evaluating single-handed folding interactions suitable for "modern flip phones": smartphones with a bendable full screen touch display. Three categories of interactions are identified: only-fold, touch-enhanced fold, and fold-enhanced touch; in which gestures are created using fold direction, fold magnitude, and touch position. A prototype evaluation device is built to resemble current flip phones, but with a modified spring system to enable folding in both directions. A study investigates performance and preference for 30 fold gestures, revealing which are most promising. Overall, our exploration shows that users can loosen their grip to physically interact with phones in new ways, and these interactions could be practically integrated into daily phone applications.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

QUOTE

"Man is the most intelligent of the animals because he has hands."

– Anaxagoras

1 INTRODUCTION

Phones have become increasingly powerful and are universally used in daily life. They integrate basic functions of many other electronic devices, such as a camera, a portable television, and even a laptop. In scenarios where portability and contextual use are important, phones could even replace such devices. In order to better support such a diverse range of functions and to make phones easier to use in different scenarios, manufacturers have created new device form factors, such as foldable [173, 177, 178], surround display [170], slidable [169], and new kinds of interactions, such as squeezing [106] and gripping [29]. These form factors and interactions can enable a larger input space (a set that comprises all potential interactions for input) and expand the input vocabulary (a set of input methods such as gestures, voice commands, and others).

Touch input remains the dominant form of phone interaction and manufacturers have increased phone size to enlarge the touch screen size. However, when the size becomes almost the same as a tablet, the phone's mobility begins to decrease. Novel interactions different from touch input, such as moving input off the screen to the side [53, 134, 154] or to the back [20, 24, 80], or adding gestures like knuckle knocks [122] have been explored to provide extra commands. These enable simple and direct commands using current phone factors. We believe how we interact with phones will play a critical role in the design of future phone form factors.

We define *physical interaction* as input that results from physical contact with a phone, such as touching [6, 20], gripping [30, 50], and whacking [56], or direct physical manipulation of the phone, such as moving [116], bending [36], and shaking [52]. On the other hand, there are interactions that do not require physical contact (i.e. voice input, in-air gestures [131], around device gestures [15]), do not use body movements (i.e. camera commands, gaze [91]), or are not related to phone content (i.e. using phone as a mediator to control other devices like a large display [127] or when used as an AR camera [27]). These are not considered as physical interactions in the context of this thesis. We place physical interactions into four categories: (1) touch input such as tap, swipe, touch and drag, and press; (2) off-screen input such as back-of-device gestures, side touch input, squeezing, pushing buttons, and grip detection; (3) motion gestures such as tilting, rotating, shaking, and knocking; and (4) deformable interactions such as folding, sliding, and detaching.

When performing physical phone interactions, the gripping posture serves an important role. The interaction scope composed of physical phone interactions and grip type is illustrated in Figure 1.1. The gripping postures to interact with the phone can be described in two categories, static grip or dynamic grip, with the main difference whether users change the grip or not. As in previous examples, many physical interactions are performed with a

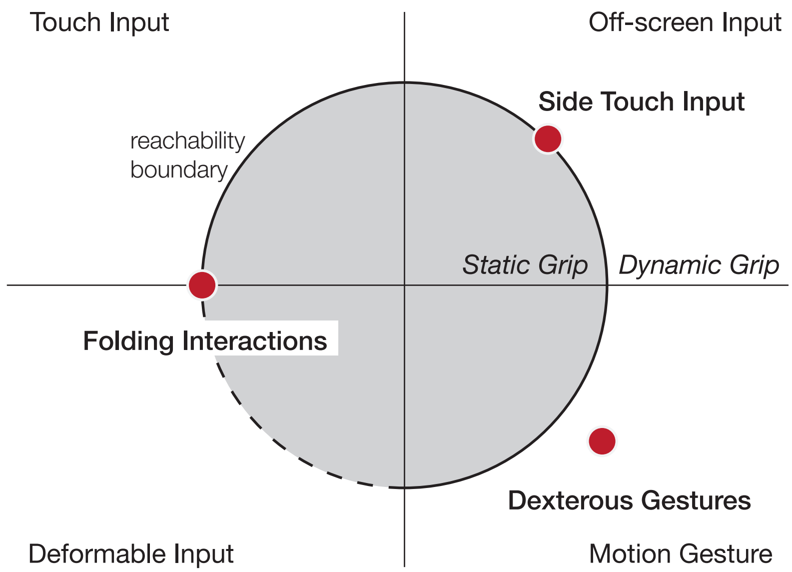

Figure 1.1: The scope of physical phone interactions. Four categories are described: touch input, off-screen input, motion gestures, and deformable input. Within each category, interactions can be described by whether the grip is changed or not.

static power grip [95] in which the hand firmly grasps the phone (the gray area in Figure 1.1). Opposite of a static grip, dynamic grips requiring finger dexterity can be used while performing physical interactions. This loosens the grip to manipulate an object's position and orientation primarily using smaller finger muscles to perform fine movements. The boundary between using a static grip and dynamic grips is often described as "reachability", especially within the touch input category [8, 74, 92]. The touch area that users can reach without changing the grips is preferred and thus called the comfortable area. However, the boundary may be less clearly defined within other physical phone interactions, especially for deformable input. Users would more likely change their grips according to the deformed device. We aim to enable more ways to physically interact with our phones through dynamic grips and reachability without the constraint of a static grip.

In this thesis, we present our exploration of possible forms of physical interactions with finger dexterity. The proposed interactions are plotted in a conceptual interaction scope (Figure 1.1). We first propose dexterous gestures that utilize dexterity to perform finger-based motion gestures. The goal is to understand users' ability and preference to loosen the grip and manipulate a phone. We then build a simple heuristics-based recognizer using IMU (Inertial measurement unit) rotation data that identifies 12 different dexterous gestures to demonstrate the possible practical applications.

Second, we investigate how users touch the side of phones with different fingers, and discuss the reachability with user preference and grip stability. We then explore the two-dimensional side touch input based on the most reachable areas with specific fingers. Applications are developed to show how we can move the input space off-screen to expand the input vocabulary.

Third, we explore folding interactions with modern flip phones, and propose a gesture space that can combine touch and fold input. We examine how users perform these folding gestures and their subjective ratings with a hardware sensing prototype. We summarize the design recommendations, and create mock-up applications to demonstrate how these gestures could be used.

1.1 RESEARCH OBJECTIVES AND OVERVIEW

The high-level research objective of thesis can be stated as:

Investigate the performance and user preference of new forms of single-handed physical phone interactions that utilize finger dexterity, and explore the possible applications.

We investigate these proposed physical phone interactions in different defined categories (illustrated in Figure 1.1). A series of research questions are examined within three categories. Overview of the questions and flow of the methodological steps are shown in Figure 1.2.
The first category of questions reveals users' previous experience to physically manipulate their phone with finger dexterity:

(a) Do people already loosen their grip and perform dexterous manipulations with their phones?

The second category of questions investigates how well can users perform the proposed gestures and their preference:

(b) How well can users perform different types of dexterous gestures and what are their perceptions and preferences? Can users improve their ability to perform dexterous gestures after one-week of practice?

(c) What is the preference regarding comfort, and grip stability when reaching different phone side locations with different fingers? Which fingers and which side area is most suited for side touch input?

(d) How well can users perform different types of folding interactions, what are their preferences, and how do they change the grip to perform them with modern flip phones?

The third category of questions explores the gesture space, prototypes that enable such interactions, and possible applications:

(e) Can dexterous gestures be reliably detected using only current built-in sensors of phones? What applications are there for dexterous gestures?

(f) How well can different kinds of taps and flicks be performed on the side when two dimensional sensing is possible?

(g) What applications are suitable for folding interactions?

To answer these research questions, we use a multi-step methodology (shown in Figure 1.2).

1. To answer question (a), we conduct a formative study in the form of a questionnaire with self-guided tasks to understand previous experiences and preferences for dexterous manipulations.

2. To answer question (b), we first conduct a controlled study to determine the speed of dexterous gestures, how participants perform them, and their preferences. We then conduct a one-week experiment to further examine the performance, preference, and usability of dexterous gestures after users gain more familiarity and practice.

3. To answer question (c), we conduct a reachability study to understand preference and ability when reaching for locations on the sides of a phone. We investigate every finger of the dominant hand and three representative phone mock-ups in various sizes. Ease and comfort rating and relative grip stability are used to measure the reachability.

4. To answer question (d), we conduct a controlled study to examine the speed of fold gestures, how many errors participants would make, their preference, and observe what grip and hand movement strategies they use to perform the gestures.

5. To answer question (e), we create an Android prototype with a rule-based recognizer based on sensor patterns collected in the study for question (b). To evaluate the recognizer, we perform off-line false positive evaluation with the H-MOG [129] and Extrasensory [144] datasets, and a real-time accuracy study. We develop potential applications making use of dexterous gestures with the Android prototype.

6. To answer question (f), we investigate thumb and index tapping and flicking along a two-dimensional side touch input space which is summarized from the study for question (c). We conduct two controlled studies to examine the preference and performance of side tap and flick gestures with a phone instrumented with capacitive sensors and optical motion tracking to determine the touch location.

7. To answer question (g), we built a hardware sensing prototype to demonstrate and evaluate the proposed folding interactions. We implemented simulated applications using the sensing prototype with the graphical user interface rendered in the Processing application.

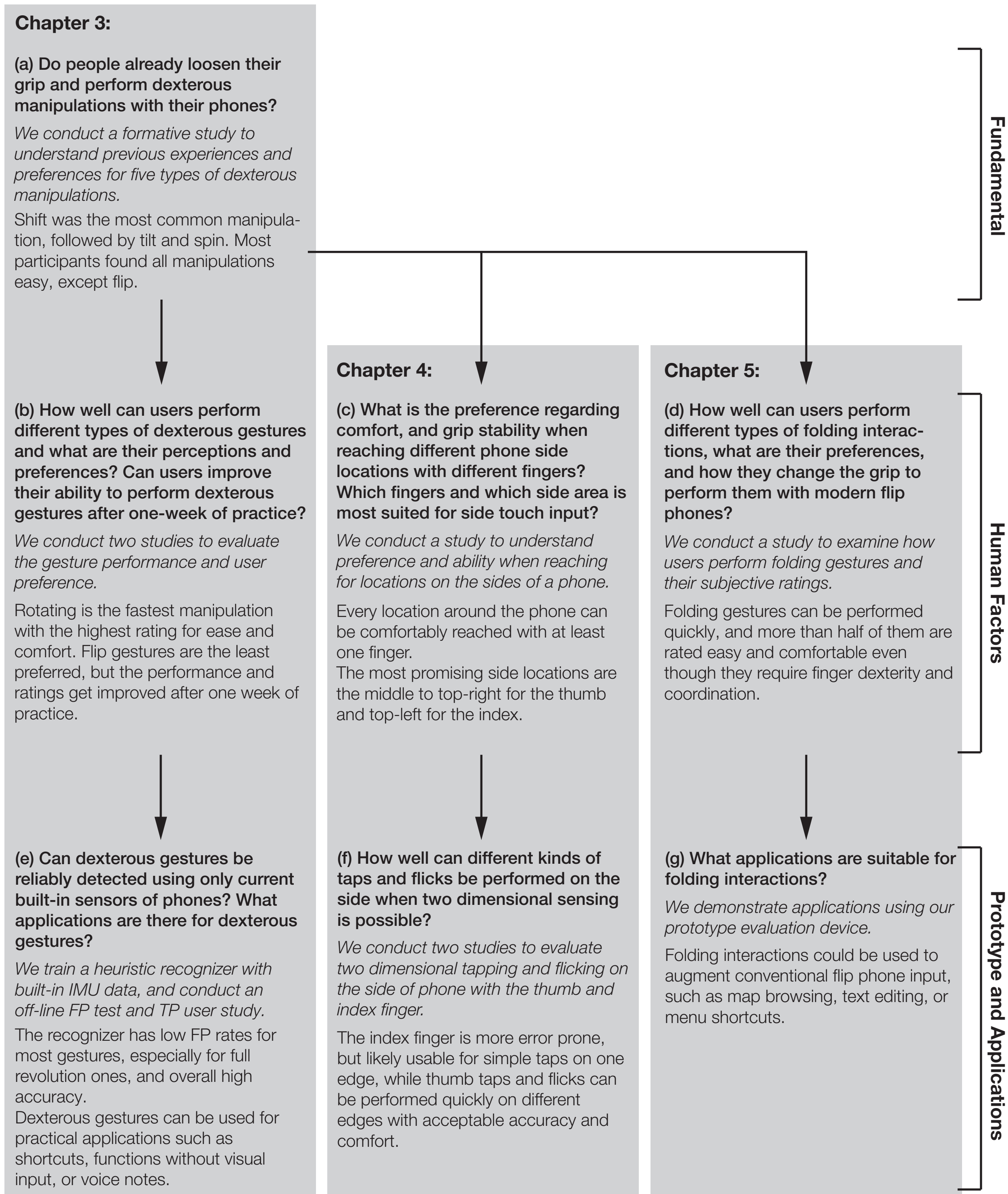

Figure 1.2: Research path showing research questions, methodology, and main results. Bold text is the research question statement; italic text is the research methodology applied; and the final block of text is the primary results that form the contributions.

1.2 CONTRIBUTIONS

We summarize the research contributions by project. For each, we outline the key results that form our contributions.

1.2.1 *Dexterous Gestures*

In chapter 3, we use a multi-step methodology to examine four dexterous phone manipulations. In the formative study with a self-guided questionnaire, we find people have some experience with these manipulations, especially for shifting manipulations. We conducted a controlled experiment to understand how well users can perform specific dexterous gestures, and what their preferences are. The results show rotating is fastest and most preferred, then spinning and flipping. A heuristic recognizer for spinning, rotating, and flipping gestures is developed with overall low false positive rates and high accuracy. To investigate how users gain more familiarity with these three gestures after one week of practice with real-time recognition, a three-phase usability study is conducted. We find gesture speed and acceptance increase for all gestures after practice. Finally, we demonstrate applications that can make use of dexterous gestures, such as declining an incoming call, opening a shortcut, or controlling widgets.

1.2.2 *Side Touch Input*

In chapter 4, we investigate the performance of one-handed touch input on the side of a mobile phone. A study is conducted to examine comfort and grip stability to reach different side locations with different fingers. We find that virtually any location around the side of a phone can be reached with at least one finger assuming some grip change, and index and thumb are the most capable and stable fingers when reaching along the left and right sides. These results are used to ground our exploration of an expanded side touch input space. We investigate the comfort, speed, and accuracy of this input space using the index and the thumb for tapping and flicking. The results show index finger taps are more usable when considering simple taps on one edge. For thumb taps and flicks, they can be performed quickly on different edges with acceptable accuracy and comfort.

1.2.3 *Folding Interactions*

In chapter 5, we explore folding interactions for modern flip phones. Three types of manipulations are defined: only-fold, touch-enhanced fold, and fold-enhanced touch. Across these, 30 gestures are derived based on fold direction, fold magnitude, and touch location. We conduct a study to examine how users perform these gestures and their preference with a created evaluation prototype. The results show users can perform more than half of folding gestures comfortably and quickly, and they prefer ones that do not require pronounced grip changes or finger stretching, such as touching a location easily in reach of the thumb then folding the top section inward. However, we find subjective ratings are likely influenced by how participants hold and manipulate the phone, suggesting the need to allow users to customize gestures and input mappings. We demonstrate potential applications such as editing text, browsing maps, or activating shortcuts with the sensing prototype.

1.3 DISSERTATION OUTLINE

The remainder of this document is structured as follows:

In Chapter 2, we establish the overall research area with a summary of relevant background literature pertaining to physical phone interactions including touch input, off-screen input, motion gestures, and deformable interactions.

In Chapter 3, we describe an interaction space that utilizes finger dexterity to manipulate a phone. We discuss the results of gesture performance and subjective ratings, and evaluate the proposed recognizer based on IMU sensor data. We also provide design guidelines and demonstrations to suggest the practical usage of proposed interactions.

In Chapter 4, we explore the utility of an off-screen touch input space on the side of a mobile phone. We first present a study to understand how users change their grip to reach different side locations and ask for their relative preference. We then evaluate a two-dimensional side touch space using a simulated sensing prototype, and discuss the design implication, example applications, and limitations.

In Chapter 5, we explore single-handed folding interactions with a modern flip phone. We present a prototype evaluation device and discuss the performance and preference of different kinds of folding gestures. To demonstrate how folding interactions could be incorporated into flip phone interfaces, applications such as map browsing, text editing, and menu shortcuts are described.

In Chapter 6, we further discuss our proposed interactions, describe the difficulties we faced to implement and test them, then sketch out a possible interaction prototyping system for physical phone interaction design.

In Chapter 7, we revisit the proposed research questions, and draw overall summary conclusions.

2 BACKGROUND LITERATURE

In this chapter, we review previous research related to physical interactions with phones within four defined categories: touch input, off-screen input, motion gestures, and deformable interactions.

2.1 TOUCH INPUT

Touch input is the dominant form of phone interaction. However, the input space is limited by the touch screen size and preferred within the reachable area. Many methods to enhance touch input and increase the touch input vocabulary have been purposed, such as menu-based gestures, bezel gestures and multi-step touches.

Menu-based Gestures

To enhance touch input, one of the most direct ways is to combine multiple swipes into one gesture, such as menu-based stroke gestures. For example, hierarchical marking menus gestures [165] were proposed for menu selection tasks. A sub-layer menu appears after each stroke and users can perform one- or multi-stroke gestures to select the desired menu item. Variations of marking menu gestures may be generated by utilizing the relative position [164] and the curvature [4] of strokes, along with the stroke orientation. To further improve user performance and reduce the stroke length, the Wave Menu was proposed to adjust the menu interface while drawing the stroke [3, 34] (Figure 2.1(a)). Zheng et al. [166] also introduced a fixed grid menu layout to increase interaction space stability. These menu-based gestures can minimize the gesture space which are more efficient to perform in small-screen phones.

Bezel Gestures

The location of touches alone can be used to differentiate with normal touch input, especially the starting position of swipe. A bezel swipe [114] is a cross-selection gesture which starting in bezel area of phone. It can be used to perform tasks such as selection, copy, and paste. Inspired by bezel swipe, more bezel-initiated gestures are proposed. Bragdon et al. [13] propose bezel mark and bezel path gestures which start the mark and free-form path gestures on the bezel. These gestures are considerably fast and can be performed eyes-free. The Bezel Menu [59] uses bezel mark gestures to support two-layer menu design. Thirty-two menu shortcuts are proposed with eight bezel starting locations and four directions of marking gestures. BezelCursor [81] combines bezel-initiated gestures with swiping movement to invoke a virtual cursor

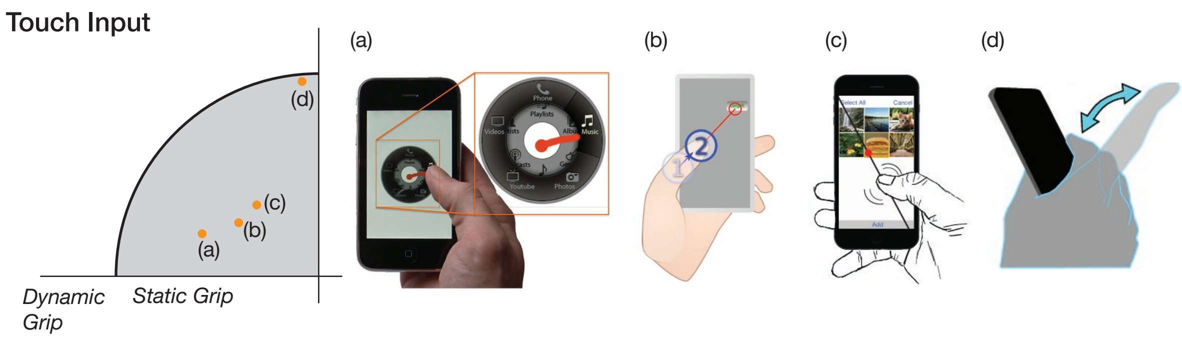

Figure 2.1: Examples of touch input: (a) Wavelet Menus [34]; (b) BezelCursor [81]; (c) ForceRay [21]; and (d) Yusuke Sei et al. [124]. Note: We examine how users perform such gestures with paper figures or videos, select ones for single-handed interaction, and plot into our scope definition.

to select a distant on-screen target. Results show that less grip adjustment is needed (Figure 2.1(b)). To understand the design space of bezel-initiated gestures, Li et al. [82] conducted an elicitation study. The results derived gesture variations from various factors, such as starting location, path length, swipe direction, or touch speed.

Multi-step Touches

Extended sequences of finger or phone movement can be used to enhance touch input. Shift [150] was proposed to address finger occlusion. Occluded content would appear near the tapping location so users can perform a following drag gesture to fine tune the intended touch point. Touch with force can be used for menu shortcuts, target selections, and increasing reachability [21–23, 55]. For example, ForceRay [21] utilizes a force sensor to extend touch input within the comfort zone of thumb. A virtual ray is cast to reach out-of-reach targets according to touch force and movement direction (Figure 2.1(c)). The movement of idle fingers can serve as a secondary input. Touch can also act as a modifier or an anchor, for example with gestures such as using idle fingers to tap the screen [44], touch across a radial target [85], tap or swipe on the touching finger [83], or perform around-device gestures [77, 124] (Figure 2.1(d)).

2.2 OFF-SCREEN INPUT

Other than touch input interactions, one general approach is to move input off the screen to other space of the phone. Examples include sensing back-of-device gestures, side input, and various forms of grip detection.

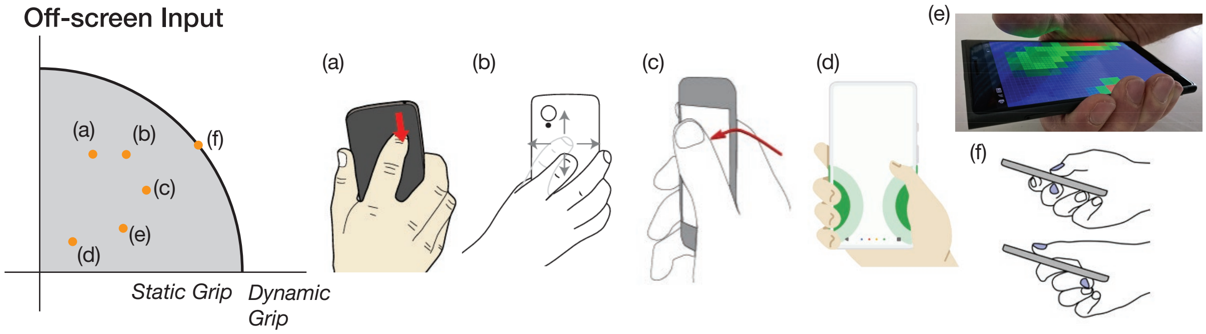

Figure 2.2: Examples of off-screen input: (a) Luca et al. [24]; (b) Le et al. [77]; (c) Spelmezan et al. [133]; (d) Active Edge [106]; (e) Hinckley et al. [50]; and (f) InfiniTouch [75]. Note: We examine how users perform such gestures with paper figures or videos, select ones for single-handed interaction, and plot into our scope definition.

Back-of-device Gestures

The back surface of a phone is the second largest space other than the touch screen, and it has been shown to be suitable for idle fingers to perform gestures. Touching the back surface can solve the finger occlusion problem and thus enable a smaller phone form factor [6]. Luca et al. [24] use a sequence of shape gestures on the back to unlock the device to reduce the chance of a successful shoulder surfing attack (Figure 2.2(a)). They found this authentication method is secure and can be performed quickly. By simplifying the shape gestures to taps, Leiva and Català find that back-of-device taps are twice faster and more useful [80]. Back-of-device interactions can also support the front touch input. Corsten et al. [20] add a pressure sensing screen on the back to enable back-of-device press interactions. They find users can distinguish three levels of pressure with high accuracy while maintaining front touch accuracy. Applications such as pressing the back to switch the keyboard for text input, change actions in games, and filter information in ranges are proposed. Le et al. [77] explore gestures on a phone with all surfaces touch sensitive when performing text editing tasks. Gestures such as swiping or circling on the back of device with single or multiple fingers can be used to move the caret, select words, copy, cut, and paste text (Figure 2.2(b)).

Side Input

Previous works have proposed different interactions on the side of the phone housing. These differ from bezel-initiated gestures [13, 114] which may be near the side, but are performed physically and conceptually on the edges of the front screen.

Perhaps the most direct way to expand side input is with more expressive physical buttons. For example, PseudoButton [58] uses pressure levels captured by a microphone to create a five-level side button. Further extending how a side button can be used, Spelmezan et al. [133] create a side button that can detect six different mid-air gestures (Figure 2.2(c)). Even more radical, Jang et al. [60] describe a Haptic Edge Display for bi-directional haptic and tactile interactions along the side of a phone using a row of button-like actuated pins.

Several works explore adding pressure sensors to the side of a phone for grip-based interactions. Unifone examines ways to use pressure on top, middle, and bottom side locations with fingers other than the thumb [53]. Spelmezan et al. use thumb and palm pressure for bidirectional navigation [134]. Wilson et al. use different combinations of finger presses for input similar to chording [154]. More recently, Quinn et al. [106] examine sensing and usability when squeezing a phone for input. They use a sensor that can localize a one-dimensional position of the squeeze along the side (Figure 2.2(d)). Side touch can be considered complementary to grip input, since it uses more precise single finger touches instead of high force multiple finger touches.

Several works focus on sensing methods for one-dimensional side touch input. BackPat [125] distinguishes finger taps on the side (or back) using the built-in microphone and gyroscope. McGrath and Li [93] use the internal motion-sensor to detect side taps. ExtensionSticker [63] extends a standard touch sensor to adjacent surfaces using adhesive stripes of conductive ink, and demonstrates touch-based slide and scroll gestures. InfiniTouch [75] uses front and back touch sensors, and one-dimensional capacitive side sensors to detect touch input all over a phone, including three sides (Figure 2.2(f)).

Grip Detection

Detecting how users grip a phone in their hand can form an explicit input method or be used to adapt the UI accordingly. Kim et al. [68] use an array of touch sensors with a pattern recognition algorithm to identify the grip and predict the intended phone usage, such as giving a call, sending a text, and taking a photo. HandSense [155] adds capacitive sensors on the side of a phone to distinguish six different grasping gestures and adjust the UI according to user handedness. IGrasp [18] changes the keyboard layout on mobile devices by detecting the grasp. Hinckley et al. [50] use self-capacitance touchscreen to sense the fingers above the screen and grip around the screen edges. They show how grip plus hover interactions can be used to control a widget or trigger a menu (Figure 2.2(e)). Eardley et al. [28, 30] investigate grip shifting and phone movements associated with factors such as different grip gestures, body postures, and phone sizes. They apply those insights to create new screen-based interactions such as changing the placement of buttons on the screen according to handedness, tilting the screen based on physical position, and adding a trackpad for selecting or scrolling [29].

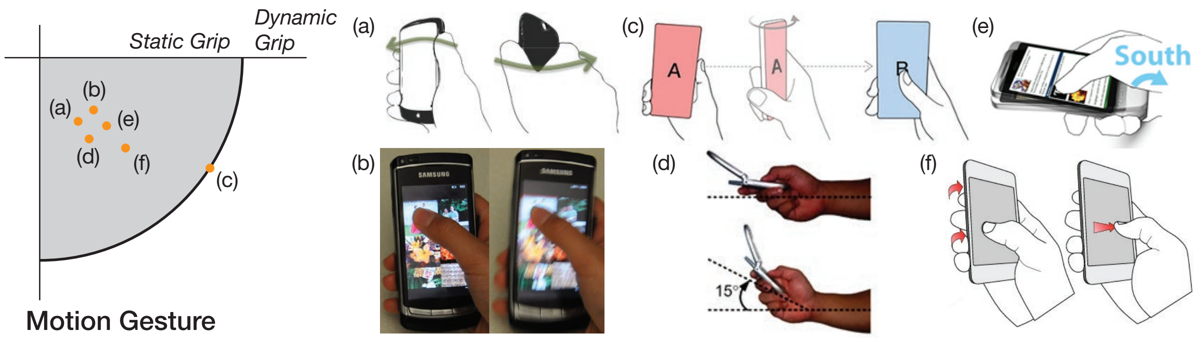

Figure 2.3: Examples of motion gesture: (a) DoubleFlip [115]; (b) Hinckley and Song [52]; (c) Yang et al. [157]; (d) Rahman et al. [107]; (e) Baglioni et al. [2]; and (f) Tsandilas et al. [142]. Note: We examine how users perform such gestures with paper figures or videos, select ones for single-handed interaction, and plot into our scope definition.

2.3 MOTION GESTURES

Motion gestures are interactions in which users intentionally move the device to issue commands.

By utilising IMU sensor data from the mobile device, motion gestures can provide direct and simple operations. Different than touch input, motion gestures can be performed without visual feedback easing demands on user attention. Hudson et al. [56] propose whack gestures, firmly striking the palm or heel of the hand onto the phone. This interaction is detected by recognizing the gross movements of device. DoubleFlip [115] creates an unique and always-active motion gesture by quickly rotating the wrist until the screen of the phone is facing away from the user and back to the original position with the screen of the phone facing the user (Figure 2.3(a)). Ruiz et al. [116] conduct an elicitation study of motion gestures for mobile interaction. Gestures such as shaking, rotating, quickly moving a phone back and forth in a particular direction, or moving a phone close to a specific location were defined and recommended. Hinckley and Song [52] combine touch and motion gestures and described two interaction spaces, touch in motion and motion in touch. Example touch-enhanced motion techniques include tilting the device to zoom relative to the touch position, shaking the device while touching an icon to apply a command (Figure 2.3(b)). Motion-enhanced touch techniques include tapping harder on the screen to distinguish from normal tapping. Yang et al. [157] used an elicitation study to examine methods to switch between front and back screens on dual-display phones. Among user proposals, there were single-handed motion gestures to turn the phone along the roll axis and a method to roll the phone in the hand using the fingers (Figure 2.3(c)).

Tilt-based interaction

Tilt-based interaction is a type of motion gesture based on the orientation of the phone. Many phone input methods use some form of tilting, such as tilt-based gestures for scrolling [5], selecting text [16, 153, 161], navigating list menus [46, 51, 98, 109], and sharing documents with other devices [47]. A well-known example was originally proposed by Hinckley et al. [51], where tilting a phone to the side changes the interface orientation between portrait and landscape. Rahman et al. [107] analyse the design space of tilting gestures when considering wrist dexterity. Multiple levels of control along the three axes of wrist movement are tested (Figure 2.3(d)). The results show that users can accurately perform 12 levels along the flexion to extension direction and 16 levels along the pronation to supination direction with a quadratic control-display function for tilt angle. With different tilting directions, Baglioni et al. propose eight quick back-and-forth gestures depending on device acceleration [2] (Figure 2.3(e)). To study the performance of tilt as continuous input, MacKenzie and Teather use a Fitts' law task [88] with parameters including tilt gain, which is used to control the speed of cursor, and two selection methods, first-entry and dwell [89]. The results show a tilt gain between 50 to 100 $\frac{px/s}{degrees}$ is optimal for time and throughput, and first-entry selection is faster.

Combining touch input with tilting gestures, Du et al. [26] demonstrate how large physical 3D space displacement can be calculated by extending touch movement with phone orientation. Tsandilas et al. [142] also enhance navigation with motion tilt and directional touch (Figure 2.3(f)). The direction of navigation gestures can be recognized from the direction of the tilt and the direction of the touch drag. The results show that most users can simultaneously control the movement of tilt and drag, and the gestures combining tilt and drag along the same direction are more accurate and highly preferred.

2.4 DEFORMABLE INTERACTIONS

Sturdee and Alexander [137] describe *shape-changing interfaces* as physically geometric dynamic computational systems with tangible input and output. They identify eight categories of prototypes from eighty-four shape-changing interfaces, including enhanced 2D, bendable, paper and cloth, elastic and inflatable, actuated, liquid, malleable, and hybrid. Boem and Troiano [11] focus on deformable input methods. They define deformable interfaces as devices made of soft and malleable materials that require physical input that cannot be performed with rigid interfaces. We define deformable interactions according to the categories of Sturdee and Alexander, and primarily focus on bendable, foldable, reconfigurable, and malleable phones.

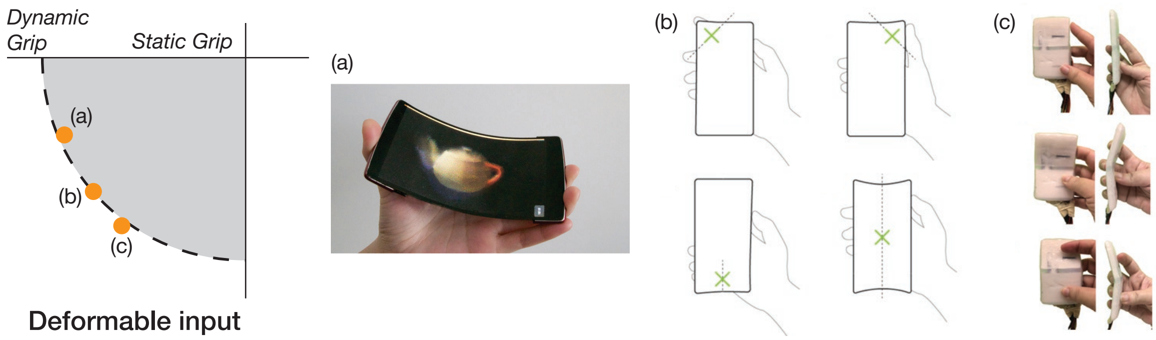

Figure 2.4: Examples deformable input: (a) HoloFlex [43]; (b) Girouard et al. [36]; and (c) Kirshenbaum and Robertson [69]. Note: We examine how users perform such gestures with paper figures or videos, select ones for single-handed interaction, and plot into our scope definition.

Bending

Bendable, even paper-like interactions have been explored with flexible displays and sensors, and mechanical structures. Gummi [123] is a working prototype of a bendable computer that supports four bending events for map browsing, text input, and menu selection. Paperphone [71] presents a paper phone and studies possible bend gestures over twenty actions in five applications. Six most frequently used bend gesture pairs are identified, including bending up or down the side of display, and bending up or down the top or bottom corners. The bend gestures can only be performed within one side of the proposed phone due to hardware limitations. Papertab [139] creates a paper-like tablet to enable bending manipulations. Bending different locations, like a corner or edge, can trigger different commands. Morephone [39] proposes shape-changing notifications with an actuated flexible phone. An actuated deformation such as full screen bends or corner bends are used to give visual feedback for things like answering a voice call or reading emails. Reflex [136] enhances bending with active haptic feedback to create new interactive experiences. Studies using the device show haptic feedback can also improve the accuracy of bend input. BEXHI [99] creates a mechanical structure for prototyping a bendable device. It features tiles that can be bent in two directions to enable interaction such as panning a map with bending gestures.

Bend input on a phone has also been used in different scenarios, such as 3D applications [43] (Figure 2.4(a)), audio manipulation [41], and gaming [84]. Girouard et al. [36] study one-handed bend input for a flexible smartphone prototype. Four bend gestures are evaluated according to bend location including bending on the top-right corner and squeezing to form a trough-like vertically centred bend (Figure 2.4(b)). Kirshenbaum and Robertson [69] study bend events for a simplified one degree-of-freedom bendable device. Seven events, like bending start, bending peak and bending threshold, and three gestures, including in-neutral, in-forward bend, and in-backward bend, are formalized with identification methods (Figure 2.4(c)). Examples of applications that detect bending time and level according to bend events are illustrated. Using a fully flexible screen, Magicscroll [40] introduces a rollable device with two configurations, rolled-up and extended. It can support motion gestures when rolled as a cylindrical shaped phone and content viewing when unrolled flat as a tablet display.

Folding

There are differences between bending and folding interactions. Sturdee and Alexander define bending as deforming a surface, and fold gestures as a specific subset in which the surface noticeably creases [137]. Bending can also be defined as forcing the straight surface to a curved one, while folding as laying one part over another part.

A foldable device can support touch input on the front and back of the device while folded, continuous input by sensing the folding angle, and of course, an expanded display when unfolded. Paperfold [42] studies the use of shape changes in a multi-segmented phone with reconfigurable electrophoretic display tiles. Fourteen kinds of shape changes, like folding the device in a portrait orientation, bending the displays inwards, and forming a cubic-like structure, are identified for applications like map viewing and text editing. Foldable3d [14] uses a dual-display device to investigate folding interactions for the exploration of 3D content. These include folding displays inwards or outwards to change the zoom level of the camera, folding the two screens to form an angle of 90° to enable model rotation and translation in 6 DOF, or to manipulate a clipping plane parallel to one of the displays. Multiplié [100] creates an accordion-fold interactive display to improve interaction in airliner cockpits. Two prototypes are created, one using four touchscreen devices and another using a pleated surface with projection. These are used to demonstrate interactions such as raising a fold to request an action or to warn of notable information at waypoints, depressing a fold to indicate action completion, and flatting the screen in front of the fold to display additional information for a waypoint. A simpler version of this general idea is proposed by Saniee-Monfared et al. [118] as a ”tent mode”, a convex configuration for a foldable device to enable multi-user interactions.

Reconfiguring

By splitting a device into pieces, reconfigurable devices can change their shape according to applications or enable multi-user interactions. Paddle [108] leverages existing manipulations of the Rubik’s Magic puzzle toy to prototype a deformable device with seven configurations. Physical controls such as peeking, scrolling, and leafing are supported. Seyed et al. [126] create a modular phone to make temporary device lending convenient. Three smartphones were combined into a single modular phone where each component can be independently replaced and used. Any module can be reconfigured and defined as the main phone to monitor the lending activity. Morphees+ [66] examines 82 reconfigurable everyday objects such as a Rubik's Cube, an umbrella, or sand to provide a better understanding of reconfiguration features when implementing similar functioning devices. Pickcells [38] proposes a fully reconfigurable device composed of small cubical cells and explores tangible and across-device interactions, such as an ad hoc remote control by snapping off cells, using cells to shape change when playing a game, or sharing files with a detached cell.

Twisting, Squeezing, Punching with Malleable Materials

Malleable materials such as clay or rubber can enable deformable input like twisting, squeezing, or punching. Follmer et al. [33] propose jamming user interfaces with programming control of material stiffness. A jamming system is developed to keep the deformation status of malleable materials like clay and enable deformable input with optical and electric field sensing. Interactions such as enabling an extra dimension for 3D modelling in a table-top system, or for back-of-device input on tablets are created. Teyssier et al. [140] integrate artificial skin on the back of phone to enable input gesures such as twisting, scratching, and punching. Capacitance readings from artificial skin were converted into multi-touch coordinates for gesture detection.

2.5 SUMMARY

This chapter covered input methods that physically contact with or manipulate a phone, including touch input, off-screen input, motion gestures, and deformable interaction. Most of these interactions can be performed with two hands or single-handed. People might use some levels of finger dexterity, the coordination of small muscles with finger movement, to perform gestures single-handed, especially with dynamic grips. For example, a one-handed pinch gesture is described with a thumb on the front screen and a predefined finger on the back [75] (Figure 2.2(f)). This gesture can be performed by shifting the thumb up against the predefined finger position. A single-handed flipping gesture can be used to turn a dual-display phone around to switch between front and back screens [157] (Figure 2.3(c)). Users can move their thumb and fingers on the back to tilt and regrasp the phone. When performing a deformable gesture, significant finger dexterity would be required to maintain phone stability. To bend a phone backward, users might change their grip and use their thumb and index finger to squeeze the phone [69] (Figure 2.4(c)). Our work builds on these physical interactions and further explores the possible input space when utilizing finger dexterity with dynamic grips. We describe these new interaction spaces, evaluations of human ability and preference, and implementation details for novel physical phone interaction in the following chapters.

3 PHONE SLEIGHT OF HAND: FINGER-BASED DEXTEROUS GESTURES FOR PHYSICAL INTERACTION WITH MOBILE PHONES

Our hands are remarkable when one considers the diverse ways we can grasp and manipulate objects. Aristotle and Anaxagoras even argue that human intelligence evolved due to the capability of human hands [90, 101]. When we interact with mobile phones, we already use a range of hand functions: from thumb input while gripping the phone, to physical interactions like squeezing [106], shaking, and wrist rotation [52]. Researchers have also proposed more elaborate types of input using wrist rotation (e.g. [2, 107, 161]) and motion gestures performed with the arm and wrist (e.g. [115, 116]). However, interactions proposed so far primarily use a power grip [95] in which the hand firmly grasps the phone during interactions, typically requiring muscular strength and producing larger movements in space.

We investigate an under-explored type of physical interaction that uses the opposite of a static power grip: a dynamic precision grip enabled by finger dexterity. By definition, dexterous manipulations include gross movements like juggling, but we focus on those that are decoupled from arm movement, i.e. *in-hand dexterous manipulations* [87]. This category uses a loose grip to allow object position and orientation to be manipulated primarily using smaller finger muscles for finer movements. In general, people have phenomenal ability to develop finger dexterity skills for activities such as playing musical instruments, specialized tasks in industry and healthcare, and crafts like knitting [103], but it is unclear if this innate human ability could also be used for phone interaction.

There have been limited demonstrations of in-hand dexterous gestures for input devices. For example, Soap [7] is a custom pointing device using mid-air manipulative gestures to interact with large wall displays, and MagPen [57] enables the detection of different dexterous pen-spinning gestures. With phones, Eardley et al. [28] note how people using a phone with one hand will loosen their grip to shift it down with finger movements when reaching far targets. Recently, Yang et al. [157] elicited ways to switch between front and back screens on a "dual-display" phone, finding some people loosened their grip to turn the phone over using a series of finger movements with the same hand. These works further motivate a systematic investigation into in-hand dexterous gestures for phone interaction to answer the research question: *"What is a general class of dexterous gestures for phone manipulation that are usable and acceptable to users"*. We imagine using this new style of interaction to trigger global or contextual actions, such as silencing a call, activating a voice assistant, or triggering a point-of-sale payment app (Figure 3.1). Such in-hand dexterous gestures would be complementary to power grip motion gestures since finger-based rotational movements likely have different

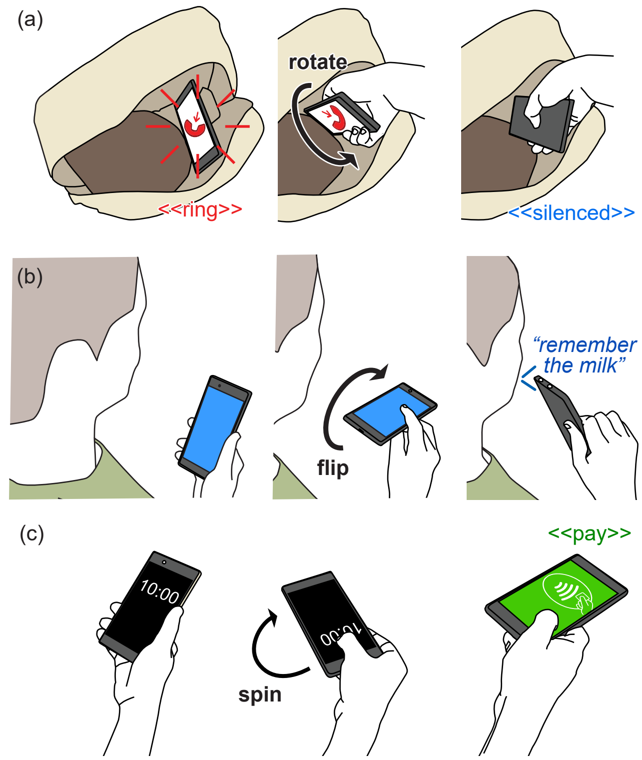

Figure 3.1: Examples of dexterous phone gestures: (a) half rotate for eyes-free actions, like silencing an incoming call; (b) half flip to activate a voice app, like note dictation; (c) half spin to open a dedicated app from the lock screen, like a point-of-sale payment.

motion characteristics, and importantly, since they are not limited by wrist range-of-motion, they enable full phone rotations.

In this chapter, we examine four dexterous phone manipulations: *shifting* by moving the phone up or down by "walking" the fingers; *spinning* by pinching the phone with one finger and the thumb and spinning it with the other fingers or using gravity; *rotating* by rolling the phone inside a loose grip; and *flipping* by turning the phone end-over-end by swapping fingers on the front or back of the phone. We use a multi-step methodology to understand how well users can perform those manipulations, what users' perceptions and preferences are, whether such interactions can be recognized algorithmically, and what kind of applications can make use of them. A formative study establishes people have some familiarity with these manipulations, and a controlled experiment measures their performance as well as gathers data to train a heuristic recognizer for spinning, rotating, and flipping. Finally, a three-phase usability study examines these three gestures after one week of practice with real-time recognition, and looks at differences in usage context like sitting versus standing. Our results show people can perform all types of gestures, with good recognition for spinning, rotating, and flipping. Rotating is fastest and most preferred, then spinning and flipping, with speed and acceptance increasing for all gestures with practice.

To summarize, we make three contributions: (1) a formal identification of in-hand dexterous manipulation as a novel class of physical phone interaction; (2) empirical evidence that a subset of in-hand dexterous gestures are practical in terms of user preference and performance; and (3) demonstrations showing in-hand dexterous gestures can be recognized reliably and used for a variety of practical applications.

3.1 background and related work

In the previous chapter, we explored a large body of work in which users intentionally move the device in space to issue commands. Different from touch input, motion gestures can be performed without visual feedback, easing demands on user attention. Our gestures also work on a commodity phone with IMU sensors, but instead of whacking or waving with gross motor skills, or making limited rotations with wrist-based movement, we explore a distinctly different interaction space when the phone is manipulated independently using finger dexterity. This enables a novel class of gestures not limited by the biomechanical constraints of wrist and arm movements as in previous work. Here, we further discuss other devices and contexts when considering previous applications of dexterity in HCI.

In-hand Manipulation

In-hand manipulations are a class of dexterous gestures when holding, moving, and manipulating an object with one hand. These are essential interactions used in daily activities such as writing with a pen or using chopsticks. ToolStone [110] is an input device that is rotated, flipped, and tilted using the non-dominant hand. Based on how the device contacts a tablet, different commands are triggered, like tool selection, 3D model navigation, and viewport selection. Van Laerhoven et al. [145] created a cube-shape device which can sense its orientation and movement with built-in accelerometers. Gestures such as shaking, twisting, and knocking were used for device control and navigation. Soap [7] is a pointing device created by placing an optical sensor core inside an elastic fabric hull. Although the device was used to remotely control a large display, it included a dexterous gesture consisting in rotating the core 360° in the hand, which is similar to our rotating manipulation. To support active reading, Yoon et al. [163] detect tablet grips and motions, including a "lateral swing" gesture when the tablet is passed to another user via a combination of top grips and rotation of the tablet. This gesture has similar characteristics to our spinning manipulation.

Dexterous gestures have been explored extensively for pens, such as tilting to select menu items [141] or reveal layers [49], rolling to scroll web pages [138], switch modes [10], acquire buttons [130], undo activities [49], or rotate graphical objects [10, 49]. MagPen [57] can sense different pen-spinning

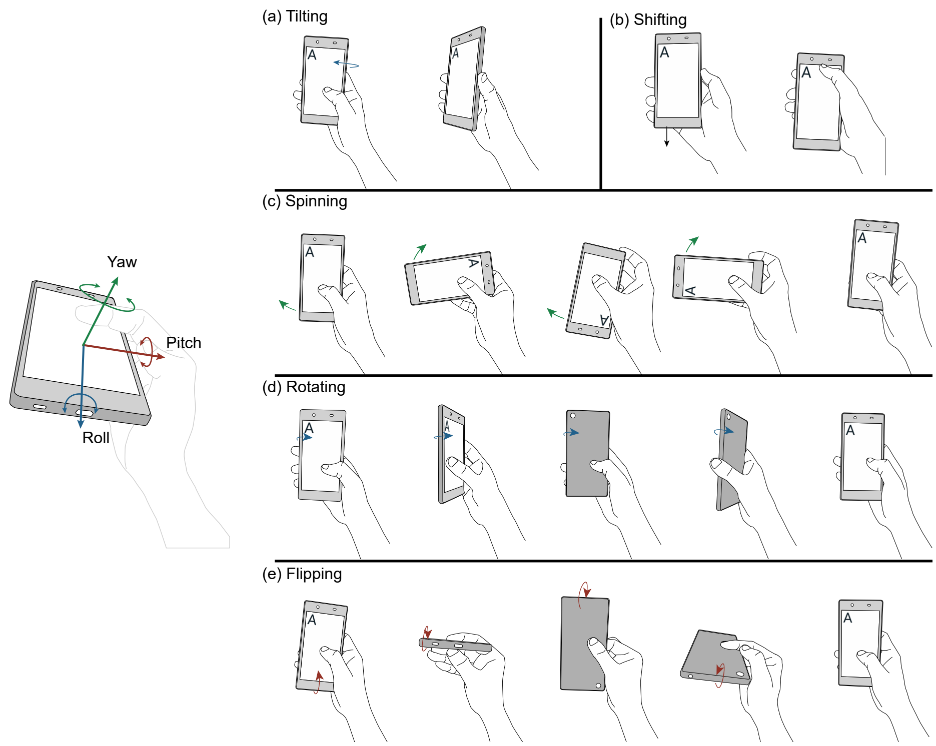

Figure 3.2: Types of dexterous finger manipulations with example variations: (a) *tilting*, showing a 'tilt left' variation, (b) *shifting*, showing a 'shift down' variation; (c) *spinning*, showing a 'spin clockwise 360°' variation; (d) *rotating*, showing a 'rotate right 360°' variation; (e) *flipping*, showing a 'flip away 360°' variation. Several manipulations can be described relative to the canonical pitch, yaw, and roll axes (shown at left).

and balancing gestures to trigger actions such as choosing ink properties and undoing strokes in a sketching application. Inspired by these dexterous techniques with other devices, we investigate extended forms of dexterous manipulations for use with a mobile phone.

In summary, previous work studied motion gestures with hand or wrist movements using phones, and dexterous object manipulations with pens or custom devices. Our work complements and significantly bridges these two spaces by exploring the new space of dexterous finger gestures for mobile phones.

3.2 DEXTEROUS MANIPULATIONS

Dexterous manipulations include a wide variety of actions. There are dexterous manipulations associated with moving objects in space, like those used in sports, magic acts, and circus performances. For example, juggling, tossing, twirling, and manipulating cards. An extreme application of this for phones was demonstrated in the ThrowMe phone app [174] in which a phone is tossed into the air to capture kinetic photos or bird's-eye view images. Balanced spinning on a single support point is another form of dexterous object manipulation. Book, plate, or ball spinning can be seen in tricks and circus performances. A more common example is how people spin a pen on the side of their hand. Although unusual, balanced single-point phone spinning can be performed with excellent skills, as demonstrated in social media videos [181].

Compared to those somewhat acrobatic acts requiring fine motor skills, in-hand dexterous gestures combining finger movements with support of the palm are likely easier to perform and therefore more suitable for everyday use. Popular examples include using a fidget spinner [180] and manipulating Chinese "Baoding balls" for exercise and stress relief [179]. Ma and Dollar [87] studied this type of dexterous manipulations for the purpose of encoding human hand dexterity into robotic hands. They defined six primary in-hand manipulative movements: regrasping, in-grasp manipulation, finger gaiting, finger pivoting, rolling, and sliding. Regrasping is a movement that momentarily releases the object followed by a quick "regrasp" in a modified position or orientation. In-grasp manipulation is a movement to make small changes to the object's orientation without removing the fingers. Finger gaiting is when the object is moved by replacing grasping fingers with free fingers in a cyclic alternating fashion. Finger pivoting is a manipulation while holding the object with two fingers and using other free fingers to rotate the object about the axis formed by the two finger points. Rolling is a movement to move the object by rotating it with a fixed pivot point. Sliding is a manipulation to move the object with a controlled slip. Our focus is on using these kinds of dexterous in-hand manipulations as explicit input for a phone. We define four new dexterous manipulations along with tilting, a simpler manipulation to use as a baseline (Figure 3.2):

Tilting is a type of "in-grasp manipulation" that changes the phone orientation similar to tilt-based interactions in previous work, but using only finger movements instead of the wrist. A typical sequence of finger motions is: grip the phone between the thumb, ring, and middle fingers, then use index and pinky fingers on the back or the top of the phone to tilt forward or backward; anchoring the side of the phone with middle, ring, and pinky fingers while moving the thumb up to tilt left; or anchoring the side of the phone with palm and thumb, then letting other fingers slide along the back of the phone to tilt right. Variations are defined using direction and angle, such as tilt right 90°, or tilt backward 45°.

Shifting translates the position of the phone relative to the palm along the *roll* axis. The motion typically uses the palm to support the phone while finger positions change in order to shift the device up or down in more than one step. A smaller shift can be achieved with "regrasping", where the phone is pushed up or pulled down with the fingers in one movement. The up or down direction is used to define variations.

Spinning circles the phone around the *yaw* axis using a "finger pivoting" dexterous movement. It is performed by pinching the phone with the thumb on top and index or middle finger at the back, then typically using the free fingers to spin the phone. For smaller spins in certain directions, gravity alone can be relied upon for the movement once the phone is pinched. Spinning variations can be defined using direction (clockwise or counterclockwise), angle (e.g., 90° or quarter turn, 180° or half turn, and 360° or full turn), and speed (slow or fast).

Rotating is circling the phone around the *roll* axis in the palm using "rolling" and "sliding" dexterous movements. We define it as an extended movement of the more common left and right variations of tilting manipulations. At the end of a left or right tilt, the side of the phone slides along the bottom of the fingers and palm until the screen is against the palm. Then the grip is adjusted in a regrasping motion, with the action repeated if needed. Variations include direction (right or left), angle (e.g., 180° or half turn, and 360° or full turn) and speed (slow or fast).

Flipping is circling the phone around the *pitch* axis using a form of "finger gaiting" movement. We define it as an extended movement of the more common forward and backward variations of tilting manipulations. At the end of a forward or backward tilt, the thumb and fingers are swapped from the front and the back of the phone. This is repeated as necessary for larger movement angles. Variations include direction (forward or away), angle (e.g., 180° or half turn, and 360° or full turn) and speed (slow or fast).

3.2.1 *Formative study*

We conducted a formative study in the form of a questionnaire with self-guided tasks to understand previous experiences and preferences for the five types of dexterous manipulations defined above. We hypothesized that tilt is simpler and more familiar, so we treated it as a baseline to compare with the four more elaborate dexterous interactions. The questionnaire was divided into three parts: (1) demographic information including phone size and hand size, (2) previous experience with dexterous manipulations, and (3) preferences after trying each manipulation in a self-guided task[1].

Participants

We recruited 30 participants (19 males, 11 females) through flyers, word-of-mouth, and social media on a volunteer basis without remuneration. Most participants (28) reported their phone experience as more than 6 years of daily use. Participants used 17 different phone models with screens from 4.7 to 6.5 inches and 25 participants used phone cases. The circumference of the palm of the dominant hand (i.e. "glove size" [175]) ranged from 16.5 to 26.2 cm.

1 See paper supplementary materials [159] for full study questionnaire and additional correlation analysis of phone weight, thickness, etc.

Procedure

Participants were asked to fill the questionnaire on a device other than their phone and to have their phone ready to try the manipulations.

In the experience part, each participant watched an animated demonstration of each manipulation and selected the ones they had done before, even if infrequently. For each manipulation they had previously experienced, participants were asked about frequency and reasons for doing them. For frequency, they were asked how often they performed the gesture on a daily, weekly, monthly, or less frequently than monthly basis. To explain why they performed a gesture, participants selected one or more reasons: reach specific location of the phone, change phone orientation, play games, fun, unintentional, and other.

In the tryout part, each manipulation was explained using a text description and animated demonstration similar to the previous part. Participants were instructed to hold their phone using a loose grip so that they could use the fingers of their dominant hand to manipulate the phone, with only the palm to support the device if necessary. Participants were asked to try to perform the manipulation shown in the animated demonstration, preferably over a soft surface such as a couch, a bed, or towels in order to avoid damaging their phone if accidentally dropped. The variations of manipulations tested were TILT in four directions with 45° to 90° magnitude, SHIFT up and down, SPIN, ROTATE, and FLIP in two directions with 360° magnitude. After each manipulation, participants were asked to rate their preference for ease and comfort on a 7-point Likert scale. The session required approximately 10 minutes.

Table 3.1: Participants' dexterous manipulation experience

		Tilt	Shift	Spin	Rotate	Flip
Total		20	26	16	13	4
Frequency	Daily	8	21	2	1	-
	Weekly	8	4	4	4	1
	Monthly	-	1	7	3	1
	Less frequently than monthly	4	-	3	5	2
Reason	Reach specific location of phone	6	22	-	-	-
(multiple choices)	Change phone orientation	12	5	3	1	-
	Play games	3	3	-	-	-
	Fun	1	2	5	3	1
	Unintentional	4	-	10	9	3
	Other	4	1	1	-	-

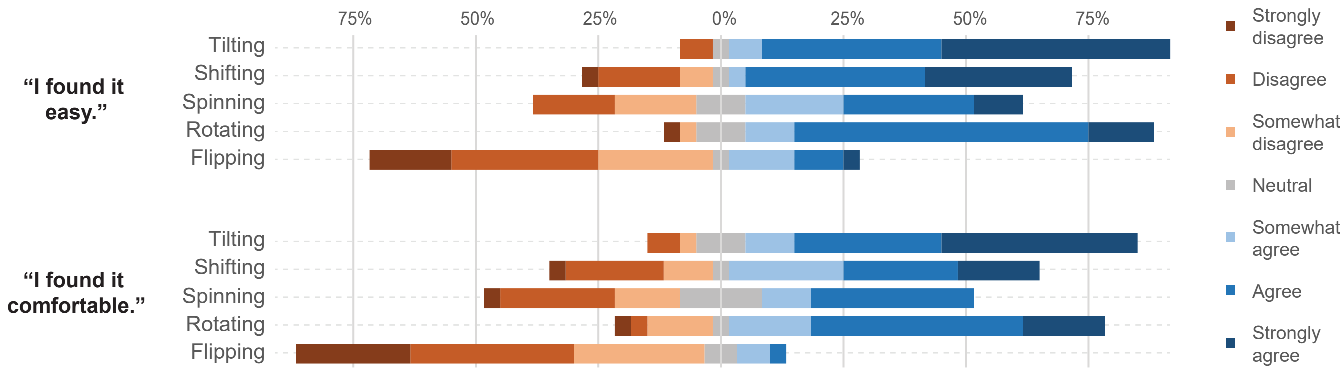

Figure 3.3: Easiness and comfort ratings.

Results

For previous experience, at least 4 participants had previous experience with all types of manipulations. SHIFT was the most common manipulation (86% of participants), followed by TILT (66%), SPIN (53%), ROTATE (43%), and FLIP (13%). Table 3.1 summarizes use frequencies and reasons reported by participants.

Figure 3.3 shows the subjective ratings after participants tried out these manipulations. For the easiness rating, most participants found all manipulations easy, except FLIP. TILT was considered the easiest movement with 91% of participants agreeing more or less strongly, followed by 88% for ROTATE, 71% for SHIFT, 61% for SPIN and 28% for FLIP. For the comfort rating, most participants found all manipulations except FLIP comfortable. TILT was considered the most comfortable gesture with 85% of participants agreeing more or less strongly, followed by 78% for ROTATE, 65% for SHIFT, 51% for SPIN, and 13% for FLIP.

3.2.2 *Dexterous Gestures*

With the manipulations defined above, dexterous gestures can be broken down into discrete atomic actions using specific combinations of manipulation variations, or continuous input of a parameter. For example, rotating 180° clockwise to decline an incoming call, or adjusting the volume based on the tilt angle. Due to phone size and physical hand motion constraints, tilt and shift manipulations are bound in their extent and repetition. However, spin, rotate, and flip manipulations can form unlimited gestures with infinite angles. Sequences of discrete actions can also form variations of dexterous gestures, including within manipulations (e.g., spin clockwise 90° then spin counterclockwise 90°), or between manipulations (e.g., flip 180° followed by rotate 180° and spin 180° to return original orientation).

We mainly focus on single discrete atomic actions to explore the gesture space in terms of people's previous experience with dexterous manipulations, user preference, gesture speed, reliability of gesture detection, and what applications are suitable for them.

3.3 Experiment 1: Performance and Preference

The results of the formative study demonstrated most dexterous manipulations were performed in the past by users for various reasons, and most were considered easy and comfortable. The goal of this experiment is to determine the speed of dexterous gestures, how participants perform them, and their preferences. Shift, spin, rotate, and flip manipulations were tested as dexterous gestures with two directions and two movement magnitudes. The study was conducted remotely due to constraints imposed by the Covid pandemic, so participants performed the designated gestures with their own phone. We measured the time to complete each gesture, collected internal sensor data, and recorded reasons for incomplete gestures as well as subjective preferences.

Participants

Participants were recruited using flyers and word-of-mouth, and received a $25 remuneration for their participation. Participants were required to have full use of their right hand and fingers and have access to an Android phone with built-in IMU sensors. From the total 26 participants who completed the experiment, 8 were removed after examining their data: 2 had missing sensor data, 2 had gesture-ending detection errors, and 4 appeared to have not followed the experiment procedure, as revealed by almost "flat" sensor data with no obvious movement, or almost identical sensor patterns for some gestures. The remaining 18 participants completed the experiment successfully, 9 females and 9 males, with average age 26.8 years (SD = 4.0). Smartphone experience, phone characteristics, and hand size were recorded as in the formative study (summarized in Table 3.2).

Table 3.2: Experiment 1 demographics (18 participants in total).

Smartphone experience (years)		Daily phone usage (hours)		Phone size (inches)		Hand size (mm)	
3-5	1	Less than 1	1	4-5	1	139-165	2
6-10	13	1-2	4	5-6	11	165-190	5
More then 10	4	2-4	6	More than 6	6	190-215	4
		4-8	6			215-241	5
		More than 8	1			241-266	2

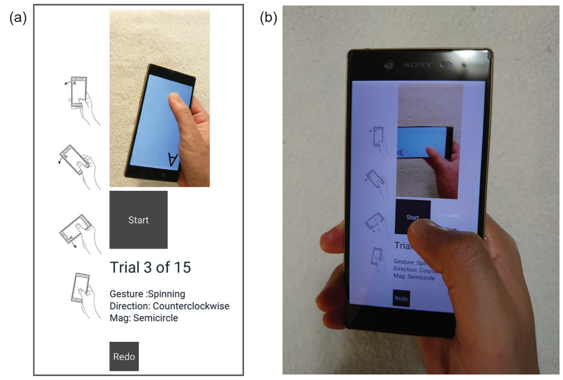

Figure 3.4: Experiment 1 task: (a) the interface before starting a trial; (b) the phone was held in the dominant hand.

Apparatus

The experiment was deployed as an Android 6.0+ app APK. Data from accelerometer, magnetometer, gyroscope, light, and proximity sensors were logged with a 50 Hz update rate. Touch input location, size, and pressure were also logged. Each trial was recorded to a file then uploaded to cloud storage. Participants were asked to remove any accessories other than protective phone cases and set the phone to "do not disturb" to avoid interruptions. The app executed in portrait orientation with auto-rotate disabled.

Task

Before starting each trial, an illustration of the gesture (similar to Figure 3.2) and an animated demonstration of each gesture was shown (Figure 3.4a). Each trial began by tapping a start button with the right thumb. The size and position of the button were such that it was comfortable to reach with a normal grip. Next, participants were asked to hold the phone still with their normal gripping posture (Figure 3.4b) for one second until a beep sounds. A simple visualization of the phone's movement was shown to help participants get a feel for the threshold according to which the device was considered still. After the beep, they started performing the gesture using only their fingers. At the end of the gesture, they were told to hold the phone still for one second again and waited for another beep. After a second beep, they returned to the normal grip posture and began the next trial. Participants were allowed to use their other hand to help return the phone to the start position between trials.

If the participant believed they performed the gesture incompletely or incorrectly, they pressed a "redo" button, provided a reason for the failure, and then repeated the trial again. The possible reasons were "phone dropped", "discontinuous movement", "app interrupted", "unfinished movement", or "other".

Procedure

The experiment was divided into three parts: pre-session instruction; main session with measured trials; and post-experiment questionnaire. Each participant attended a 10-minute one-on-one online meeting with instructions and a question-and-answer period. During this time, the participant installed the Android app and verified it was working as expected, the flow of the experiment was introduced, the task explained, and general guidance for completing the study was given. Next, the participant went through the main session of measured trials covering each gesture at a convenient time for them. This main session lasted approximately 45 minutes. Participants were asked to be seated and to do the experiment on top of a soft surface (e.g. bed, couch) or use towels in case they accidentally dropped their phone. Additionally, they were requested not to rest their forearm or hand on any supporting surface. After the main session was completed, participants rated each gesture on four aspects using a numeric rating from 1 to 7: ease, comfort, confidence, and social acceptance. The experiment was approximately one hour in total. The full text of the questions is provided in the supplementary material[1].

Design

Our study follows a within-subjects design with three primary independent variables: MANIPULATION { SHIFT, SPIN, ROTATE, FLIP }; DIRECTION { ADD, ABD }; and for all MANIPULATION conditions except SHIFT, MAGNITUDE { HALF, FULL }. ADD is adduction and describes gestures toward the middle of the body: shift down, spin counterclockwise, rotate right, and flip forward. ABD is abduction and describes gestures away from the body: shift up, spin clockwise, rotate left, and flip away. This creates 14 different dexterous gesture conditions, one for each combination of MANIPULATION, DIRECTION, and MAGNITUDE. Each participant completed 15 trials, including two practice ones, for each gesture condition as one sequence, with the order of all gesture conditions randomized. In summary: we recorded 182 completed trials per participant, 3276 trials in total.

There are five dependent measures: *Time* is the time from the start (the first beep) until the end (one second before the second beep) of the gesture. *Ease*, *Comfort*, *Confidence*, and *Acceptance* are numeric ratings for ease-of-use, comfort, confidence of not dropping the phone, and willingness to do the gesture in public.

Analysis

We used the $1.5 \cdot \text{IQR}$ (interquartile range) rule to detect trial outliers for each combination of participants, MANIPULATION, DIRECTION, and MAGNITUDE according to trial time. In total, 216 trials (6.6%) were removed. Due to the unbalanced design for SHIFT without MAGNITUDE, to analyze the effect of MANIPULATION, a MANIPULATION $\times$ DIRECTION ANOVA with Bonferroni-corrected pairwise comparisons was used. To understand the effect of MAGNITUDE, we removed the trials of SHIFT and used a MANIPULATION × DIRECTION × MAGNITUDE ANOVA with Bonferroni-corrected pairwise comparisons. Residuals for *Time* were not normally distributed, so Tukey's Ladder of Powers transformation [143] was used for statistical analysis. We visually inspected the Q-Q plot to confirm normality. Aligned Rank Transform [156] was used for numeric ratings as the distribution was not normal. Figure 3.5 summarizes main results for dexterous gesture conditions with a summary by MANIPULATION. Spearman correlation tests were used for the phone form factor and hand size analysis. We focused on phone size for simplicity since it normally correlates with other factors such as weight, height, width, and thickness. The full table for all phone factor correlation results can be found in the supplementary materials[1], and analysis scripts can be obtained on a public repository[2].

Results

To streamline the presentation of results, details of statistical tests and significant differences are provided as tables in the appendix (Section 3.8). References are in the form "A.1: Table 1a" where A.1 refers to subsection 1 of the appendix.

Time — We found ROTATE is the fastest gesture and about 0.4s, 0.7s, and 0.9s faster than SHIFT, FLIP and SPIN (Figure 3.5a; see A.1: Table 3.4a(i) for statistical tests showing MANIPULATION main effect). The mean time for ABD, and ADD are 2.98s and 3.08s respectively (but no significant main effect of DIRECTION). For SHIFT, movement in the ADD direction is faster than ABD; and for FLIP, movement in the ABD direction is faster (see A.1: Table 3.5a for statistical tests showing MANIPULATION and DIRECTION interaction). Overall, HALF gestures are 0.96s faster than FULL (see A.1: Table 3.4b(i) for statistical tests showing MAGNITUDE main effect). For FULL gestures, ROTATE is the fastest manipulation in both directions (see A.1: Table 3.5b for specific pairwise differences showing MANIPULATION, DIRECTION, and MAGNITUDE interaction). In addition, participants with larger hands can perform dexterous gestures slightly quicker (Spearman correlation showed a negative weak relationship between gesture time and hand size (r(3058) = -0.16, $p < .001$)).

Ease — We found ROTATE was considered the easiest gesture and FLIP the least easy; HALF gestures were, as expected, rated easier than FULL gestures (Figure 3.5b; see A.1: Table 3.4a(ii) and b(ii) for statistical tests showing MANIPULATION and MAGNITUDE main effect, but no interaction effect). The ease rating is lower when performing the gestures with a larger phone (Spearman correlation showed a negative weak relationship between ease and phone size (r(250) = -0.19, $p < .01$) and also between ease and hand size (r(250) = -0.18, $p < .01$)).

Comfort — Participants considered ROTATE the most comfortable gesture and FLIP the least; and HALF gestures were considered more comfortable than FULL (Figure 3.5c; see A.1: Table 3.4a(iii) and b(iii) for statistical tests showing MANIPULATION and MAGNITUDE main effect, but no interaction effect). The

2 https://github.com/exii-uw/phone-dexterity

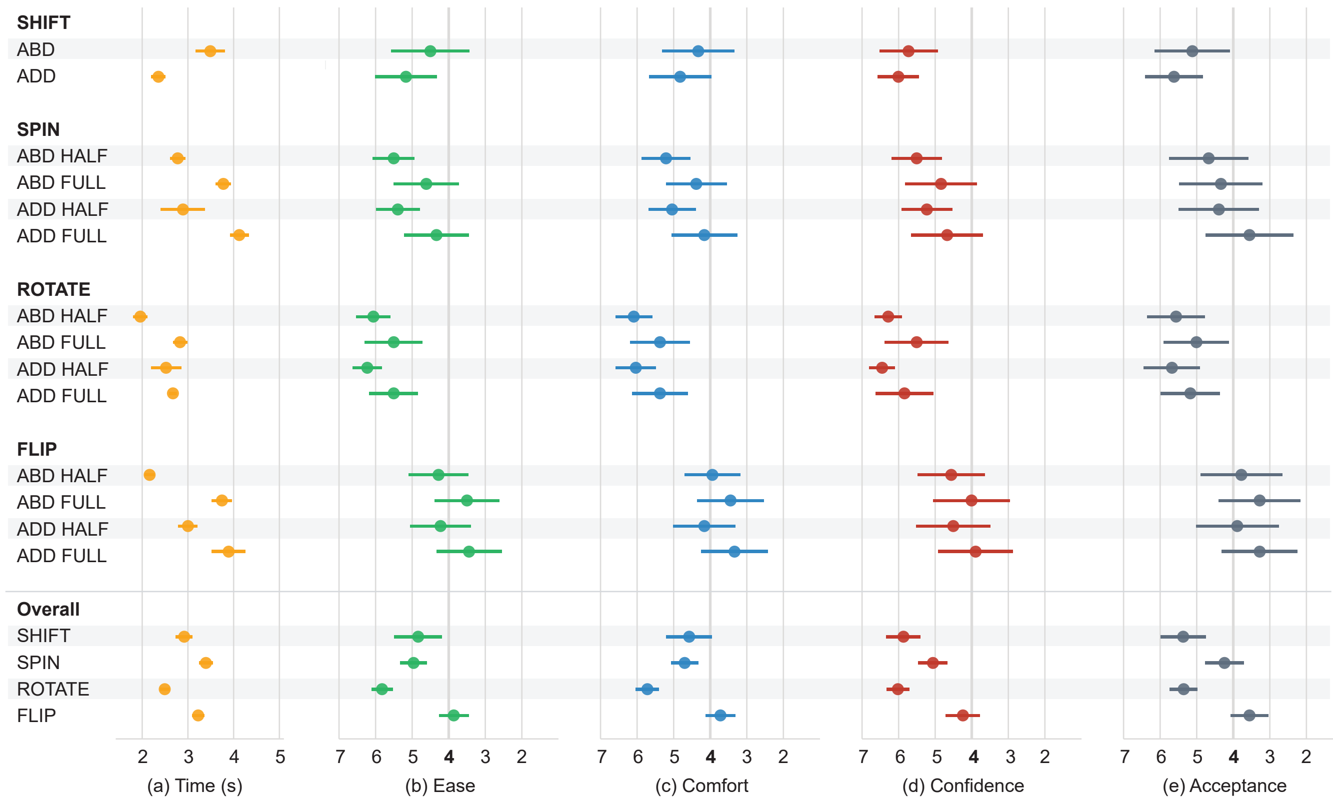

Figure 3.5: Comparison of gestures defined by MANIPULATION, DIRECTION, MAGNITUDE, as well as overall by MANIPULATION: (a) Time; (b) Ease rating; (c) Comfort rating; (d) Confidence rating; (e) Social Acceptance rating. Note: rating scales inverted to enable comparison with time, left-most points in each sub-graph are better. (error bars are 95% confidence intervals)

comfort rating is lower when performing the gestures with a larger phone (Spearman correlation showed a negative weak relationship between comfort and phone size (r(250) = -0.15, $p < .05$) and also between comfort and hand size (r(250) = -0.17, $p < .01$)).

Confidence — We found participants are most confident about not dropping their phone for ROTATE and SHIFT, and least confident with FLIP, but all ratings were neutral or above (Figure 3.5d). Participants also have higher confidence in HALF gestures than FULL (see A.1: Table 3.4a(iv) and b(iv) for statistical tests showing MANIPULATION and MAGNITUDE main effect, but no interaction effect). Participants with smaller phones tend to be more confident performing the gestures (Spearman correlation showed a negative weak relationship between confidence and phone size (r(250) = -0.27, $p < .001$) and moderate relationship between confidence and hand size (r(250) = -0.44, $p < .001$)).

Social Acceptance — We found SHIFT and ROTATE are the gestures that participants are most willing to perform in front of people or in public areas (Figure 3.5e). They also perceive HALF gestures are more socially acceptable than FULL gestures (see A.1: Table 3.4a(v) and b(v) for statistical tests showing MANIPULATION and MAGNITUDE main effect, but no interaction effect). Using dexterous gestures in public was deemed more acceptable with a smaller phone (Spearman correlation showed a negative weak relationship between acceptance and phone size (r(250) = -0.16, $p < .01$) and also between acceptance and hand size (r(250) = -0.17, $p < .01$)).

Summary

Overall, rotating is the fastest manipulation with the highest rating for ease and comfort. Shifting is rated as more socially acceptable, which may be due to it also being the most familiar manipulation. However, compared to rotating, the ease and comfort score is lower, likely because of the loosened grip and the relative difficulty of the gesture. This result is similar to Eardley et al.'s findings [28], where loosening and shifting grips were associated with lower comfort and secure scores. Spinning is considered slower, especially with full magnitude. This is likely because the gesture includes a short shifting movement between each half spin. Flip gestures are the least preferred for ease, comfort, and confidence. However, a half flip away (abduction) gesture can be performed in 2.16s, which is comparable to the fastest gesture times. The movement of this gesture is similar to pen-spinning techniques, which may be the reason for its speed. In summary, rotate is perhaps the most promising manipulation, especially rotate gestures with half magnitude.

Due to our experiment protocol, our results for the gesture time may not exactly be representative of real use. In order to record clean and complete sensor data while the gesture was performed, participants were asked to hold the phone still at the start and end and wait for a beep sound. This filtered out extraneous movements such as lifting the thumb after pressing the start button, but likely added some reaction time. Additionally, gesture times recorded in controlled conditions might be different from in-the-wild gestures detected using motion thresholds. Furthermore, since dexterity skills are typically learned and honed through time, experiments over longer periods of time would be needed to examine possible learning effects and determine how fast users can ultimately execute such dexterous manipulations.

To obtain a better understanding of confidence and ability, we examined the "redo reasons" when participants did not complete trials. From all the possible reasons, phone dropped was the most critical issue since the consequence was possible phone damage. Within the whole experiment (3,276 completed trials), 24 redos were due to phone drops, including 13 times during flipping, 6 times during shifting, 4 times during spinning, and once during rotating. Notably, 15 cases of such phone drops occurred in the first 7 trials. This is somewhat consistent with the lowest confidence score given to flip manipulations. Combining phone dropped and discontinuous movement as reasons for redoing a trial, 31 such "redos" happened during flipping, followed by rotating (27), spinning (25), and shifting (21). It is possible that unwanted contacts between screen and fingers or the palm may cause standard system gestures to be triggered, causing the experiment app to be interrupted. Another possibility is pressing the power button during a gesture. However, we found these were not too frequent. Only 12 such interruptions during flip, 8 during rotate, 9 during spin, and 4 during shift were recorded.

3.4 PROTOTYPE SYSTEM

We create an Android prototype with a rule-based recognizer based on sensor patterns in order to demonstrate the potential of dexterous gestures. Examining the IMU sensor data, we can identify patterns for different gestures such as the z value of the accelerometer dropping from near 1 to almost -1 when rotating or flipping 180°, and the x, y, or z value from the gyroscope sensor mainly affected by the axis corresponding to flipping, rotating, or spinning gestures. Based on a visual comparison with IMU patterns in the H-MOG dataset of phone use while reading or texting [129], the sensor pattern of shift gestures are likely very hard to distinguish from normal movements. We made several attempts to recognize shift gestures using deep learning methods, including LSTM and CNN models, but those interactions could not be reliably discriminated. Consequently, we focus on flipping, rotating, and spinning for the recognizer and applications below.

3.4.1 *Recognizer*

We build a recognizer based on accumulated differences of quaternions (which are commonly used to represent rotations) to classify spinning, rotating, and flipping with two directions and magnitudes. Differences of quaternions simplify the raw IMU sensor data so that rotation angles can be better distinguished. We sum the quaternion differences between each consecutive frame of each rotation sensor axis to compute the angle difference, and check the value of the corresponding Euler axis for different gestures (x for flip, y for

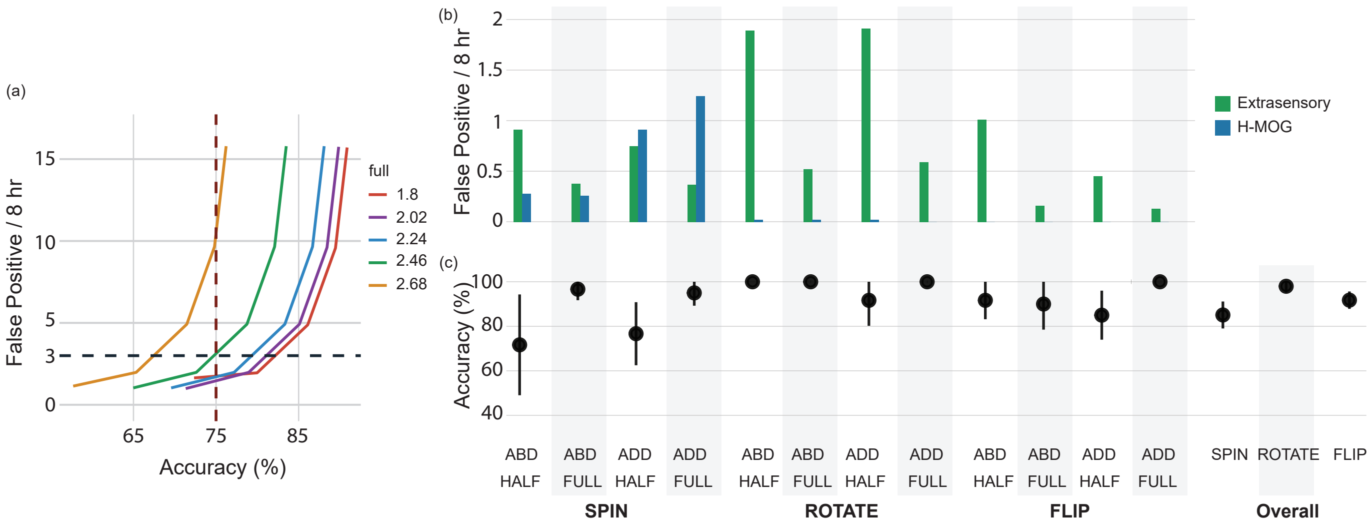

Figure 3.6: Recognizer validations: (a) ROC curves of average accuracy and maximum false positive rate among all gestures: for 25 different FULL and HALF thresholds, each curve shows different HALF thresholds (1.4, 1.3, 1.2, 1.1, and 1.0) when used with the same FULL threshold; (b) false positive analysis of Extrasensory and H-MOG dataset; (c) accuracy of gestures as defined by combination of MANIPULATION, DIRECTION, MAGNITUDE, as well as overall by MANIPULATION (error bars are 95% confidence).

rotate, and z for spin). For example, for a quaternion representing a rotation θ around the z-axis during a spin gesture, the quaternion difference on the z-axis would be $\sin\frac{\theta}{2}$. With a high sampling frame rate, the accumulated quaternion difference on the z-axis for a half spin gesture would approach $\frac{\pi}{2}$.

$$\lim_{k\to\infty} k \sin\frac{\pi}{2k} = \frac{\pi}{2} \tag{3.1}$$

To reduce false positives, we only recognize a gesture when three conditions are satisfied for accelerometer data: (1) at least one axis has a zero crossing, (2) at least two axes cross each other, and (3) at least one axis has a difference greater than 3 m/s^2.

A sliding time window segments real-time data for recognition. The average time for FULL gestures in the experiment data is 3.52s (SD = 1.74) and 2.56s (SD = 2.13) for HALF gestures. We therefore use a 4s window for FULL and 2.5s window for HALF gestures. The sensor update rate is 50 Hz, and the system checks for a gesture every 0.2s. For each check, we calculate the accumulated quaternion difference and see if a FULL gesture was performed within the 4s window, or a HALF gesture within the 2.5s window. Since a FULL gesture includes a HALF gesture, we introduce an additional 0.2s delay after recognizing a HALF gesture to test if it actually ended, or if the phone is still rotating to perform a FULL gesture. This means the maximum delay for recognizing a gesture action is 0.4s.

Threshold Selection

We analyzed the data collected from the experiment to determine thresholds to detect each dexterous gesture. There are 2615 trials after removing shift gestures and 193 outliers (6.9%) using the same $1.5 \cdot \text{IQR}$ method as the experiment. To further improve consistency, we also applied the same $1.5 \cdot \text{IQR}$ to identify outliers for each MAGNITUDE according to accumulated quaternion differences, which removed another 348 trials (12.4%). With this dataset, we found the average accumulated quaternion difference in the corresponding Euler axis for HALF gestures across participants is 1.4 ($\text{SD} = 0.2$), and 2.68 ($\text{SD} = 0.44$) for FULL gestures. They are approximately equivalent to 160° ($\text{SD} = 22^\circ$) and 308° ($\text{SD} = 50^\circ$) Euler angles. This indicates that participants tend to rotate less than expected, so a lower angle detection threshold is needed to conform to actual user behaviour.

To fine-tune those thresholds, we tested our recognizer on a 6-person (10%) subset of the Extrasensory [144] dataset of in-the-wild phone usage (210 hours). Like DoubleFlip [115], we used the rate of false positives per 8 hours as our metric. Figure 3.6a shows ROC curves plotting average accuracy using our dataset and maximum false positive rates across all 12 gestures. The five curves plot different threshold combinations. To minimize false positives and maximize accuracy, we choose thresholds with accuracy higher than 75%, and false positive less than 3. The selected thresholds are 1.3 for HALF and 2.02 for FULL gestures, which are approximately equivalent to 149° and 231° Euler angles.

False Positive Test with Datasets

We tested our recognizer on two datasets: H-MOG [129] (341 hrs of more stable phone usage) and Extrasensory [144] data not used for threshold selection (54 people, 1514 hrs of in-the-wild usage with more diverse movements).

Figure 3.6b shows the rate of false positives of each gesture per 8 hours. With H-MOG, adduction spinning has a higher rate (1.24 full, 0.91 half), likely due to similarity with landscape and portrait changes. All other gesture rates are less than 0.28. With Extrasensory, half-rotations have higher rates (1.89 abduction, 1.91 adduction). We believe this is likely due to movements when setting down or picking up the phone. The rates for the other two half gestures are low: SPIN (0.91 abduction, 0.75 adduction) and FLIP (1.01 abduction, 0.45 adduction); and all full gestures are below 0.59. For comparison, the single DoubleFlip gesture has a rate of one false positive per 8 hours [115].

True Positive Test with Users

To evaluate recognition accuracy in real-time, we recruited 12 participants: 6 females and 6 males, average age of 25.8 years (SD = 2.8). Five also participated in our previous experiment conducted more than 11 months before. The apparatus, task, and procedure are similar to Experiment 1, but with the addition of the gesture recognizer and 12 dexterous gesture conditions (i.e.

without shifting). Participants completed 2 practice trials and 5 measurement trials for each gesture condition as one sequence, 60 measurement trials per participant The dependent measure is the recognizer accuracy.

Overall, our recognizer shows high accuracy: ROTATE (97.9%), FLIP (91.7%), and SPIN (85%) (Figure 3.6c). For specific dexterous gestures, both ROTATE-ABD, ROTATE-ADD-HALF, and FLIP-ADD-FULL were recognized perfectly. SPIN-HALF had the lowest accuracy (71.7% for ABD and 76.7% for ADD), likely due to participants sometimes stopping a spin gesture early when the accumulated quaternion difference had not reached the required threshold. This can happen after the phone contacts the palm.

Limitations and Improvements

Our recognizer based on quaternion differences cannot distinguish gestures that are performed only with fingers from similar phone movements using the wrist. However, due to anatomical constraints, it is not possible to perform full gestures or half spins using only the wrist. For half gestures, additional sensor data could distinguish those actions. For example, wrist manipulations with power grip tend to not touch the screen while finger-based dexterous gestures do. The threshold selection plays a critical role in our recognizer, especially for reducing the false positives. Selecting thresholds for individual manipulations could address those with higher false positives, such as choosing a higher half threshold for rotate gestures.

3.4.2 *Applications*

We consider potential applications making use of dexterous gestures, for which there are general design principles and constraints:

- Gestures ending with the screen away from the user are only useful for tasks that require no immediate visual feedback with only little touch input. Such gestures would be suitable for voice input and output.
- Gestures inverting the phone so the microphone is up and close to the mouth are useful for voice commands [158].
- Less preferred and more cumbersome gestures are more suitable for infrequent commands, or commands that incur a high penalty if triggered accidentally (e.g. power off, system diagnose).
- Gestures should preferably be activated from the lock screen to minimize accidental touches.

Dexterous gestures can be used as global commands (e.g., opening a camera app while the phone is locked, invoking assistance tools, or checking time and weather) or interaction with applications (e.g., declining an incoming call, dismissing an alarm, or issuing commands to a music player). We implement applications in the following categories (please also see the accompanying video for demonstrations [159]):

Functions Without Visual Input or Feedback — Dexterous gestures can be performed without looking at the screen or visual feedback. This can be useful when the phone screen is not immediately visible, such as when it is in a bag. An example scenario is declining a phone call by reaching into the bag and rotating the phone (Figure 3.1a). The risks of dropping and damaging the phone are significantly reduced when the device is in a bag, which may lower the barrier for using dexterous manipulations in such situations. Gestures can also benefit users with visual impairments. For blind people, dexterous gestures expand the input options they have to quickly and conveniently trigger phone actions [147].

Application Shortcuts — Opening particular apps and looping between opened apps with pre-defined gestures enable simple and direct commands with or without visual feedback. For example, rotating left full to open a calendar, and spinning clockwise half to open a mobile payment application (Figure 3.1c). Spinning can be used to loop through or swap opened apps. Spinning clockwise or counterclockwise full could switch to the next or previous app. Although the flip gesture might be more difficult to perform, it can be used to open infrequent but critical apps, such as flipping away full to open system settings and flipping forward full to power off.

Camera — The rear or front camera can be opened by rotating left or right full directly without unlocking the device. Rotating left half would open the rear camera with auto capturing, or users could tap the screen to take a photo as back-of-device interaction.

Voice Notes and Intelligent Assistant Queries — ProxiTalk [158] showed that bringing the phone to the mouth is a promising method to activate speech input. A half flip of the phone can bring the microphone up to record audio. The flip away gesture can be used for dictating voice notes (Figure 3.1b), and flip toward gesture could open the search function. The phone can be rotated right half to hear time and weather information.

Alarm Functions — Using fine motor skills to perform dexterous gestures requires concentration, which can reduce the likelihood of unintentional operations [86]. For example, rotating right full can dismiss an alarm, or rotating left half and full can snooze the alarm 5 and 15 minutes respectively, instead of using swipe gestures.

Music player — Dexterous gestures can also be mapped to functions inside an application like a music player. A full rotate could change the song and a half rotate could skip forward or backward. A half spin can control the volume while a full spin can mute or un-mute the phone directly. Because rotating gestures can be performed in a narrow space, changing songs with rotating gestures in the pocket may be useful while running or training.

3.5 EXPERIMENT 2: PRACTICE AND CONTEXT

We conducted a one-week experiment to further examine the performance, preference, and usability of dexterous gestures after users gain more familiarity and practice. Because a half gesture is included in a full gesture, we focus on three “full” manipulations for spin, rotate, and flip, each in two directions. To examine usage context, sitting and standing conditions were tested. Participants used their own phone throughout the study.

Participants

Participants were recruited using our institution’s student mailing list and word-of-mouth, each received $50 for completing the study. With the same phone requirements as Experiment 1, we recruited 12 participants, ages 23 to 31 (M=26.83, SD=2.79), of which 8 were male, and 4 were female. Note that 4 of these participants also completed Experiment 1 more than one year before. Smartphone experience, phone characteristics, and hand size are summarized in Table 3.3.

Dexterity Training App

We created a dexterity training app that detects each gesture, counts the repetitions, and displays scores for smoothness and speed in a graphical style reminiscent of meditation apps[3]. Users can track their progress in terms of gesture speed and smoothness over multiple days. The scores are calculated according to the deviation of quaternion differences between frames and gesture time, and the app displays simple graphical rewards when thresholds of these scores are exceeded. The idea is that the app encourages users to manipulate the phone smoothly and quickly, and also trains the dexterity of fingers (similar to Chinese “Baoding balls” [179]). Source code is available on the project’s public repository[2].

Procedure

The experiment was conducted in three phases: pre-practice, practice, and post-practice.

The *pre-practice* phase was conducted in-person. An experiment app was installed on the participant’s phone similar to the one used in the true positives experiment (Section 3.4.1). After receiving instructions about the 6 dexterous gestures and experiment task, participants completed measured

3 The training app is demonstrated in the paper video [159].

Table 3.3: Experiment 2 demographics (12 participants in total).

Smartphone experience (years)		Daily phone usage (hours)		Phone size (inches)		Hand size (mm)	
6-10	5	1-2	3	5-6	3	165-190	2
More then 10	7	2-4	4	More than 6	9	190-215	2
		4-8	5			215-241	5
						241-266	3

trials while sitting. At the end of the session, they provided subjective ratings and then installed a second app for dexterity training.

For the *practice* phase, the participant used the training app at home for at least 10 minutes every day for 7 days.

The *post-practice* phase was conducted after practice. Five participants completed it in-person 1 day after completing practice, and the rest completed it remotely using a live video call 7 to 9 days after practice. There were two post-practice sections: first, participants completed the same measured trials as those in pre-practice while sitting and also when standing. Then, they answered additional questions about their preferences in multiple scenarios, and their feedback about demonstrations and possible applications was recorded[1].

Design

We used a within subjects design with three primary independent variables: SESSION with 2 levels (BEFORE, AFTER practice); MANIPULATION with 3 levels (SPIN, ROTATE, FLIP); and DIRECTION with 2 levels (ADD, ABD). There was another independent variable for the AFTER practice condition: SCENARIO with 2 levels (SIT, STAND). We tested STAND in the AFTER practice condition to understand the performance and preference of gestures in a more difficult scenario. As such, there are a total of 18 gesture conditions: (12 SESSION × MANIPULATION × DIRECTION + 6 MANIPULATION × DIRECTION for AFTER & STAND). There were 7 trials per gesture condition, including two practice ones. The order for SESSION was fixed, the order for SCENARIO was counter-balanced using a Latin square, and the order for MANIPULATION × DIRECTION was randomized. In summary we recorded 90 completed trials per participants, i.e. 1080 trials in total.

The primary measures obtained or computed from logs are *Accuracy*, *Time*, and *Smoothness*. *Accuracy* is the gesture accuracy of our proposed recognizer. *Time* is the gesture time from the start of the trial until the gesture is recognized. *Smoothness* is calculated from the quaternion difference in continuous frames while the gesture is executed. We define high smoothness using two criteria: (1) the quaternion difference values of the corresponding Euler axis for different gestures should be roughly constant, and (2) the quaternion difference values of the other two axes should be close to 0. Specifically, a gesture generates a series of accumulated quaternion difference values $[QD_1...QD_n]$. Each QD_i has components representing the three Euler axes: X_i, Y_i, and Z_i. We calculate *Smoothness* as the sum of two terms: (1) the sum of absolute differences between each primary axis component with the median primary axis component, and (2) the sum of the components for the other two axes. For example, Y is the primary axis for the rotate gesture, so *Smoothness* is calculated as:

$$Smoothness_{rotate} = \frac{\sum_{i=1}^{n} |Y_i - Mdn(Y)|}{n} + \frac{\sum_{i=1}^{n} |X_i| + |Z_i|}{2 \times n} \tag{3.2}$$

There are four subjective measurements for each dexterous gestures which are the same as in the previous experiment.

Analysis

To analyze the effect of SESSION, we remove the trials of STAND and use a SESSION × MANIPULATION × DIRECTION ANOVA with Bonferroni-corrected pairwise comparisons. To understand the effect of SCENARIO, we remove the trials of BEFORE practice and use a SCENARIO × MANIPULATION × DIRECTION ANOVA with Bonferroni-corrected pairwise comparisons. Greenhouse-Geisser correction is used when there is a sphericity violation. We use generalized linear mixed models for *Accuracy* analysis because the distribution is close to a Poisson distribution. Residuals for *Time* and *Smoothness* are not normally distributed, so Tukey's Ladder of Powers transformation [143] is used. Aligned Rank Transform [31, 156] is used for numeric ratings due to a non-normal distribution. Figure 3.7 summarizes the main results for dexterous gesture conditions with a breakdown by MANIPULATION type.

Results for Before and After Practice

We only report the main effect of SESSION, or interactions involving SESSION. For *Accuracy* and *Smoothness*, there was no effect.

Time — Participants can perform dexterous gestures 0.3s faster AFTER practice (Figure 3.7b; see A.2: Table 3.6a(i) for statistical tests showing SESSION main effect).

Ease, Comfort, Confidence, and Social Acceptance — Participants rated all four subjective scores higher AFTER practice than BEFORE (Figure 3.7d, e, f, g; see A.2: Table 3.6a(ii, iii, iv, v) for statistical tests showing SESSION main effect). FLIP is rated easier, more comfortable, and more socially acceptable AFTER practice (see A.2: Table 3.6b(i, ii, iii, iv) for statistical tests showing SESSION and MANIPULATION interaction).

Results for Sitting versus Standing

There were no main effects or interactions involving SCENARIO, so we only report main effects for MANIPULATION and DIRECTION.

Accuracy — There was no effect of SCENARIO, MANIPULATION, and DIRECTION. Overall, our recognizer has high accuracy: 94% for both SIT and STAND (Figure 3.7a).

Time — ROTATE is 1.2s and 1.0s faster than SPIN and FLIP (Figure 3.7b; see A.3: Table 3.7a(i) and b(i) for statistical tests showing MANIPULATION and DIRECTION main effect).

Smoothness — ROTATE is better than SPIN and FLIP (Figure 3.7c; see A.3: Table 3.7a(ii) for statistical tests showing MANIPULATION main effect).

Ease, Comfort, Confidence, and Social Acceptance — We found ROTATE was rated highest in all four subjective ratings, and FLIP received the lowest ratings

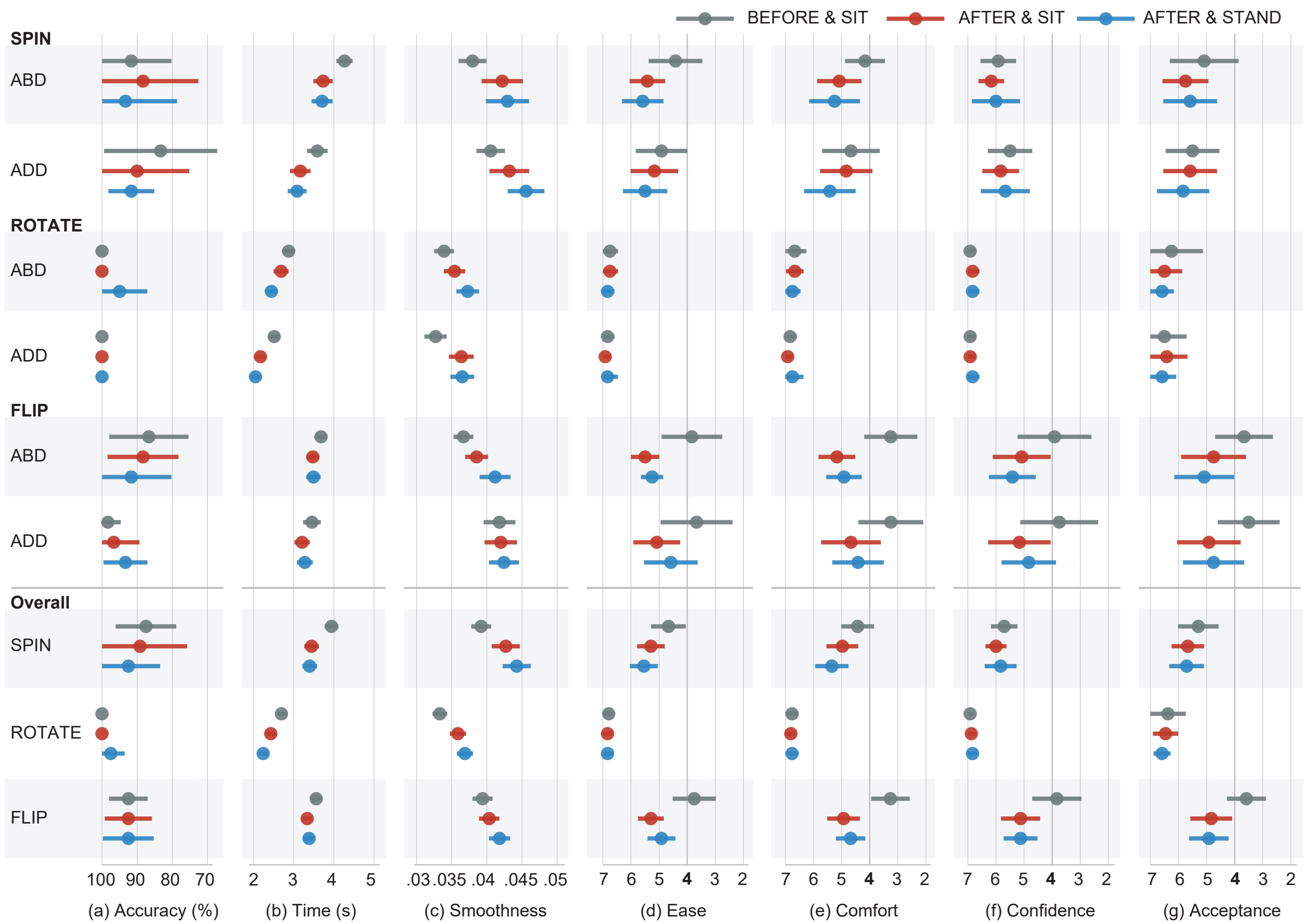

Figure 3.7: Comparison of gestures defined by MANIPULATION, DIRECTION, as well as overall by MANIPULATION: (a) Accuracy; (b) Time; (c) Smoothness; (d) Ease rating; (e) Comfort rating; (f) Confidence rating; (g) Social Acceptance rating. Note: rating scales inverted to enable comparison with time, left-most points in each sub-graph are better. (error bars are 95% confidence intervals)

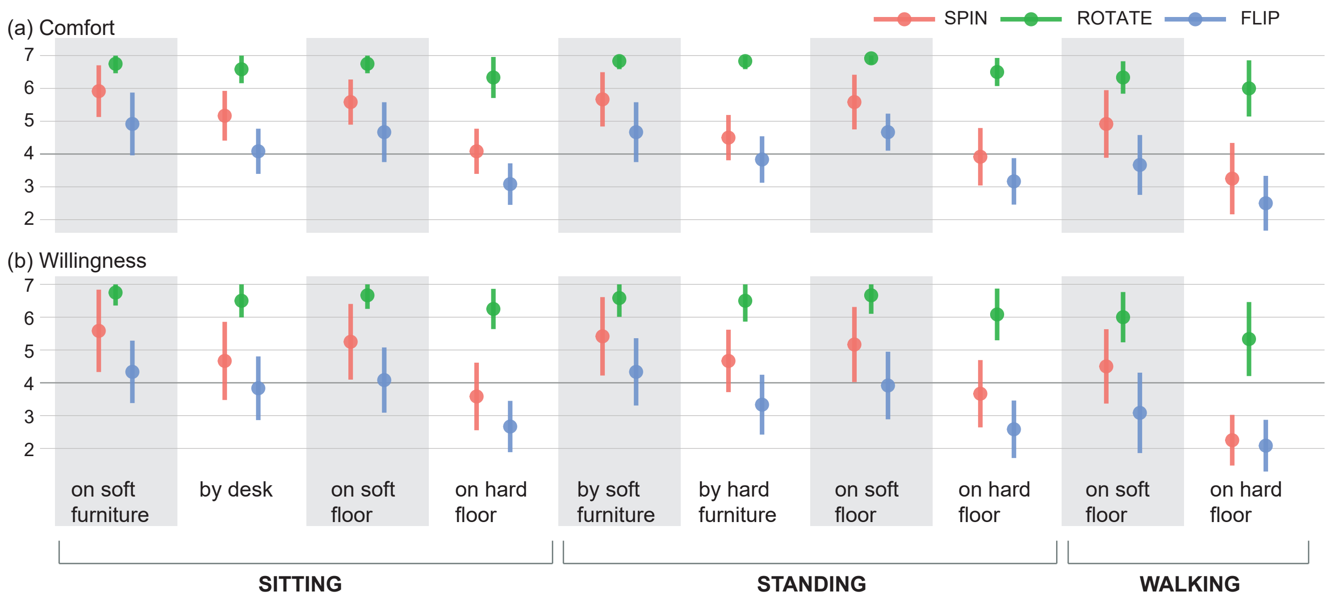

Figure 3.8: Comparison of scenarios: (a) *Comfort* rating; (b) *Willingness* rating. (error bars are 95% confidence intervals)

for confidence and acceptance (Figure 3.7d, e, f, g; see A.3: Table 3.7a(iii, iv, v, vi) for statistical tests showing MANIPULATION main effect).

Questionnaire Results

To better understand comfort and willingness to perform dexterous gestures in multiple scenarios, two additional subjective measures are included in the questionnaire at the end of the post-practice session. The scenarios are split into sitting, standing, and walking in various environments. Figure 3.8 summarizes the main results for performing dexterous gestures in different contexts. Most participants found ROTATE comfortable and were willing to perform it in all situations, even while walking on hard floor (comfort: 6, willingness: 5.3). Participants expressed they were more comfortable performing dexterous gestures while sitting on, standing by, or walking on soft surfaces such as soft furniture (e.g. couch, bed) or floor (e.g. grass). Following the lower comfort ratings, participants were less willing to flip the phone especially on a hard surface or while walking. However, some participants were more willing to do half-flips, e.g. *"I like the half flip, not the full one. I can do it quite comfortably."* [P10]

To gain more insights about how participants would be willing to perform dexterous gestures practically in their daily lives, they watched the video of demonstrations (Section 3.4.2) and provided feedback as well as proposed other applications. Most participants found the demonstrations practical and expressed they would like to use them, especially for snoozing and dismissing alarm, or opening the payment application: *"I would definitely use the* *half spinning to open the payment app. It's easy and I don't need to open the NFC manually."* [P4]; *"Snoozing an alarm for a certain period based on a gesture is really nice."* [P5]; and *"I like the half flip to take notes because the flipping gesture is more controllable than the voice input."* [P7]. On the other hand, participants also reported that they would not use dexterous gestures compared to current phone gestures, such as pressing buttons, or shaking phone: *"I can shake my phone to open the flashlight in Motorola Moto G5+, so I prefer that than rotating."* [P7]; and *"If I were already using the phone (i.e. phone is awake), swiping or tapping are easier than dexterous gestures."* [P2]

Participants made some interesting suggestions for potential applications making use of dexterous gestures, such as making an emergency call, integrating gestures in games to increase interactivity, or helping hand rehabilitation: *"The gestures would be useful in the situations that making a movement without letting other people know, like calling the police with a simple rotate, or starting phone recording directly."* [P9]; *"The gestures can be applied into games to increase the fun elements, such as flipping the phone to fire weapons."* [P3]; and *"...using such gestures with the training app to rehabilitate people who are suffering partial disabilities in their hands due to a stroke or injury because the smoothness and speed scores are good indicators of improvement!"* [P5]

Summary

Overall, the results for the pre-practice session align with experiment 1 and the true positive test with users in section 3.4.1: all full gestures can be recognized accurately at a rate above 88%; rotating is the fastest manipulation with the highest subjective ratings; spinning is slower; and flipping is rated lowest. After one week of practice, the speed and subjective ratings of dexterous gestures improved, especially the comfort and confidence ratings. Some participants found better ways to perform gestures during practice: *"For spinning gestures, I found the sweet spot to pinch the phone, and used gravity and momentum to spin the phone quickly"* [P10]. Most participants became more confident about not dropping their phone: *"I become more comfortable and confident to do the gestures, even while talking to other people"* [P3].

We found some evidence of a trade-off between gesture speed and smoothness. Spearman correlation showed a negative moderate relationship in spinning (r(358) = -0.58, $p < .001$), rotating (r(358) = -0.47, $p < .001$), and flipping (r(358) = -0.52, $p < .001$). To increase smoothness, participants seem to slow down for more control, e.g. *"I found that doing the gesture slowly can increase the score for spinning"* [P11].

There was no quantitative differences between sitting and standing. Some participants did comment about feeling less confident, *"... while standing I noticed that I was more careful trying not to drop my phone"* [P5], but others felt more comfortable because of the increased range of motion, *"I prefer standing because the arm can fall down naturally, I have to lift up my arm to hold the phone while sitting"* [P7].

3.6 DISCUSSION

We discuss and summarize design recommendations based on overall results.

Manipulation

The formative study and the experiments show that the rotating manipulation is perceived as the easiest and most comfortable with higher social acceptance, which suggests it can be used to trigger regular phone actions. The rotation half gesture recognition has higher false positives, likely because it is accidentally triggered when putting down or picking up the phone. This makes it less suitable for global commands, but we believe it can still be used for contextual functions such as declining an incoming call, dismissing an alarm, or triggering functions in an active application. Spinning the phone may require more time and finger movement, but this is a familiar gesture that was rated as easy. Spinning gestures are well suited for functions which need visual feedback since the screen remains visible during the movement. As exemplified by Yoon et al.'s lateral swing gesture [163], spinning manipulations can be used in collaborative situations like sharing content with coworkers. Since this motion involves several people, it could be used to protect privacy, such as locking the phone with a spin. Flipping gestures should be used less frequently since they had lower ratings and were associated with higher chances of dropping the phone. However, half flip gestures, especially away from the body (abduction), are relatively fast and rated high enough to warrant use for less frequent functions.

Magnitude

Rotating and flipping halfway end with the phone screen facing away. This means these gestuers should be used to trigger functions that do not require visual feedback or touch input, such as using speech and audio for note dictation, and dismissing a call. Recent commercial developments suggest phones with screens on both sides could become more common [170, 172, 178]. The practical benefits of half gestures are more evident for dual screen phones as a way to switch between screens [157]. These explicit motions would be distinguishable from simple static detection of phone orientation to trigger specific actions. For example, users could switch between main and secondary screens to view multiple applications using half-rotation gestures, or display private content using half flips.

Full gestures can be improved after practice. With increased speed and comfort, performing full gestures to activate the camera, turn on the flashlight, or start a recording can be useful with current phones. One advantage of gestures relying on finger dexterity rather than full wrist or arm motions is that they can be repeated indefinitely. Due to hand anatomy limitations, only half gestures can be performed with the fingers in a power grip. With a loose grip and dexterous finger manipulations, multiple phone rotations are possible. Although the speed of such gestures would be slower, they can be used to control a continuous parameter such as increasing the duration of the alarm snooze by rotating the phone multiple times. Individual dexterous gestures can also be combined for security purposes, like unlocking the device after 2 full-right rotations, 1 full-left rotation and 3 full-flip-away gestures.

Accidental Input

Accidental input when performing dexterous gestures, such as touching the screen with the palm or pressing the power button while moving fingers, may be a concern. This only happened a few times in our experiment (1%), but it still is something to be addressed for reliability. Methods such as recognizing palm touch events [73], detecting unintentional touch events similar to palm rejection for pen input [121] or grip recognition [75] can be applied to reject accidental inputs. Restricting dexterous gestures to the lock screen would also largely mitigate this issue.

Single-hand vs Two-hand Gesturing

Our interaction space is defined by in-hand manipulations, so we only examined single-handed gestures. Single-hand phone usage is important for phone interaction techniques since the other hand may be encumbered [97] and people use their phone more often with one hand than two [54]. However, single-hand dexterous gestures can also be performed with some assistance of the other hand. For example, flipping the phone with fingers on both sides to make sure the weight of the device is equally distributed and grip stability is increased. Users may wish to first safely practise their dexterous gesturing skills using two hands before perfecting them with one hand. These aspects, as well as learning effects, can be explored in future work.

Risks

Although our results showed that people could perform dexterous gestures when holding the phone in a loose grip, there were a few cases of phone drops, especially with the flipping gesture. But with some practice, those risks diminish as users gain more confidence. When running the studies, we asked participants to perform gestures above a soft surface. This may have lead to higher subjective scores compared to other "riskier" situations where the gestures are performed while standing or walking on a hard floor, which is shown in the results of the questionnaire. However, phone protection accessories such as rubber cases and screen protectors, may help reduce user apprehension by alleviating the risk of phone damage from accidental drops. A more thorough examination of these situations is required to obtain a better understanding of benefits versus risks.

Fatigue

Large motion gestures may cause "gorilla arm" [12, 48], but this kind of fatigue is unlikely with dexterous gestures since the arm can remain at a comfortable position. However, dexterous movements require a high amount of finger movement, which likely introduces muscle fatigue in the hand. In our experiments, participants could take breaks between blocks or pause practising when they felt finger or hand soreness. We found they usually required a break after multiple blocks, but generally felt comfortable performing single manipulations, especially after a full week of practice. This suggests that applications requiring many dexterous gestures during a concentrated time should be avoided. For this reason, most of our applications demonstrate dexterous gestures for less frequent, single manipulations. Future work could specifically investigate fatigue in dexterous gestures, perhaps over a longer period or in a controlled way where the number of gestures per time span is controlled.

Practical Usage Verification

Although we collected ideas for how dexterous gestures could be used in experiment 2, our participant feedback was based on our demonstration videos and their imagination. Future work should explore and validate how practical these potential applications are.

Comparisons with Conventional Gestures

We did not conduct experiments to compare dexterous gestures with standard phone interaction techniques for two reasons. First, dexterous gestures are complementary to other forms of phone input like touch, squeezing, and motion gestures: our ultimate goal is to increase expressiveness with phones, not to replace current methods. Second, the goal of this work is to gain an understanding of dexterous gestures, how usable and socially acceptable they are, whether they can be reliably recognized, what kind of applications could exploit them. We recognize that dexterous gestures appear novel to most users, and by definition, they require an element of skill to perform. For example, it is likely that simple gestures, such as swiping, tapping, and even squeezing, would be rated as faster and easier to perform. Below, we offer some high-level comparisons with other phone input techniques with respect to speed and diversity of gesture set, memorability and semantic mapping, and eyes-free interaction.

Dexterous gestures can be used as direct commands with comparable speed to methods combining a delimiter and subsequent commands [96]. All 12 dexterous gestures can be reliably detected with very high true positive rates and low false positive rates. These rates could likely be further improved by optimizing our recognizer. Addtionally, the top-speed of half-gestures is about 2 seconds and 3 seconds for full-gestures after practice. Consider how DoubleFlip [115] and Active Edge [106] are single gestures used to delimit a subsequent action to specify the actual command. With a greater diversity in our dexterous gesture set, we can directly trigger multiple different commands. In terms of speed, dexterous gestures are comparable to using the

DoubleFlip motion gesture to delimit a command mode with a flick motion (average 3.22 s) [96].

The action of some dexterous gestures can have matching semantic associations to improve their memorability [94]. For instance, the spinning gesture performs a lateral rotation which suggests giving or sharing, and therefore could be associated with payment or file sending actions. Flip brings the microphone up and close to the mouth, which creates a possible association with voice commands. Using longer full-gestures makes sense for prolonged actions, such as snoozing an alarm for a longer time.

Dexterous gestures also lend themselves to eyes-free interaction. Negulescu et al. [96] found that motion gestures can decrease the time looking at the smartphone during walking, and since dexterous gestures require even less motion, that finding likely applies as well. A very promising application of eyes-free dexterous gesturing is for people with visual impairments [148]. In an elicitation study, Dim and Ren [25] found that motion gestures are more efficient for blind users, but Romano et al. [112] found that blind users used motion gestures less often because they were unfamiliar and concerned about accidentally hitting nearby objects. Dexterous gestures may have an advantage because they are highly tactile when learning and they require no large movement of the hand or arm.

3.7 CONCLUSION

We explored a new form of physical phone interactions called dexterous gestures which use fine motor skills of fingers to manipulate the device in-hand. We defined a gesture design space consisting of shifting, spinning, rotating, and flipping manipulations, with tilting used as a baseline. A formative study showed that all manipulations except flipping had been previously performed by participants. A performance experiment showed that rotating was fast and the most preferred gesture while a full flip was rated lowest. A prototype system using a heuristic recognizer demonstrated that most spinning, rotating, and flipping gestures can be recognized reliably on standard phones with 91.2% average accuracy, which illustrates how this style of gestures could be used in real applications. A one-week experiment further showed that speed and willingness to adopt dexterous gestures improve after practising, and that there is little difference in using the gestures while sitting or standing. Our exploration shows how human dexterity can be harnessed for new forms of phone interaction.

3.8 APPENDIX: TABLES OF STATISTICAL TESTS

This appendix presents tables of ANOVA and post hoc statistical tests for main effects and interactions of our results in experiment 1 and 2 (Section 3.3 and 3.5).

A.1 Experiment 1: Results

Table 3.4: Main effect

(a) MANIPULATION

		(i) *Time*		(ii) *Ease*		(iii) *Comfort*		(iv) *Confidence*		(v) *Acceptance*	
		$F_{3,51} = 7.31$, $p < .001$, $\eta^2_G = 0.08$		$F_{3,51} = 29.52$, $p < .001$		$F_{3,51} = 30.93$, $p < .001$		$F_{3,51} = 29.78$, $p < .001$		$F_{3,51} = 21.22$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
ROTATE	SHIFT	-0.43	$< .001^{***}$	0.99	$< .01^{**}$	1.16	$< .001^{***}$	0.15	1	-0.01	1
ROTATE	SPIN	-0.9	$< .001^{***}$	0.86	$< .001^{***}$	1.03	$< .001^{***}$	0.95	$< .001^{***}$	1.11	$< .001^{***}$
ROTATE	FLIP	-0.73	$< .001^{***}$	1.96	$< .001^{***}$	2.02	$< .001^{***}$	1.77	$< .001^{***}$	1.79	$< .001^{***}$
SHIFT	SPIN	-0.47	$< .001^{***}$	-0.13	1	-0.13	1	0.8	$< .01^{**}$	1.12	$< .01^{**}$
SHIFT	FLIP	-0.3	$< .001^{***}$	0.97	$< .001^{***}$	0.86	$< .01^{**}$	1.62	$< .001^{***}$	1.8	$< .001^{***}$
SPIN	FLIP	0.17	.15	1.1	$< .001^{***}$	0.99	$< .001^{***}$	0.82	$< .01^{**}$	0.68	.05

(b) MAGNITUDE

		(i) *Time*		(ii) *Ease*		(iii) *Comfort*		(iv) *Confidence*		(v) *Acceptance*	
		$F_{1,17} = 36.42$, $p < .001$, $\eta^2_G = 0.19$		$F_{1,17} = 0.34$, $p < .001$		$F_{1,17} = 28.10$, $p < .001$		$F_{1,17} = 13.86$, $p < .001$		$F_{1,17} = 12.57$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
HALF	FULL	-0.96	$< .001^{***}$	0.8	$< .001^{***}$	0.74	$< .001^{***}$	0.63	$< .001^{***}$	0.56	$< .001^{***}$

Table 3.5: Interaction for *time*. Note: Only the comparisons with significant difference are shown.

(a) MANIPULATION × DIRECTION ($F_{3,51} = 10.69, p < .001, \eta^2_G = 0.05$)

comparisons for ABD		*diff (s)*	*p-value*
ROTATE	SHIFT	-1.11	$< .001^{***}$
ROTATE	SPIN	-0.89	$< .001^{***}$
ROTATE	FLIP	-0.6	$< .001^{***}$
FLIP	SPIN	-0.29	$< .05^{*}$
comparisons for ADD		*diff (s)*	*p-value*
SHIFT	SPIN	-1.16	$< .001^{***}$
SHIFT	FLIP	-1.11	$< .001^{***}$
ROTATE	SPIN	-0.91	$< .001^{***}$
ROTATE	FLIP	-0.86	$< .001^{***}$
comparisons for SHIFT		*diff (s)*	*p-value*
ADD	ABD	-1.14	$< .001^{***}$
comparisons for FLIP		*diff (s)*	*p-value*
ABD	ADD	-0.48	$< .05^{*}$

(b) MANIPULATION × DIRECTION × MAGNITUDE ($F_{2,34} = 5.42, p < .01, \eta^2_G = 0.013$)

comparisons for HALF		*diff (s)*	*p-value*
ROTATE-ABD	SPIN-ABD	-0.82	$< .001^{***}$
ROTATE-ABD	SPIN-ADD	-0.93	$< .001^{***}$
ROTATE-ABD	ROTATE-ADD	-0.57	$< .05^{*}$
ROTATE-ABD	FLIP-ADD	-1.05	$< .001^{***}$
ROTATE-ADD	SPIN-ABD	-0.25	$< .01^{**}$
ROTATE-ADD	FLIP-ADD	-0.48	$< .001^{***}$
FLIP-ABD	SPIN-ABD	-0.62	$< .001^{***}$
FLIP-ABD	FLIP-ADD	-0.85	$< .001^{***}$
comparisons for FULL		*diff (s)*	*p-value*
ROTATE-ABD	SPIN-ABD	-0.94	$< .001^{***}$
ROTATE-ABD	SPIN-ADD	-1.3	$< .001^{***}$
ROTATE-ABD	FLIP-ABD	-0.92	$< .001^{***}$
ROTATE-ABD	FLIP-ADD	-1.06	$< .001^{***}$
ROTATE-ADD	SPIN-ABD	-1.1	$< .001^{***}$
ROTATE-ADD	SPIN-ADD	-1.46	$< .001^{***}$
ROTATE-ADD	FLIP-ABD	-1.08	$< .001^{***}$
ROTATE-ADD	FLIP-ADD	-1.22	$< .001^{***}$

A.2 Experiment 2: Results for Before and After Practice

Table 3.6: Main effect and interaction for SESSION. Note: Only measures with significant difference are shown.

(a) SESSION

	(i) *Time*	(ii) *Ease*	(iii) *Comfort*	(iv) *Confidence*	(v) *Acceptance*
	$F_{1,11} = 9.31$, $p < .05$, $\eta^2_G = 0.07$	$F_{1,11} = 19.98$, $p < .001$	$F_{1,11} = 23.6$, $p < .001$	$F_{1,11} = 14.95$, $p < .001$	$F_{1,11} = 15.46$, $p < .001$

comparisons	*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
AFTER BEFORE	-0.32	< .05*	0.74	< .001***	0.75	< .001***	0.51	< .001***	0.57	< .001***

(b) SESSION $\times$ MANIPULATION

	(i) *Ease*	(ii) *Comfort*	(iii) *Confidence*	(iv) *Acceptance*
	$F_{2,22} = 5.66$, $p < .01$	$F_{2,22} = 9.99$, $p < .001$	$F_{2,22} = 6.83$, $p < .01$	$F_{2,22} = 7.11$, $p < .01$

comparisons for FLIP	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
AFTER BEFORE	1.54	< .05*	1.67	< .001***	1.29	0.29	1.25	< .05*

A.3 Experiment 2: Results for Sitting versus Standing

Table 3.7: Main effect. Note: Only measures with significant difference are shown.

(a) MANIPULATION

		(i) *Time*		(ii) *Smoothness*		(iii) *Ease*		(iv) *Comfort*		(v) *Confidence*		(vi) *Acceptance*	
		$F_{1.09,11.96} = 34.49$, $p < .001$, $\eta^2_G = 0.47$		$F_{1.32,14.54} = 6.11$, $p < .05$, $\eta^2_G = 0.12$		$F_{2,22} = 81.44$, $p < .001$		$F_{2,22} = 83.34$, $p < .001$		$F_{2,22} = 45.66$, $p < .001$		$F_{2,22} = 42.03$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
ROTATE	SPIN	-1.21	< .001***	-0.007	< .001***	1.41	< .001***	1.62	< .001***	0.93	< .001***	0.83	< .001***
ROTATE	FLIP	-1.03	< .001***	-0.0048	< .01**	1.73	< .001***	1.98	< .001***	1.73	< .001***	1.64	< .001***
SPIN	FLIP	0.18	1	0.0022	1	0.32	.12	0.36	.13	0.8	< .01**	0.81	< .01**

(b) DIRECTION

		(i) *Time*	
		$F_{1,11} = 22.59$, $p < .001$, $\eta^2_G = 0.14$	
comparisons		*diff (s)*	*p-value*
ADD	ABD	-0.47	< .001***

4 EXPANDING SIDE TOUCH INPUT ON MOBILE PHONES: FINGER REACHABILITY AND TWO-DIMENSIONAL TAPS AND FLICKS USING THE INDEX AND THUMB

Phones are increasingly powerful, but the dominant form of phone interaction, touch input, still has issues like occlusion [128, 149] and imprecision [45, 150]. Moreover, limited screen real-estate means graphical user interface controls (like buttons) compete with the document of interest (like a photo being edited). When designers must choose between showing more of the document or more of the interface, the solution is usually hiding the interface inside menus or behind delimiters like press-and-hold, both of which slow down interaction. Consequently, researchers continue to investigate new forms of phone input. One general approach is to move input off the screen to the side. Examples include more expressive physical buttons [58], various forms of grip sensing [53, 106, 134, 154], as well as sensing side taps [125] and side touches [63, 75, 93]. With new bezel-less phones, wrap-around touch screens [170], and foldable phones [167], a move from side buttons to side touch input could be next. This also makes sense when you consider how phones already transitioned from front physical keys to full screen touch input to gain more versatility.

Accessing many commands with side touch input could reduce time for menu navigation and press-and-hold delays, but moving some touch interaction to the side has other advantages. The front display is not occluded by the finger, and the front display is nearby for side touch feedback and contextual help. Moreover, users already interact on the side using physical buttons for functions like power, volume, and triggering the camera shutter. Some forms of side touch input have been proposed before. For example, McGrath and Li detected side taps using an accelerometer [93], Kato et al. used conductive strips to extend standard phone screen capacitive sensing to the side [63], and Le et al. developed sensing methods for a fully touch sensitive phone that included one-dimensional capacitive sensors on the sides [75]. Our work extends these initial ideas with an empirically-grounded exploration of a larger side touch input space designed for one-handed usage.

Beginning with a "reachability" study, we examine comfort and grip stability when holding a phone one-handed and reaching to different side locations using one of the five fingers, measured with three representative phone sizes. The results show that virtually any location around the side of a phone can be reached with at least one finger assuming some grip change, but the most capable and stable fingers across phone sizes are the index and thumb when reaching along the left and right sides.

We use these reachability results to ground an investigation into an expanded side touch input space. We add a second dimension by distinguishing which part of the side "edge" is contacted: upper edge, middle surface, or

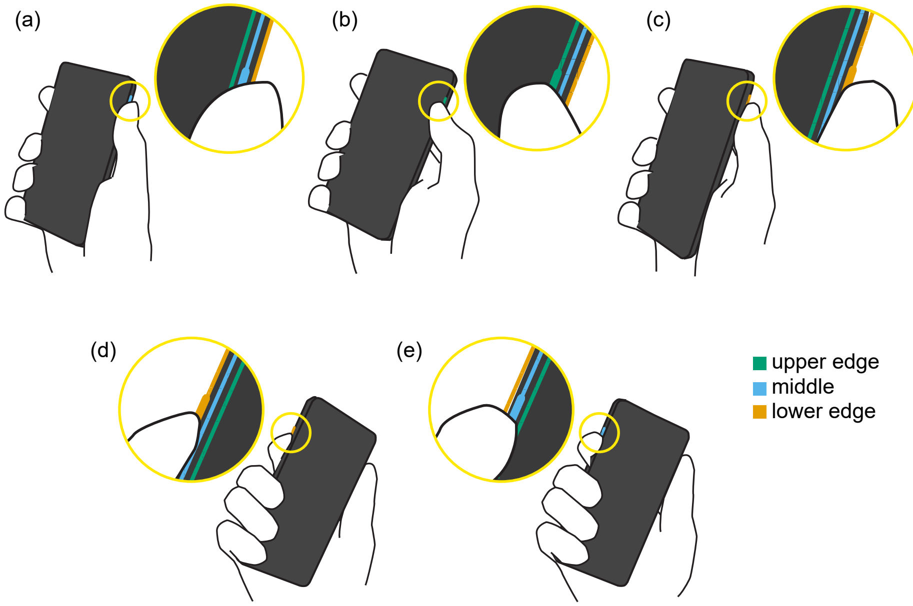

Figure 4.1: Two-dimensional side touch input uses the two edges and middle surface, for example: (a) thumb on middle surface; (b) thumb on upper edge; (c) thumb on lower edge; (d) index finger on lower edge; (e) index finger on middle surface.

lower edge (see Fig. 4.1). Similar to work exploring touch along and across the end of a table [61], we investigate two-dimensional side taps, based on the position along the side and which edge was touched, and two-dimensional flicks that can be performed along or across the edges. In two experiments, we investigate the comfort, speed, and accuracy of this expanded side touch interaction space using the index and the thumb. Our results show the index finger is more error prone, but likely usable for simple taps on one edge, while thumb taps and flicks can be performed quickly on different edges with acceptable accuracy and comfort.

This expanded input space could be used to augment, accelerate, or even replace widgets or commands in current phone interfaces. For example, index finger side taps at two positions could switch the mode for thumb touchscreen input (e.g. selecting landmarks or panning a map). Thumb taps along the lower side edge could switch between applications (e.g. between the last few active ones, or personal shortcuts); thumb taps and flicks along the middle surface of side could be used to access the application menu (e.g. tap to trigger the item, flicks to show the menu on screen and scroll through a longer menu); and thumb taps and flicks along the upper side edge could be used for more expressive access to global commands (e.g. taps for functions like opening system settings, showing notifications, returning to home, turning on the flashlight, and two directions of flicks at certain locations for adjusting volume, brightness, or zoom). In addition, two directional flicks across multiple edges at different locations could be used for common actions like answer or ignore a phone call, the contextual back button, or locking the phone. We provide more example applications later in this chapter and in the paper video [160].

Our work contributes two new aspects to the study of side touch input: (1) key results and a comprehensive dataset of one-handed comfort and grip stability when reaching for different side locations; and (2) a more expressive two-dimensional side touch input space investigated in two experiments.

4.1 BACKGROUND AND RELATED WORK

In chapter 2, we describe previous works related to side touch interactions. Here, we further look at researches of finger touch reachability of mobile phones.

Reachability

Understanding how easy it is to reach touch screen locations can guide the design of applications and interfaces. Early work by Karlson et al. investigated one-handed phone use, including an empirical evaluation into how device size, input location, and movement direction influenced "thumb agility" [62]. Bergstrom-Lehtovirta and Oulasvirta [8] modelled reach locations of the thumb using multiple quadratic expressions. Eardley et al. [28] examined the effect of grip shifts and hand movements measured by resulting phone movement during a selection task. Across four different phone sizes, four different grips, and touch targets inside and outside Bergstrom-Lehtovirta and Oulasvirta's functional area, they found phone movement increased with larger phones and when using a one-handed grip. Two follow-up workshops examined how interaction designers considered the reachability of the thumb when designing for different grips, including one-handed thumb input [28].

Other works have looked are reachability beyond the front touchscreen. Yoo et al. [162] measured reachable areas on the front and back using the thumb or index finger, finding reachable areas on the back can compensate for those unreachable on the front. Le et al. [78] examined the natural placement of fingers when holding a phone for the purpose of minimizing false positives of back-of-device touches. Most related to our reachability study is Le et al.'s work [74]. They measured the comfort zone and extreme reach area for all five fingers on the front and back surfaces when using a phone one-handed. Their task asked participants to not change their grip and the sides were not explicitly tested. Unlike previous work, we specifically focus on reachability around the sides and corners of a phone. Moreover, we allow participants to change grip which we use as a quantitative objective measure for how difficult locations are to reach.

In summary, previous work modelled finger reach when touching the top or back of the device, and demonstrated sensing for simple one-dimensional side input like taps and slides. We combine and extend these areas by studying

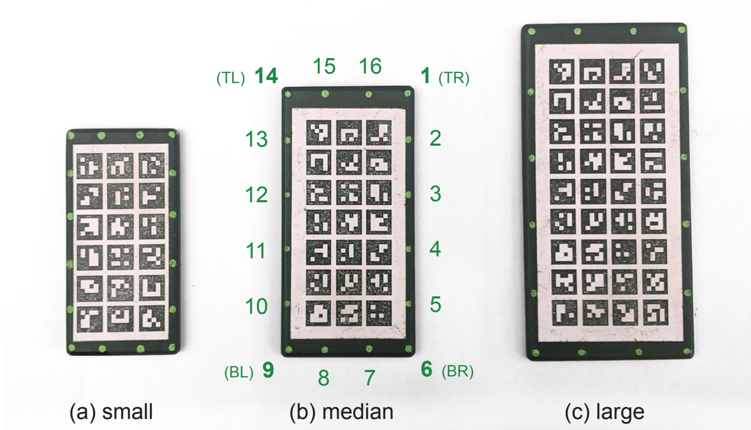

Figure 4.2: Three sizes of phone mock-ups used in reachability study. The 16 green dots are target locations, in our results, each location is labelled 1 to 16 clockwise, starting at top-right.

reachability around sides and use the results to motivate a human factors investigation into a more expressive two-dimensional side input space.

4.2 EXPERIMENT 1: REACHABILITY

The goal of this first experiment is to understand preference and ability when reaching for locations on the sides of a phone. All five fingers of the dominant hand are tested using three representative phone mock-ups. We use the results to scope our explorations of tap and flick side input in the experiments that follow.

Participants

We recruited 18 right-handed participants from a university, the average age was 24 years (SD = 3.7), with 13 males and 5 females. Participants were required to have full use of their right hand and fingers (e.g. no osteoarthritis). Average hand measurements are (in mm): thumb (64 SD = 6), index (74 SD = 5), middle (81 SD = 6), ring (73 SD = 6), pinky (59 SD = 5), palm width (83 SD = 7), and hand length (187 SD = 14, from 164 to 215). All participant hand lengths are in the 95th percentile of anthropometric measures [104]. Remuneration was $15.

Apparatus

We built three phone mock-ups to control for phone dimension and weight (Fig. 4.2). Each was 3D printed, sanded, spray painted, and weighted using lead pellets. To ensure dimensions and weight were representative of current phones, we analyzed characteristics of commercial phones released from 2015 to 2018 by eight major companies (Apple, Samsung, LG, Google,

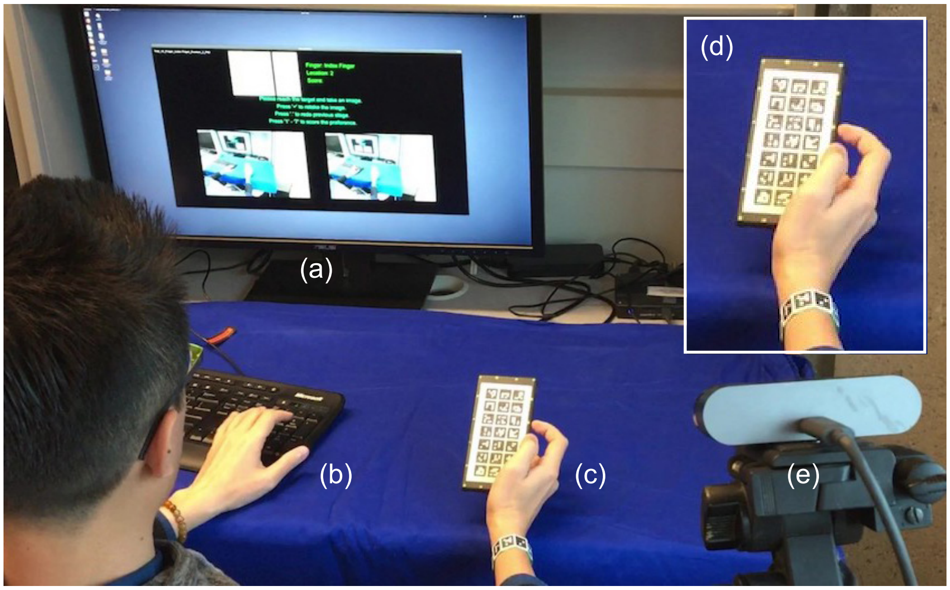

Figure 4.3: Reachability apparatus and setup: (a) display showing stimulus and rating question; (b) keyboard to indicate trial start and end, and enter rating; (c, d) mock-up held in dominant hand with tracking markers on wristband; (e) over-the-shoulder camera.

Motorola, Sony, HTC, Huawei) by scraping data from an online comparison website [176]. We calculated the minimum, maximum, and median of the largest diagonal measurement of the entire phone, then calculated the corresponding height, width, thickness, and weight with linear regressions. This resulted in these three mock-ups: *Small* ($61 \times 123 \times 9$ mm, 110 g); *Median* ($73 \times 148 \times 8$ mm, 157 g); and *Large* ($91 \times 184 \times 7$ mm, 220 g).

Participants sat in a chair with no armrest in front of a desk, and they held a mock-up using only their dominant hand without resting it on the desk (Fig. 4.3). A keyboard operated with their other hand captured frames and entered numeric ratings. The screen area of each mock-up was covered with a grid of printed tracking markers [35, 113], and the participant wore a paper wristband covered with the same type of markers. This enabled the position and orientation of the mock-up and the participant's wrist to be tracked in 3D using a wide angle camera (82°, 1920×1080 px, 60 fps). A blue cloth covered the desk, so the phone and hand could be reliably isolated using skin detection and thresholding.

Procedure

Each trial was divided into three distinct steps. This normalized the initial grip across trials. First, the participant held the mock-up with a comfortable grip, and pretended to perform a left-to-right swipe gesture with their thumb (like the common unlock gesture). At the end of the swipe, they pressed a key with their other hand to capture an image of the mockup and their dominant hand with the camera. We call this the *initial grip*. Then, the target location and finger to use were displayed, and the participant touched the side of the phone at the requested dot location. Participants were instructed to balance speed and accuracy, and they could change their grip as long as they did not use their other hand and they could see the simulated mock-up screen at all times. They could declare the location to be unreachable, but in most cases a second image captured the positions of the mock-up and hand to calculate how much the grip changed. We call this the *reaching grip*. Third, the participant rated how easy and comfortable it was to reach the target using the required finger. The rating was a numeric scale from 1 to 7, with the addition of a special "0" rating used when the location was unreachable.

Design

The experiment was within-subjects with three factors: phone SIZE with 3 levels { SMALL, MEDIAN, LARGE }; FINGER used with 5 conditions { THUMB, INDEX, MIDDLE, RING, PINKY }; and LOCATION with 16 levels { $1, 2, 3, ..., 16$ } representing the 16 locations around the side of the phone (illustrated in Fig. 4.2). The order of SIZE was determined using a balanced Latin square and the orders of other factors was randomized. An experiment session lasted 1.5 h on average.

Results

The dependent measures are the subjective *Ease and Comfort Rating* and an objective metric for relative *Grip Stability*. Figure 4.4 summarizes the main results by plotting the thumb and index finger compared to the best performing across the remaining three fingers. A complete dataset and graphs showing results for each finger are available[1].

Ease and Comfort Rating — Overall, the thumb was rated highest followed by the index, and no finger had an average rating below neutral. Using an ART [156] due to a non-normal distribution, then an ANOVA, there is a main effect of FINGER ($F_{4,68} = 333.66$, $p < .0001$), with Bonferroni corrected pairwise comparisons finding all fingers significantly different ($p < .05$ between RING and PINKY, $p < .0001$ for all other pairs). Ratings in descending order, are THUMB (5.4, SD = 1.6), INDEX (5.0, SD = 1.8), MIDDLE (4.3, SD = 1.9), RING (3.7, SD = 2.1), and PINKY (3.4, SD = 2.3).

A smaller phone size is easier and more comfortable to reach overall. This is shown by a main effect of SIZE ($F_{2,34} = 43.76$, $p < .0001$), with all sizes significantly different (all $p < .001$): SMALL is rated highest (4.6, SD = 2.1) followed by MEDIAN (4.3, SD = 2.1) and LARGE (4.1, SD = 2.1).

When combining all finger and phone sizes, the locations on the left side are rated higher (likely because four out of five fingers can reach many locations on the left, but very few on the right). In addition, there is some preference for

1 Complete dataset, additional graphs, and an interactive tool to visualize reachability results provided as paper supplementary materials [160].

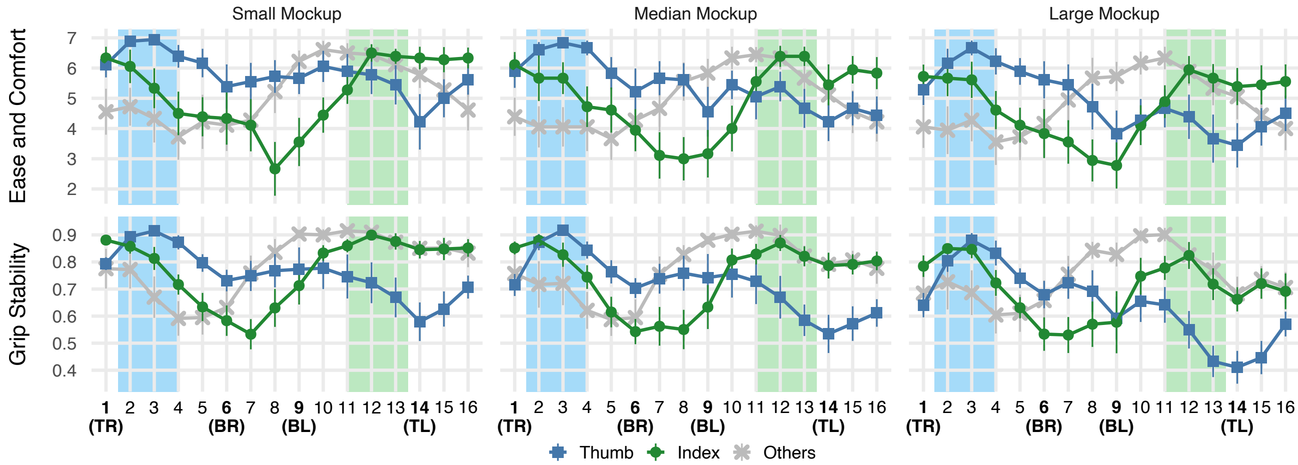

Figure 4.4: *Ease and Comfort Rating* and *Grip Stability* by LOCATION and SIZE for THUMB, INDEX, and best rating/stability across *other* three fingers. Shaded areas show locations tested in later experiments. (Error bars 95% CI)

the middle-right position. There is a main effect of LOCATION ($F_{15,255} = 52.45$, $p < .0001$) with pairwise comparisons showing groups of location differences (all $p < .05$). First, the bottom-left side (LOCATIONS $\{10, 11, 12\}$) are rated higher than all other locations, the left locations LOCATIONS $\{9, 13\}$ are higher than those around the right side (LOCATIONS $\{1, 4, 5, 6, 7, 15, 16\}$), and the top-left corner (LOCATION $\{14\}$) is rated more highly than the bottom-right corner (LOCATIONS $\{5, 6\}$) and nearby left locations ($\{13, 16\}$). Second, the middle-right location (LOCATION $\{3\}$) is more comfortable than bottom-right locations (LOCATIONS $\{5, 6\}$).

There is both a FINGER $\times$ LOCATION interaction ($F_{60,1020} = 36.65$, $p < .0001$) and a FINGER $\times$ SIZE interaction ($F_{8,136} = 2.95$, $p < .0001$). Pairwise comparisons are unreliable for interactions with ART data [156], so we discuss overall effects. The first interaction is unsurprising, it only confirms different locations are more easily reached with different fingers. For the second interaction with SIZE, Figure 4.4 and additional graphs in supplementary materials[1] suggest it is unlikely to involve the index and thumb finger.

Grip Stability — This is a dependent measure capturing how little the hand changes when reaching for a location with a finger. It is a relative measure calculated using the initial grip image (at the start of a trial) and the reaching grip image (at the end of the trial). The measure combines three different metrics of grip stability, all capture relative changes for the reaching grip: (1) phone *translation*; (2) phone *rotation*; and (3) visible skin area (i.e. visible area of the hand). Note Le et al.'s study of unintentional touch input [76] used a related "grip shift" metric based on grip range, finger movement speed and fingertip trajectory length. However, that metric requires full hand motion tracking which is time consuming to setup for each participant and is ultimately dependent on calibration quality and performance of the hand tracking software. Our metric uses a much simpler setup, and incorporates

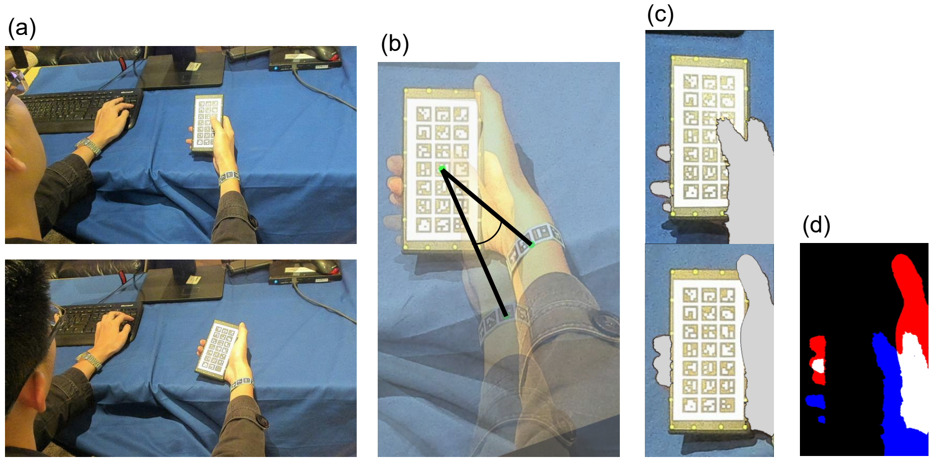

Figure 4.5: Grip stability calculation. (a-top) initial grip image; (a-bottom) reaching grip image at end of trial when touching the target; (b) images superimposed after perspective rectification, translational and angular differences measured between wrist and phone centre; (c) skin detection results for initial (top) and reaching (bottom); (d) ratio of skin area change, blue is skin area only at initial grip, red is skin area only at reaching grip, white is skin area in both grips.

images of the actual hand in the form of the visible skin area. In addition, we consider phone rotation, a likely side effect of larger grip changes.

The fiducial markers on the phone and on the wrist are used to find their 3D positions and orientations in the captured initial grip image and reaching grip image. With these positions and orientations, the translation change and angular change can be calculated. To find the change in visible skin area, the initial and reaching images are rectified and scaled to a standard frame-of-reference using the 3D mockup position determined by the fiducial markers. This places the front face of the mock-up in a dimension-accurate rectangle, with the hand and fingers captured in the rectangle (over the mock-up) and around the rectangle (over the blue fabric covered desk). In each rectified image, Kolkur et al.'s skin detection algorithm isolates skin pixels [70]. The ratio of skin area that changed is calculated by finding the absolute difference between the skin masks in the two images, over the skin area in the initial grip. These three metrics are combined into a single grip stability measure by normalizing each metric per participant to range from 0 to 1 (using min and max for that participant), then averaging the three values. We subtract this average from 1 to create a measure of grip stability, where 1 is most stable (requiring the least grip change).

Since our protocol allowed participants to declare a location unreachable, some *Grip Stability* data is missing, making standard ANOVA unsuitable. In addition, data residuals from linear mixed modelling (LMM) are not normally distributed, so an LMM-based analysis is also not reliable. Instead, we make observations based on simple effects in Fig. 4.4.

The THUMB has high grip stability for centre to top right side locations peaking around (LOCATION 3). The top right corner (LOCATION 1) is the only right side location where the thumb did not have the highest stability across sizes (the INDEX appears more stable there). On the top left side, INDEX stability is comparable to the best performing of RING, MIDDLE, or PINKY, and much more stable than the THUMB. At most locations, there appears to be a trend of decreasing stability as size increases, most pronounced with left side locations when moving to the LARGE mockup. In addition, little grip change was detected for the location nearest that finger's rest area with little impact from SIZE: around LOCATION 3 for THUMB, 12 for INDEX, 11 and 12 for MIDDLE, 10 and 11 for RING, and 9 and 10 for PINKY. This trend confirms the suitability of our combined grip stability measure.

Discussion

To our knowledge, this study is the first to explore side-touch reachability, but our results do relate to previous front-touch reachability studies, in particular Le et al. [74]. For example, we observed larger comfortable areas for side touches, possibly due to the geometry of side versus front touches or that users are comfortable changing their grip to reach further with side touches.

Overall, the thumb and the index alone can reach most of a phone's side, exclusive of the very bottom-left area. For every side location, at least one finger was rated greater than 5 in preference, suggesting all locations can be comfortably reached. The bottom side is least comfortable and should be used only for infrequent functions. The most promising side locations are the middle to top-right for the thumb and top-left for the index (blue and green shading in Fig. 4.4). Both are good candidates for primary side touch interaction, which we investigate in detail in experiments 2 and 3. To make our results accessible to designers, we created an interactive "reachability viewer" showing interpolated measures for each finger on any device size between our small and large mockups (see supplementary materials[1]).

Grip stability is moderately correlated with ease and comfort ratings (r(4081) = 0.44, $p < .001$), less grip change is generally associated with a higher preference score. However there are exceptions, such as the bottom right corner on the largest phone, where thumb ease and comfort was rated higher than the right-most bottom side, despite reduced grip stability (see Fig. 4.4). It is possible that corner locations are more comfortable, even if reaching them requires more movement.

Comparisons to Related Reachability Studies

Previous work showed the reachability of the topmost touch screen locations is a problem on large phones [8], our results confirm this is also true for phone sides. Indeed, locations on the side of the smaller phone were easier to reach.

Our results reveal nuanced differences when compared to previous reaching studies for front and back displays. The reason is likely due to how reaching

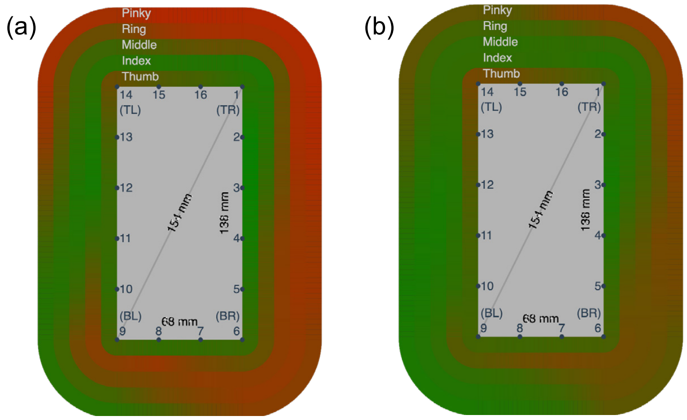

Figure 4.6: Visualizations created with the interactive reachability viewer[1], showing results for a Nexus 5 size for: (a) ease and comfort; (b) grip stability. Interpolated measures are shown as a green-to-red gradient in bands for each finger.

for side positions requires slightly different grips and finger movements, and that our study allows the grip to change when reaching. Yoo et al. [162], Bergstrom-Lehtovirta et al. [8], and Le et al. [74] all report a general trend where the reachable display area with the thumb is about halfway between the top and bottom, for locations near the right side. Our ease and comfort ratings and grip stability support this pattern, but also remain high when near the top. Results for side reachability with the index, align more closely with previous studies examining reachability of the back of a phone [74, 162].

4.3 EXPERIMENT 2: TAPPING

The results of Experiment 1 demonstrate the thumb and index fingers are the most comfortable for side touch interaction, and that the upper portion of the left and right side is preferred. In this experiment, we investigate thumb and index tapping along those side surfaces in detail, with the addition of controlling for which "edge" is contacted: either the upper edge, lower edge, or the space in between (the "middle edge"). This creates a two-dimensional side touch input space. A phone instrumented with three strips of capacitive sensors determines what edge is touched, and optical motion tracking determines the touch position along the side. With this task and apparatus, we measure speed and accuracy, and we also record subjective preference for edge and side position.

Participants

We recruited 12 right-handed participants, average age 25.5 years (SD = 2.7), 3 females and 9 males (one also participated in experiment 1, but the experiments were conducted about one year apart). Again, participants were required to have full use of their right hand and fingers. Average hand measurements (in mm): thumb (64 SD = 5), index (72 SD = 5), palm width (82 SD = 7), and hand length (180 SD = 12, from 157 to 205). Hand lengths are in the 95th percentile [104]. Remuneration was $10.

Apparatus

We combined capacitive sensing with a motion tracking system to simulate touch events on the side of phone (Fig. 4.7b). Two devices were created, one for sensing touches on the right side with the thumb, and one for sensing touches on the left with the index finger. Three 1 mm wide copper foil strips were attached to the side of a Google Nexus 5, (138 × 69 × 8.6 mm), which is slightly smaller than the median-sized mockup. The strips are attached to a MPR121 capacitive sensor and Arduino Uno, both mounted to a PCB and attached to the back of the phone with a USB cable connected to a laptop. For the position of the touch along the side, we use a Vicon motion tracking system. One tracking marker is attached to the nearest top corner of the phone and three markers are attached to the participant's thumb or index fingernail. The Arduino and Vicon both stream raw input to the laptop, then combined to identify the edge and position of the side touch. The laptop sends a stream of these events to the experiment web application running on the phone using a websocket.

The capacitive strips register when a touch occurs, but each strip does not strictly represent an edge. Participants are told to touch the position where they think the target edge is, regardless if they contact one or more strips. With this in mind, the input edge is determined as follows: (1) if only the lower strip or both lower and middle strips were touched, then the input is lower edge; (2) if only the middle strip or all three strips were touched, then the input is middle edge; (3) if only the upper strip or both upper and middle strips are touched, then the input is upper edge. Note that each pattern of strip touches is mapped to one input edge. When the index finger is tested with only lower and middle edge targets, any touches that would have resulted in an upper edge input, like touching only the upper strip, or both upper and middle strips, were considered a non-touch, meaning no edge input was registered at all. This means touching the middle edge with the index was no easier than the thumb in terms of sensing rules.

Initial tests showed the bottom of a strip may be unintentionally touched by the palm or other fingers when reaching for the top portion of the side. To compensate, we implemented a simple type of "palm rejection" by splitting each 68 mm strip into two sections with a 3 mm gap. The right "thumb" side has a 25 mm top section and a 40 mm lower section. The left "index" side has a 53 mm top section and a 12 mm lower section. The split point differs to accommodate how the hand grips the phone. Each strip section is sensed independently, so when combined with the tracked finger position, we can reject unintentional touches when reaching for the top part of the strip.

The tap event is triggered when the finger is lifted, known as a "take-off strategy" [105] commonly used in touch interfaces. The tap location uses the tracked finger position at the median timestamp between the first and last

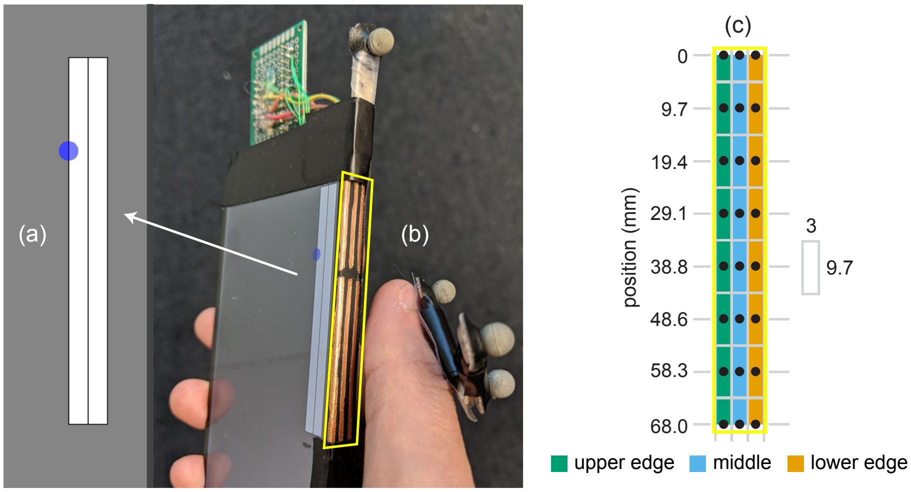

Figure 4.7: Experiment 2 apparatus and task: (a) example tapping task stimulus; (b) simulated side touch sensor using capacitive strips to detect edge and marker-based tracking for finger position; (c) schematic showing tapping task target positions and sizes.

capacitive contacts. Note this introduces no additional latency. The finger tip angle also changes for different touch points along the side, so the motion-tracked finger position must be calibrated. We use a method similar to Joshi and Vogel [61] where the participant completes a sequence of taps at known target locations to interpolate a position correction offset. In our case, we had 9 targets from combinations of the 3 edges and 3 positions along the side (strip top, strip split point, and strip bottom). The logged positions for top and bottom targets are used to create a linear interpolation of tracked-finger to intended-touch position offsets. The strip split location is used for rejecting unintentional palm touches from the palm or other fingers.

Task

Each trial begins by tapping a 9 by 9 mm start button on the screen, always using the right thumb. The button is positioned 38 mm from the bottom and 8 mm from right side of the device, putting it near the comfort "sweet spot" [92]. This normalizes the initial grip on the phone. After, a stimulus shows the target tap position and edge (Fig. 4.7a). If the trial is successful, the recognized touch position is displayed for 0.5 s for additional feedback. If the trial was an error, the recognized position is shown in red for 3 s as a penalty (the penalty time is not included in analysis). Participants are told to complete the task both quickly and accurately, but when we piloted the task, we found they favoured speed without this additional error penalty. Fig. 4.7c illustrates the locations of the 3 mm by 9.7 mm targets. Our pilot tests found touching only the upper edge with the index finger was very error-prone, so only the lower edge and middle are tested for that finger. All three edges are tested with the thumb.

Procedure

The experiment is divided in two parts, thumb and index finger. Each part began with instructions and attaching tracking markers to the participant's finger. After an initial calibration (described above), the participant completed a practice block of all task trials, then six blocks of recorded trials. Pilot tests found that some participants continued to make slight adjustments to their grip and finger angles as they became more comfortable with the task, so the calibration procedure was repeated between each of the first four blocks. After all blocks were completed for a part, the participant rated their preference by considering the comfort and ease-of-use for each target position at each edge using a numeric score from 1 to 7 score. The experiment lasted approximately 60 min.

Design

The design is within subjects with BLOCK and three main factors: FINGER { THUMB, INDEX }; POSITION along side of phone from the top in mm { 0, 9.7, 19.4, 29.1, 36.8, 48.6, 58.3, 68 } (see Fig. 4.7c); EDGE { UPPER, MIDDLE, LOWER } in THUMB condition, and { MIDDLE, LOWER } in INDEX condition. The order of FINGER was counter balanced. The order of the other factors was randomized, with each combination of EDGE and POSITION occurring once per block. We recorded 240 trials per participant, 2880 trials in total.

There are three dependent measures. The *Ease and Comfort* preference rating describe above. The *Time* elapsed between the start button press, and the tap on the sensor, measured in seconds. An an erroneous trial should not result in a different or longer motor action by the participant, and visual inspection of the patterns of *Time* data including or excluding trials with errors revealed little difference between the two. Following Soukoreff and Mackenzie [132], our *Time* analysis includes both correct and erroneous trials. The *Error Rate* is the number of trials where one or more errors occurred over the total number of trials. Error tolerance was 4.9 mm for along-edge positions.

Analysis

ANOVA and Bonferroni corrected pairwise comparisons were used. Because the design is not identical for each FINGER, and we are primarily interested in examining performance of each finger for given positions and edges, we conduct primary analysis separately for INDEX and THUMB. To compare INDEX and THUMB directly, we remove UPPER and use the remaining levels in a complete design.

Results: Thumb Tapping

Learning Effect — An ANOVA found a significant effect of BLOCK on *Time* ($F_{5,55} = 5.28$, $p < .001$, $\eta^2_G = .016$). Pairwise comparisons show significant differences between block 1 and blocks 4, 5, 6, and between block 3 and block

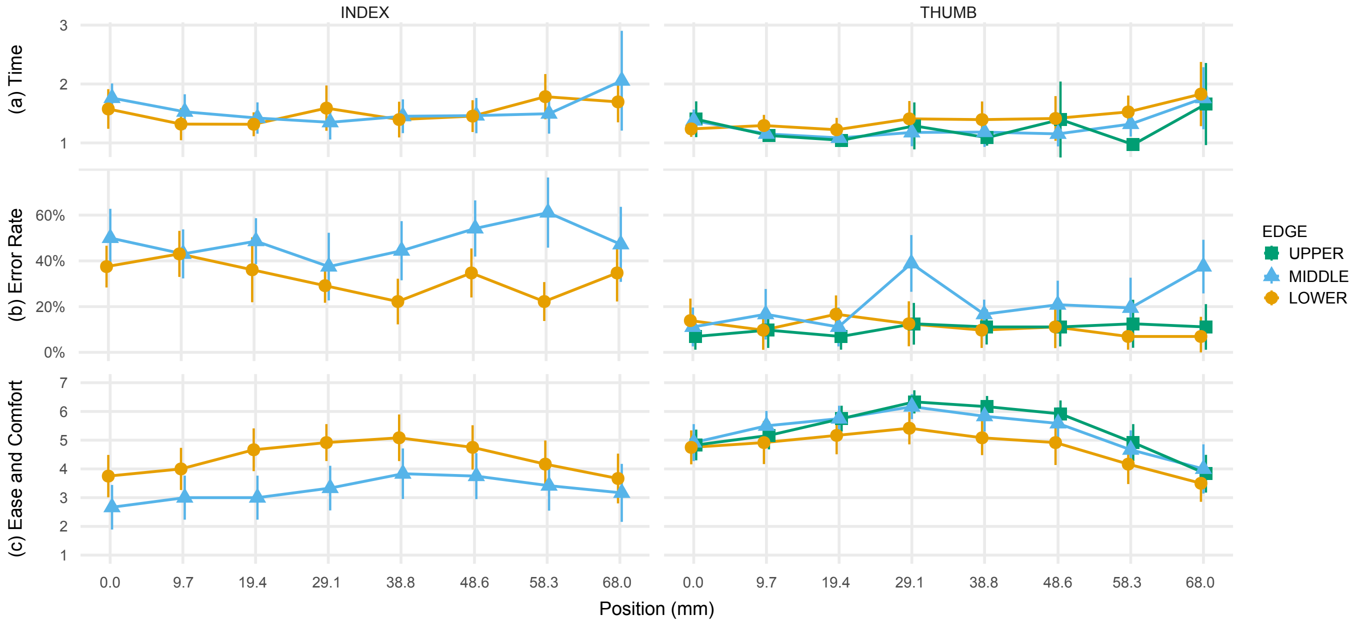

Figure 4.8: Experiment 2 results for tapping: (a) Time; (b) Error Rate; (c) Ease and comfort rating (error bars are 95% CI).

6 (all $p < .05$). Given the small effect size for *Time*, and no effect on *Error Rate*, all blocks are used in analysis.

Time — Tapping on the bottom position is 0.41s slower than the other positions (Fig. 4.8a right), but no difference in time was found between edges. There was a main effect of POSITION ($F_{7,77} = 3.812$, $p < .01$, $\eta^2_G = .071$), with pairwise differences between POSITION 68mm (the bottom target) and all others (all $p < .05$). The mean time of POSITION 68mm was 1.75s while other position means ranged from 1.19 to 1.34s. There was no significant effect of EDGE. The mean time for UPPER, MIDDLE, and LOWER are 1.24s, 1.27s and 1.41s.

Error Rate — Errors can be due to wrong POSITION, the tap point is outside the target cell (Fig. 4.7b), or wrong EDGE. Any unintended touches also count as errors. Overall, selecting upper and lower edge targets was 11% more accurate than the middle edge (Fig. 4.8b right). There was a main effect of EDGE ($F_{2,22} = 5.01$, $p < .05$, $\eta^2_G = .084$), with pairwise differences between LOWER and MIDDLE ($p < .001$) and between UPPER and MIDDLE ($p < .001$). Error rates for UPPER, MIDDLE, and LOWER were 11%, 22% and 10%. There was also an interaction between EDGE and POSITION ($F_{14,154} = 2.95$, $p < .001$, $\eta^2_G = .025$), with pairwise differences between (MIDDLE, POSITION 29.1 mm) and all other pairs except bottom positions of MIDDLE (POSITION 48.6, 58.3, 68 mm) ($p < .05$). There are differences between (MIDDLE, POSITION 68mm) and all others except (MIDDLE, POSITION 9.7 mm), (LOWER, POSITION 19.4 mm) and the bottom part of MIDDLE (POSITION 38.8, 48.6, 58.3 mm) ($p < .05$). The bottom positions of MIDDLE are less accurate. The average error rate across participants is 14% (SD = 7%).

Ease and Comfort — Tapping upper or middle edge midway up the side is more comfortable than at other positions (Fig. 4.8c right). Using ART data, there was a main effect of EDGE ($F_{2,22} = 7.658$, $p < .001$) with post hoc tests revealing that LOWER was more uncomfortable (4.7) than UPPER (5.4) and MIDDLE (5.3). There was a main effect of POSITION ($F_{7,77} = 15.11$, $p < .001$). Pairwise comparisons show midway POSITIONS (29.1, 38.8 mm) are rated higher than POSITIONS (0, 58.3, 68 mm) ($p < .05$) and bottom POSITION 68mm is rated lower than POSITIONS (0, 9.7, 19.4, 48.6 mm) ($p < .05$).

Results: Index Tapping

Learning Effect — An ANOVA found a significant effect of BLOCK on *Time* ($F_{5,55} = 2.61$, $p < .05$, $\eta^2_G = .014$) and *Error Rate* ($F_{5,55} = 2.51$, $p < .05$, $\eta^2_G = .009$). However, pairwise comparisons showed no significant differences.

Time — Tapping on the bottom position is 0.51s slower than POSITION 19.4mm when using the index (Fig. 4.8a left). There was a main effect of POSITION ($F_{7,77} = 2.41$, $p < .05$, $\eta^2_G = .02$) with pairwise comparisons showing the bottom-most POSITION 68mm was slower than POSITION 19.4mm ($p < .05$). Mean times were 1.88s and 1.37s respectively.

Error Rate — Overall, selecting lower edge targets was 16% more accurate than the middle edge with lower edge targets closer to the bottom most promising (Fig. 4.8b left). There was a main effect of EDGE ($F_{1,11} = 18.65$, $p < .01$, $\eta^2_G = .03$) with pairwise comparisons showing LOWER was more accurate than MIDDLE ($p < .001$), 32% and 48% respectively. There was also an interaction between EDGE and POSITION ($F_{7,77} = 2.15$, $p < .05$, $\eta^2_G = .014$) with comparisons showing (LOWER, POSITION 58.3 mm) was more accurate than (MIDDLE, POSITION 48.6, 58.3 mm), and (LOWER, POSITION 29.1, 38.8 mm) was more accurate than (MIDDLE, POSITION 58.3 mm) (all $p < .05$). These lower edge targets had error rates close to 20%. The average error rate across participants is 40% (SD = 13%).

Ease and Comfort — Tapping on the lower edge is more comfortable than the middle edge (Fig. 4.8c left). There was a main effect of EDGE ($F_{1,11} = 55.12$, $p < .001$) with post hoc tests revealing that LOWER was rated better (4.3) than MIDDLE (3.3). There was also an effect of POSITION ($F_{7,77} = 3.51$, $p < .01$) with comparisons showing the midway POSITION 38.8 mm was rated higher (4.5) than the top POSITION 0 mm (3.2) or the bottom POSITION 68 mm (3.4) ($p < .05$).

Results: Index Compared to Thumb

There is no significant difference between fingers for *Time*, but tapping with the THUMB was 26% more accurate than INDEX. There was a main effect of FINGER on *Error* ($F_{1,11} = 42.84$, $p < .001$, $\eta^2_G = .266$), THUMB (14%) was much lower than INDEX (40%). In addition, tapping with the THUMB was more comfortable than INDEX. The main effect of FINGER on *Ease and Comfort*

($F_{1,11} = 106.64$, $p < .001$) shows the 5.1 rating for THUMB was higher than the 3.8 rating for INDEX.

Discussion

Overall, thumb tapping is more accurate and rated more highly than the index, but not significantly faster. Greater dexterity with the thumb, and more familiarity with using it one-handed with a phone, likely contributed to this finding. When using the thumb, the upper and lower edges were more accurate than the middle surface. This is likely due to greater tactile feedback on the edge. However, the lower edge was least preferred, perhaps because reaching it required more movement away from the touch screen, and sometimes required a looser grip where the palm pulled away from the back of the phone. As expected, with the thumb, midway side positions, closer to a rest position, were preferred compared to higher or lower positions. Overall, two-dimensional side touch input appears feasible with the thumb. The middle edge was difficult to reach with the index, and judged harder to use and less comfortable. Reaching the middle edge with the index can require a curling motion, introducing some finger strain. One-dimensional side input may be more suited to the index. Many errors with the index finger were due to accidental contact by the middle finger with the lower part of the sensor. Consequently, participants tended to keep the middle finger raised which is less comfortable. This may be alleviated by trimming the bottom portion of the capacitive strip, or by detecting the gripping posture [75].

4.4 EXPERIMENT 3: FLICKING

In this experiment, we investigate side input with another common touch action, short and fast dragging actions, commonly called swipes or "flicks". Initial pilot tests found performing flicks with the index finger was unreliable, so this experiment focuses on the thumb. The apparatus and basic protocol is the same as Experiment 2.

Participants

We recruited 12 right-handed participants, average age 26.3 (SD = 3.0), 5 females and 7 males. None participated in Experiment 2. Average hand measurements (in mm): thumb (62 SD = 4), index (71 SD = 4), palm width (80 SD = 7), and hand length (182 SD = 11, from 163 to 201). Hand lengths are in 95th percentile [70]. Remuneration was \$10.

Task and Procedure

The task and procedure was the same as Experiment 2, except there were fewer targets (3 per edge), the targets were larger (3 by 19.4 mm), and the stimulus also indicated a flick direction (Fig. 4.9). Each trial required the participant to flick in a certain direction, starting at a certain position and

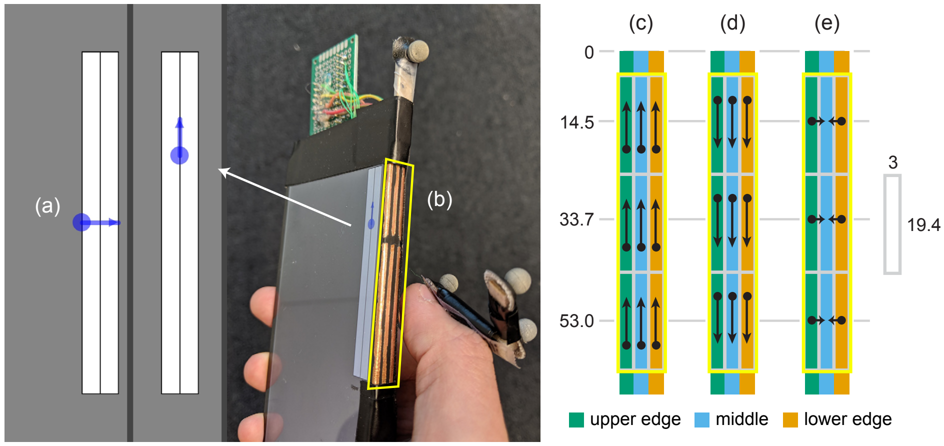

Figure 4.9: Experiment 3 apparatus and task: (a) example stimulus for across-edge and along-edge trials; (b) simulated side touch sensor; (c) schematic showing flick task target positions for along-edge flick abduction; (d) along-edge flick adduction; (e) across-edge flick abduction and adduction.

edge. There are two orthogonal types of flicks, *along-edge* flicks that move along only one edge and *across-edge* flicks that move across two or more edges. For each, there are two movement directions: *adduction* when moving the thumb towards the body (towards the phone front for across-edge flicks, towards the bottom end of the phone for along-edge flicks); and *abduction* when moving the finger away from the body (towards the phone back for across-edge flicks, towards the top end of the phone for along-edge flicks). In addition, along-edge flicks could be along the lower edge, the upper edge, or the middle. Flicks along an edge started at the end of the target opposite to the flick direction. Flicks across edges started on either the upper or lower edge, at the centre of longest dimension of the target. When flicking along an edge, the actual edge used for input is the average edge determined from the capacitive strips during the motion. The rest of the task and procedure was the same as Experiment 2. The experiment lasted approximately 30 minutes.

Design

The experiment was within subjects with four main factors: FLICK type, { ALONG-EDGE, ACROSS-EDGE }; DIRECTION { ADDUCTION, ABDUCTION }; POSITION along side of phone { 14.5, 34.0 and 53.4 mm, from top } EDGE { LOWER, MIDDLE, UPPER } (only in ALONG-EDGE conditions). The order of the factors was randomized, with every combination appearing once per block. We recorded 168 trials per participant, 2016 trials in total.

Results: Along-Edge Flicking

Time — Flicks are slower when performed on the lower edge, or when starting near the topmost position along the side (Fig. 4.10). Trial *Time* is measured on

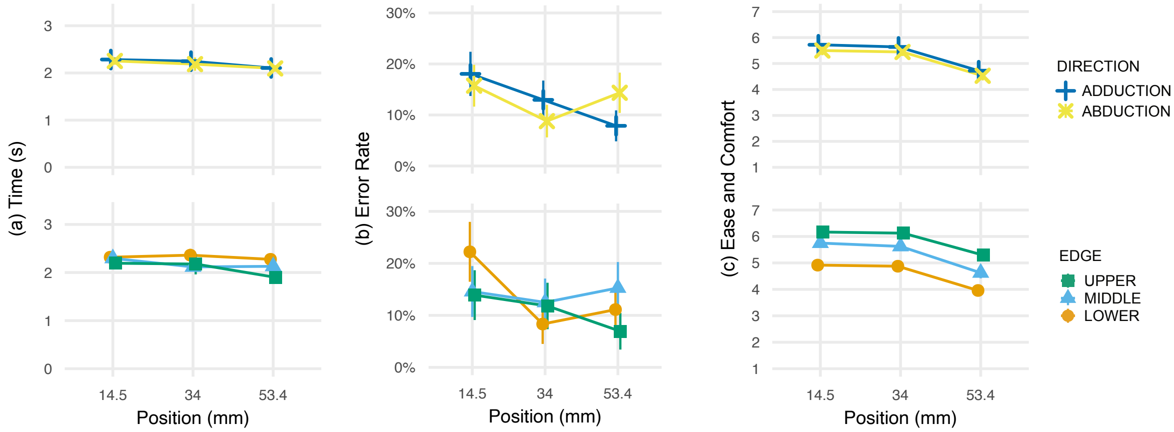

Figure 4.10: Experiment 3 ALONG-EDGE flicks: (a) Time; (b) Error Rate; (c) Ease and comfort rating (error bars are 95% CI).

both correct and erroneous trials, from the moment the start button is pressed until the moment the finger leaves the sensor at the end of the flick. There is a main effect of POSITION ($F_{2,22} = 4.256$, $p < .05$, $\eta^2_G = .027$), with pairwise comparisons revealing the top POSITION 14.5 mm (2.26 s) was slower than the bottom *position* 53.4 mm (2.10 s) ($p < .01$). There is also a main effect of EDGE ($F_{2,22} = 5.66$, $p < .05$, $\eta^2_G = .048$), with pairwise comparisons showing the LOWER edge is slower (2.32 s) than the other two edges (2.18 s for MIDDLE and 2.09 s for UPPER) (both $p < .05$).

Error Rate — An error was recorded when the participant used the wrong POSITION (i.e. starting point of the flick), wrong EDGE (i.e. average edge input during the flick), wrong DIRECTION, or wrong FLICK type when performing the flick. There were main effects on *Error Rate*, and post hoc tests for a DIRECTION × POSITION × EDGE interaction ($F_{4,44} = 2.85$, $p < .05$, $\eta^2_G = .002$) found no significant differences (likely due to small effect size and multiple comparison corrections). The average error rate across participants is 13% (SD = 8%).

Ease and Comfort — Flicking near the top end of the side was rated less than other positions, and the lower edge was rated less than the upper edge. There is a main effect of POSITION ($F_{2,22} = 17.05$, $p < .001$), with pairwise tests finding topmost POSITION 53.4 mm (4.6) to be lower than the other two positions, POSITION 34 mm (5.5) and POSITION 14.5 mm (5.6) (all $p < .0001$). There is also a main effect of EDGE ($F_{2,22} = 22.12$, $p < .001$), with post hoc tests showing UPPER considered most comfortable to use (5.9) and LOWER least comfortable (4.6) ($p < 0.01$).

Results: Across-Edge Flicking

There were no effects of POSITION or DIRECTION on *Time* or *Error Rate* (see Fig. 4.11 for results). An error was recorded when the participant used the wrong POSITION (i.e. starting point), wrong DIRECTION, or wrong FLICK type

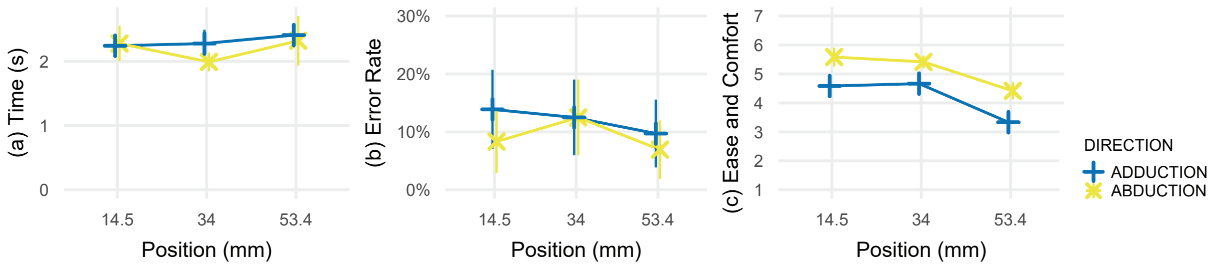

Figure 4.11: Experiment 3 ACROSS-EDGE flicks: (a) Time; (b) Error Rate; (c) Ease and comfort rating (error bars are 95% CI).

when performing the flick. The average error rate across participants is 11% (SD = 7%).

Ease and Comfort — Bottom side positions were rated lower, and flicking away from the body (ABDUCTION) is rated higher than towards the body (ADDUCTION). Using ART data, an ANOVA found a main effect of POSITION on *Ease and Comfort* ($F_{2,22} = 10.57$, $p < .001$) with post hoc tests showing 53.4 mm (3.87) was rated lower than 14.5 mm (5.08) ($p < .001$) and 34 mm (5.30) ($p < .01$). There is also a main effect of DIRECTION ($F_{1,11} = 18.13$, $p < .001$), where ABDUCTION (5.1) is rated more comfortable than ADDUCTION (4.2).

Discussion

The ease and comfort of abduction across-edge flicks (towards the back of the phone) was rated higher. One participant said adductive across-edge flicks (towards the front of the phone) pushed the phone away from the palm, making it harder to maintain a firm grip. As a result, abductive across-edge flicks are a better candidate for frequent functionality.

For flicks along an edge, all positions, and both directions, were rated above neutral. However, those near the bottom were rated lower, even though they were quicker to perform. This follows the pattern of Experiments 1 and 2, likely due to how the thumb bends more acutely when reaching bottom side positions.

4.5 DESIGN IMPLICATIONS

We first summarize design recommendations based on overall results, then present a hardware prototype with demonstration applications for side touch, and finally, discuss limitations in our methods.

Design Recommendations

Location — Overall, middle to upper locations are more appropriate for frequent functions. Moreover, for each location, one finger in particular is often preferred. Consequently, Figure 4.4 provides designers with precise insights in how a side touch gestures are likely to be performed by users, with more details in our supplementary material.

Finger — The thumb, and the area where it is preferred, should almost always be prioritized. It is generally faster, more accurate, and more comfortable. In addition, it is able to comfortably reach a larger side area, and to interact on all upper, middle, and lower "edges", expanding the side touch input space. In contrast, the index is slightly slower, and more error prone. If restricted to non-edge specific 1D side-touch taps, and with more attention to palm rejection, it may be useful for less frequent commands. Based on the reachability of the pinky, ring and middle fingers, there could be some opportunity for using them as reduced side touch input, though this remains untested, and they are critical for gripping the phone. More work is required to evaluate their effectiveness.

Taps and Flicks — Taps are generally faster than flicks, and are more appropriate for frequent commands. However, bi-directional along-edge flicks can enable continuous control, for example to increase or decrease volume, or scroll up and down a page without occlusion.

Flick Position, Edge, and Direction — For both across- and along-edge flicks, using the upper side positions should be prioritized since they were perceived as more comfortable. For along-edge flicks, the lower edge should be privileged in most cases as it is most comfortable. However, using the middle surface is slightly faster, and would be a good compromise. Along-edge flicking is usable in both directions, but more comfortable when flicking from front to back.

Number of Edges and Phone Thickness — Our results show three different edges can be distinguished with the thumb. We used an 8.6 mm thick phone, comparable to 7 mm to 9 mm thicknesses in the market, although there exist very thin high-end phones approaching 5 mm thickness. It is unclear if more than three distinct edges could be reliably used, especially with very thin phones. However, even reducing the number of edges to two would still more than double the capability of a single 1D side touch surface, especially considering along and across edge flicks.

Side Profile Shape — Another factor for reliably sensing multiple edges along the side is the geometric profile of the side of the phone case. A faceted profile, potentially with built-in haptic cues like well-defined ridges, should make "feeling" different edges possible. A perfectly smooth, featureless profile would make feeling multiple edges more difficult. We intentionally designed our the experiment apparatus, and the fully capacitive prototype introduced below, to have a faceted profile to make edges easier to distinguish.

Importance of Palm Rejection — Designing a robust palm rejection method is important part of making side touch techniques practical in real devices. Possible approaches include grip recognition [75] or probabilistic models trained to recognize patterns of unintentional touches along side touch capacitive sensors, similar to approaches for pen input palm rejection [121].

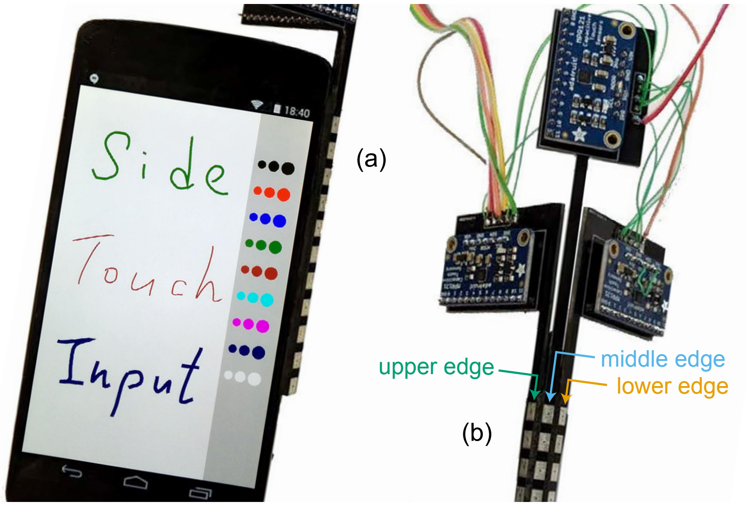

Figure 4.12: Side Touch Prototype: (a) example application; (b) side electrode pad pattern.

Prototype and Example Applications

To illustrate the potential of side touch input, we created a fully touch sensing two-dimensional side touch prototype using self capacitance (Fig. 4.12). It uses three custom PCBs, each with a MPR121 capacitive sensor and eleven electrodes. Readings from the boards are combined with an Arduino Mega, which streams touch events with 11 × 3 positions. Using the prototype, we created two simple demonstration applications (also see accompanying video [160]).

A simple drawing application provides an example of a two-dimensional side tap command menu (Fig. 4.12a). Commands are arranged in rows and columns corresponding to side positions and edges. We mapped brush colour to row positions and brush width to edges. For example, a tap on the upper edge near the top sets the brush stroke to thin black. By default, the toolbar is hidden, so the drawing occupies the entirety of the screen. Flicking across the edges reveals or hides the toolbar, but expert users can select an item when the toolbar is hidden. This is a type of rehearsal-based interface [120].

A simple map application demonstrates how taps and flicks could be combined. Flicking along the edge zooms the map in or out, with zoom factor controlled by which edge is used: the lower edge zooms slowly, the upper edge quickly. Tapping the middle surface of the side centres the view at the user's current location, and tapping the upper edge re-centres the view to a predefined location.

Limitations

Our experiments used a simple method to reduce accidental touches, but high error rates for index in particular illustrate more refinement is needed.

This becomes even more critical if both left and right sides are instrumented. A model similar to Le et al. [75] could track hand posture, so touches due to the grip may be differentiated. Also, the Vicon motion tracking system used in experiments 2 and 3 is accurate, but our participants sometimes adopted unusual postures causing the markers to become occluded. Tracking issues could increase error rates, but we did not attempt to filter these out in post processing because our observations suggest they were very infrequent and they are hard to identify automatically. Many of our results likely relate to hand size, for example women typically have smaller hands than men. Our first two experiments have approximately three times as many male participants as female, so there may be a sample bias. Finally, we did not test for more demanding usage settings, such as walking where previous work observed larger grip areas and more finger activity due to hand oscillations [76]. More examination is needed to understand how such settings affect side touch input.

4.6 conclusion

We explored the potential of an expanded one-handed two-dimensional touch input space along the side of a phone. A first study shows that virtually every location around the phone can be comfortably reached with at least one finger. Two subsequent studies evaluate the performance and preference for side taps and flicks, showing that taps and flicks with the thumb has great potential, but the index is less suitable except for simple in-frequent input. We hope our investigation of side touch input provides ideas and evidence to inspire hardware designers to consider this alternative to physical side buttons: harnessing the expressive potential of smooth, touch-sensitive sides on a phone.

5 SINGLE-HANDED FOLDING INTERACTIONS WITH MODERN FLIP PHONES

Deformable input such as bending [39, 123, 139] and folding [42, 65] provides an innovative method to interact with hand-held devices other than touches [36, 65]. Manufacturers have created devices with deformable attributes, such as foldable devices [173, 177, 178] and sliding phones [169]. However, touch remains the dominant input for these devices, the deformable attributes are used for mechanical purposes, like minimizing phone size when not in use or expanding the display size.

To better utilize deformable attributes and bridge the gap between deformable input and created devices, we explore fold gestures as an input method with a modern "flip phone" form factor like the Samsung Flip [177], Motorola Razr [173], and Huawei Pocket [168]. These flip phones appear like a regular smartphone when unfolded, but can be folded in half to form a small pocket-sized square. We focus on single-handed interactions because people more often use their phone one-handed [54] out of habit or convenience, such as when the other hand is encumbered [97]. There has been some exploration of deformable input with novel devices. Fold me [65] is a paper-shaped device with a double-sided display supporting two-handed folding, and Girouard et al. [36] built a bendable smartphone prototype that can be deformed along multiple axis with one hand. However, single-handed fold gestures with a flip phone form factor have not been studied. Inspired by Sensor Synaesthesia combined device motion and touch input [52], we combine device folding with touch input to expand the potential smartphone input vocabulary. Our goal is to answer the research question: *"What types of folding interactions are easy and comfortable for users with modern flip phones"*.

In this chapter, we define three types of manipulations: only-fold, touch-enhanced fold, and fold-enhanced touch. 30 gestures are derived based on fold direction, fold magnitude, and touch location. A hardware sensing prototype resembling current flip phones is created to evaluate these gestures. A study examines how users perform these gestures and their subjective ratings. Results show more than half of the gestures can be comfortably and easily performed. Gestures that do not require pronounced grip changes or finger stretching are preferred, such as touching a location easily in reach of the thumb then folding top section inward. However, subjective ratings seem influenced by how participants choose to hold and manipulate the phone, suggesting the need to allow users to customize gestures and input mappings. Design recommendations for using folding interactions are summarized, and we create mock-up applications demonstrating how these gestures could be used in map browsing, text editing, and menu shortcuts.

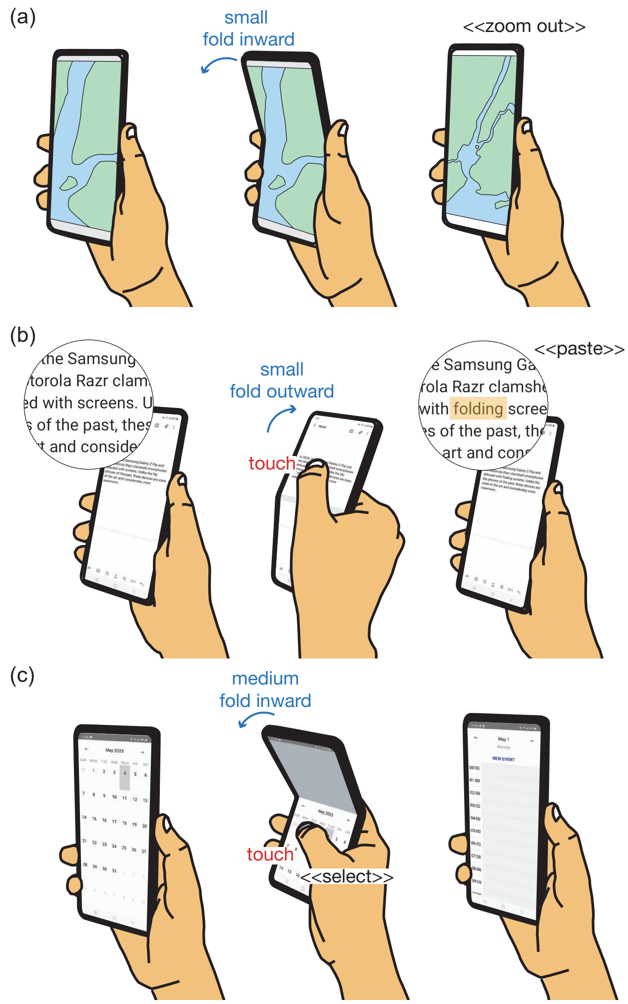

Figure 5.1: Examples of fold gestures: (a) a small inward fold to zoom out the map; (b) touch the top section and fold outward to paste clipboard content into a specific location; (c) a medium inward fold to bring down the calendar interface for selecting a specific date.

In sum, we contribute a formal empirical investigation of folding interactions for modern flip phones in terms of performance and user preference, and demonstrations of possible applications.

5.1 BACKGROUND AND RELATED WORK

In chapter 2, we present physical phone interactions which relate to touch enhanced input and deformable input. Our work relates primarily to bending and folding input, but since we propose combining touch with folding, we further examine previous methods to enhance touch input with deformable interactions.

Touch and Deformable Input

There has been some investigation into deformable gestures to enhance touch input. Rendl et al. [111] propose a phone case with an e-paper display on the cover. By adding pressure and bend sensors, they support bi-manual interactions such as bending the cover to flip pages while touching the screen to select the desired page with two hands. Vogl et al. [151] stitch elastic sensors into a textile band and explore deformable input by stretching it. By integrating it into a phone case, gestures such as using one hand touching the screen and stretching the band with the other hand can be performed to zoom or rotate maps. An experiment is conducted to understand the simplicity and usefulness of proposed applications. However, the performance of gestures is not addressed. FoldMe [65] is a paper-like device prototype that uses projection mapping to simulate a double-sided display device controllable by two-handed fold gestures. Multiple fold gestures are proposed, including two that combine folding with touch gestures, and demonstrated for multitasking, exploring menus, or controlling continuous UI widgets.

In summary, previous work proposed different methods to enhance touch input, and bend or fold gestures on proposed prototypes. A modern flip phone, with a foldable smartphone-sized touch screen, is the first commercial deformable device suitable for single-handed folding interactions that include touch. With such phone form factor, we explore the gesture space of single-handed folding interaction, and further investigate these gestures combining touch input with a user study to understand performance and preference.

5.2 FOLDING INTERACTIONS

Fold gestures can be used for discrete or continuous input. For example, fold a phone past some threshold angle to activate dual-screen mode (discrete), or adjust a brightness level according to the fold angle (continuous) [65]. We focus on discrete gestures, since they are atomic, simple, and easier to perform single-handed.

In our exploration of this folding interaction space, we assume a standard full screen smartphone can be folded partially or fully along one central hinged 'crease' aligned with the smallest screen dimension (i.e. when held in portrait orientation, the phone can fold in half forming a shape resembling a square). We refer to the two sections on either side of the hinge as the 'top' and 'bottom', based on the usual way a portrait oriented phone is held. We further assume there is a double-acting hinge to enable folding in both 'inward' and 'outward' directions, defined relative to the user. In addition, we assume the phone can sense touch input on the 'front' of both sections and the 'back' of the top section, enabling back of device input. We use these terms to refer to the section, fold direction, and touch surface when describing folding interactions throughout this chapter.

Adopted from previous work exploring related kinds of folding and bending [36, 69] and the combination of touch and motion gestures [52], we propose three types of folding interactions each with input parameters that can be used to define different fold gestures (Fig. 5.2):

Only-Fold

This interaction uses only a fold event. Input variations include *inward* and *outward* fold direction and the angular magnitude of the fold. Magnitude is defined as a target angle with a discretized range, such as "more than 90°" or "less than 45°". It is possible to perform a one-handed fold without touching the front or back screen by gripping and contacting along the bezel and side of the phone. However, due to limited space in those areas, it may be difficult to fold the phone easily or accurately, perhaps even resulting in the phone slipping. These are the kinds of issues we explore in the study below.

We define 6 only-fold variations to evaluate: either an *inward* or *outward* fold combined with fold magnitude that is *small* (less than 45°), *medium* (between 45° and 90°), and *large* (more than 90°).

Touch-enhanced Fold

This interaction uses touch as a before-fold modifier: the user touches the device screen, then performs a fold while maintaining the touch. The same fold direction and magnitude variations can apply, but with the additional variation of an X-Y touch location on the front of the bottom or top sections, or on the back of the top section. Examples include touching at the bottom section and folding the top part inward, or touching the front of the top section to push as an outward fold. The ease of maintaining a touch at a location while folding very likely varies. Some combinations seem promising due to how a phone is held and the forces needed to fold; such as touching the back of the top section then folding inward, or touching the front of the top section and folding outward. The X-Y touch location is likely also to have a strong effect, depending what can be reached with a thumb or finger [8]. Other combinations seem to be infeasible, such as touching the front of the top section, then folding inward. In general, users may need to adjust their grip to achieve some gestures, which would increase time and discomfort.

We define 16 touch-enhanced fold gesture variations to evaluate: touching one of 4 locations on the front of the top section, then folding outward; touching one of 4 locations on the back of the top section, then folding inward; touching one of 4 locations on the front of the bottom section, then folding inward or outward. Due to expected demands for dexterity and coordination, all gestures use a single fold magnitude of "more than 20°".

Fold-enhanced Touch

This interaction uses fold as a pre-touch modifier: the user folds the device first, then touches the screen while maintaining the folded angle. Input variations are the same as the touch-enhanced fold interaction: fold direction, fold magnitude, and touch location. Examples include folding the top section

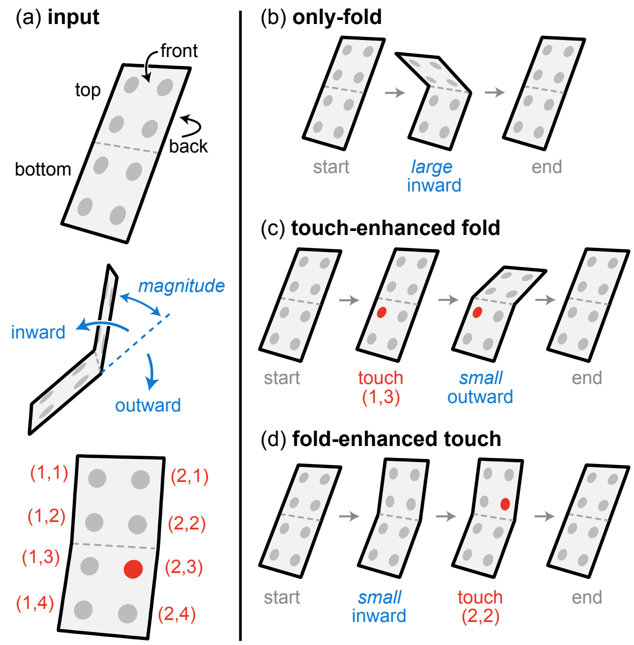

Figure 5.2: Folding interactions: (a) input terminology and dimensions; (b) example of an only-fold gesture; (c) example of a touch-enhanced fold gesture; (d) example of a fold-enhanced touch gesture.

inward 90°, then tapping on the front of the top section, and a 45° inward fold followed by a touch at the bottom section. Touching the front of the top section after an inward fold should be easier since the touch location is closer. However, touching the top section after an outward fold is likely very difficult since the touch location moves out of reach.

We define 8 variations to evaluate: folding inward with magnitude of *small* (less than 45°) or *medium* (between 45° and 90°), then touching one of 4 locations on the front screen, specifically 2 locations on each sections (location $(*, 2)$ and $(*, 3)$ in Fig. 5.2a). Compared to touch-enhance fold interaction, we only evaluate 4 locations which are inside the reachable area [8] to reduce gesture difficulties within the experiment.

Foldable Flip Phone Prototype

Current commercial flip phones can be only folded in one direction and the Android system supports detection of limited folding states (open, half-open, or close). For these reasons, we built a hardware sensing prototype to demonstrate and evaluate the proposed folding interactions[1].

The phone prototype is $72 \times 166 \times 8$ mm, 123 g, similar to the Samsung Galaxy Z Flip 3. It is constructed from custom designed 3D printed PLA parts for the hollow top and bottom sections (with removable covers) and a solid hinge (Fig. 5.3). The top and bottom sections are each connected to the hinge

1 All schematics, 3D models, and software will be provided open source.

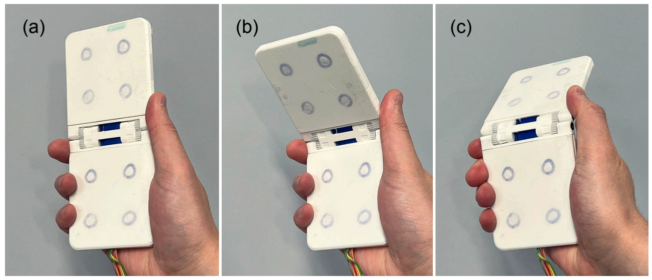

Figure 5.3: Foldable flip phone prototype: (a) held flat with no fold; (b) folded inward; (c) folded outward.

using two $M3 \times 16$ screws. The hinge uses 2 sets of 18 tooth, 8 mm nylon gears with one side of each gear filed to be flush with the inside face of the top or bottom section (Fig. 5.4b). This forces each pair of gears to rotate in a planetary motion so the hinge is approximately half the angle of which the prototype is folded. This mechanism creates a smooth and continuous fold between the top and bottom sections regardless of fold direction, essentially is a simplified version of the gear-based hinge used in the Samsung Flip 3. A bar 3D printed in flexible TPU works like a spring to introduce some resistance and return the prototype to the flat neutral position when a fold gesture is released (Fig. 5.4a). This "spring" is $43 \times 16.2 \times 7.6$ mm solid fill, printed with 0.2 mm layer height.

Each section contains an IMU (MPU6050) mounted in the same orientation and the bottom section also contains a MPR121 touch sensor and Arduino pro-mini microcontroller. The microcontroller is interfaced with the IMU and capacitance sensor using the I2C protocol. Each phone section has four 10mm circular touch points uniformly printed as recesses on the underside of the cover in each section. Copper tape is attached into each recess and connected to the MPR121 sensor to detect touches at 8 different locations in total. Six lightweight wires connect the microcontroller to an external serial-to-USB converter which is connected to a laptop to provide power, program the microcontroller, and read sensor values.

A realtime folding angle is determined from the orientation difference between the IMU sensors placed in the top and bottom sections. A heuristic method classifies fold and unfold events along with the fold gesture magnitude, which is simplified from bending events proposed by Kirshenbaum and Robertson [69]. We define a fold event when the folding angle is larger than 20°, and unfold event when the folding angle is 20° less than the maximum angle during the fold. The maximum folding angle is used as the fold magnitude. A Processing program visualizes the 3D orientation of each section using the folding angle and sensed touch locations (Fig. 5.5).

Applications

To demonstrate how folding interactions could be used, we implemented simulated applications using the sensing prototype with the graphical user

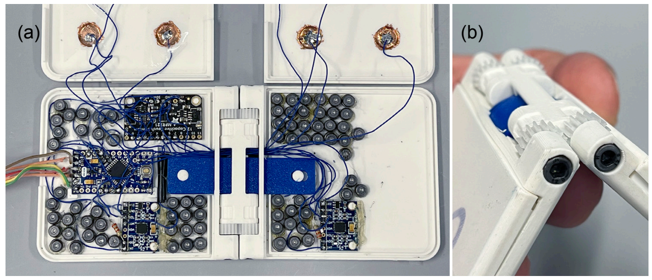

Figure 5.4: Prototype detail: (a) internal hardware components, capacitive touch pads, TPU spring (blue), and lead weights; (b) hinge mechanism detail showing pairs of gears.

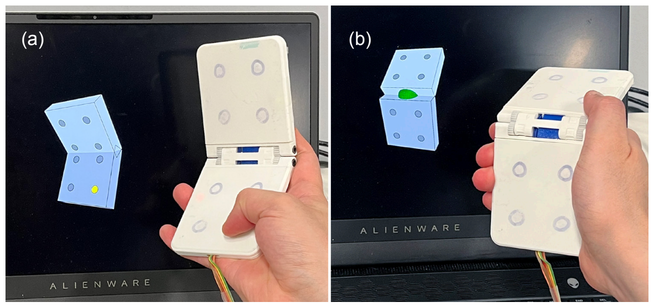

Figure 5.5: Sensing and laptop 3D visualization: (a) inward fold with sensed touch (yellow circle); (b) outward fold.

interface rendered in the Processing application. The accompanying video demonstrates these applications[2].

Text Editing — Le et al. [77] showed that touches on a fully touch sensitive phone can be used as shortcuts for text editing. Only-fold interactions can be mapped to such shortcuts with basic semantic bindings. An outward fold could be considered as an extension of a swipe up gesture with abduction motion. It could scroll a page down with a small angle, or jump down multiple pages with a medium angle. Likewise, an inward fold could scroll a page up, or jump up multiple pages. An inward fold could also suggest taking selected content out of a document, where touching a word and folding inward cuts the word out of a paragraph. Conversely, an outward fold suggests putting elements into a document. By touching an insertion point and folding outward, content in the clipboard could be pasted into a specific location (Fig. 5.1b). Fold-enhanced touches could be used to select widgets from hidden menus. An inward fold could pop up menu items, with a subsequent touch used for selection.

Map Application — Browsing maps with a single hand can be challenging, users needs to perform double-tap and drag gestures for single-handed zooming. Instead, a small outward or inward fold could be mapped to zooming in or out (Fig. 5.1a). In addition, touching a specific location and

2 https://youtu.be/jw5JAmWmkJU

folding the device could zoom centred on that location. A medium fold could switch between different map layers, and similar to the text editing application, fold-enhanced touches could select hidden widgets.

Soft or Hard Tap — Hinckley and Song [52] proposed the "Soft-vs-Hard-Tap" technique using motion sensing to differentiate a soft or a hard tap. Similarly, touch-enhanced folding could be used to distinguish the force users apply with the fold magnitude. Users could softly tap on the top section as a normal touch input, or touch on the top section to push the front screen outward as a hard tap.

Reachability — Girouard et al. [36] proposed one-handed bend interactions on deformable phones to address finger reachability. A "middle bend gesture" was used to shift down the graphical interface to make a target widget easier to reach. Fold-enhanced touch could be utilized to combine the effect of UI adjustment and target selection. An inward fold could bring down the interface half screen for user to easily press the bottom section to select the target (Fig. 5.1c).

Unlocking Pin — Lakier et al. [72] used pre-touch information to enable unlocking smartphones with a 3D pattern. The motivation is that the three dimensional thumb location is harder to determine in shoulder surfing attacks, improving phone security. Multiple fold-enhanced touches could be applied for the same purpose because the fold magnitude is also difficult to determine due to viewing angle and relative orientation. Fold angle could be combined with touch location to create a complicated unlocking pattern. A shoulder surfing attacker would also be discouraged by how high magnitude inward folding naturally shields touches on the lower section.

5.3 EXPERIMENT

The goal of this experiment is to examine the speed of fold gestures, how many errors participants would make, their preference, and observe what grip and hand movement strategies they use to perform the gestures. We evaluated 30 fold gestures described in section 5.2 by measuring the completion time of each gesture, the error counts, and subjective ratings. We also observed finger placement when performing the gestures.

Participants

We recruited 24 participants, ages 18 to 39 (M=26.08, SD=4.51), 14 identified as men and 10 as women, and 2 reported they were left-handed. Recruitment was through on-campus flyers and word-of-mouth, participants were required to have full use of their dominant hand and fingers, and they received $15 for remuneration. Overall hand measurements (in mm) are: palm width (M=80.58, SD=7.2, from 67 to 92), and hand length (M=182.42, SD=10.33, from 163 to 202). All participants used a smartphone for more than 5 years, and all but 2 reporting using their phone for more than 1 hour each day (13 used their phone for 4 hours or more). For their own phone size (diagonal screen size):

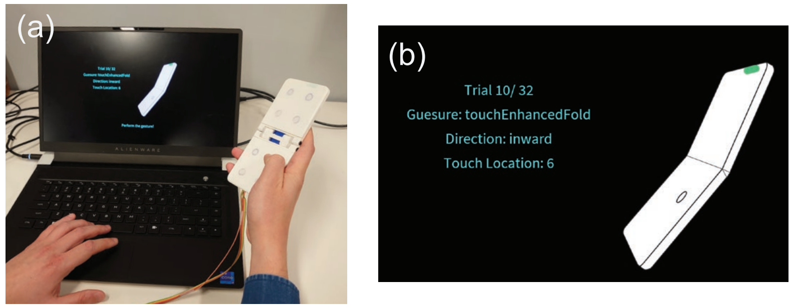

Figure 5.6: Task: (a) participant held the prototype in their dominant hand and pressed the space key with the other hand to indicate trial start; (b) experiment interface showing target gesture.

3 had 4-5 inch phones; 7 had 5-6 inch phones; and 14 had phones more than 6 inches. No participants had the experience with modern flip phones.

Task and Procedure

The participant was seated at a desk with a laptop, and they held the foldable flip phone prototype in their dominant hand (Figure 5.6a). Before starting each trial, the target gesture was shown as brief descriptive text with an illustration on the laptop screen (Figure 5.6b). Participants were told to perform each gesture quickly and accurately without resting their hand on the table. To begin each trial, they held the prototype using their normal gripping posture, and pressed the space key of the laptop with their non-dominant hand. Next, they performed the target gesture, then returned back to their normal gripping posture with the phone unfolded without any screen touches registering. The gesture ends with an unfold event or a touch up event, depending on which event occurred first. The heuristic classifier determined if the gesture was correct with the result displayed on the laptop screen. If it was not correct, the participant had to perform the gesture again.

The experiment had three parts: (1) pre-experiment instruction; (2) main experiment with measured trials and gesture ratings; and (3) overall feedback questionnaire. First, each participant was instructed with the experiment goal, tasks, and flow, then given a period to interact with the prototype and view the visualization in the experiment interface to better understand folding interactions (Fig. 5.5). Next, the participant completed the main experiment part in three sections, each with one type of folding interaction. The beginning of each section had one practice block covering all gestures in the section once. Then, they completed three experiment blocks, each with 2 repetitions of each gesture. Each section ended with four subjective ratings for each gesture: ease, comfort, confidence, and social acceptance. After the main experiment part was completed, the participant filled a general questionnaire about their 3-5 minutes experience with a Samsung Flip 3, overall feedback for folding interactions, and possible practical usage of fold gestures. The experiment was approximately 60 to 75 minutes in total, depending on how many errors the participant encountered during the experiment.

Design

This is a within subjects design with one primary independent variable: folding INTERACTION type with 3 levels (ONLY-FOLD, TOUCH-FOLD, FOLD-TOUCH).

Fold DIRECTION, fold MAGNITUDE, and touch LOCATION form secondary independent variables.

- For ONLY-FOLD INTERACTION, there were 2 DIRECTIONS (INWARD, OUTWARD) $\times$ 3 MAGNITUDES (SMALL: $< 45°$, MEDIUM: $45° - 90°$, LARGE: $> 90°$).
- For TOUCH-FOLD INTERACTION, there were 2 DIRECTIONS (INWARD, OUTWARD) $\times$ 8 LOCATIONS.
- For FOLD-TOUCH INTERACTION, there were 2 MAGNITUDES (SMALL, MEDIUM) $\times$ 4 LOCATIONS.

To analyze the effect of touch location, we encode LOCATION as LOCATIONX and LOCATIONY and label them with numeric coordinates. Location $(1,1)$ indicates the top-left location on the prototype for right-handed participants. We flip the label of x axis for left-handed users. There are 30 different fold gesture conditions, we refer to each using the form "DIRECTION-MAGNITUDE-LOCATION" (Figure 5.2).

The order for INTERACTION was counter-balanced using a Latin square. Each gesture variation was repeated consecutively 2 times per BLOCK. There were 3 blocks per INTERACTION. For each gesture variation, touch LOCATION was randomized as the primary factor. DIRECTION and MAGNITUDE were randomized as the secondary factor. Participants completed all tasks for a single touch location first, then moved to the next location to reduce the cognitive load of the experiment. In summary: 24 participants $\times$ 30 gestures $\times$ 3 blocks $\times$ 2 repetitions = 4,320 trials in total.

The primary measures are:

- *Time*, the duration from when participant pressed the space key until the gesture completed event.
- *Error Count*, the number of times the correct gesture was not recognized in a trial. The minimum error count is 0, when the participant finished the trial correctly on their first try. The maximum error count is 2, when the participant performed the gesture incorrectly twice during the trial.

In addition, the questionnaire provides 4 subjective measures. *Ease* is how easy the gesture was to perform; *Comfort* is how comfortable the participant felt while performing the gesture; *Confidence* is how confident they were holding the device without dropping it; and *Acceptance* is how acceptable they would be to perform the gesture in a public setting. All measures are on a 7-point numerical scale, with 1 representing the lowest rating, 7 the highest, and 4 neutral.

Results

For each measure, trials are aggregated by participant and factors being analyzed. Figure 5.7 summarizes the main results for fold gesture conditions with a breakdown by INTERACTION type. Fold gesture is highlighted as cautious one for future application design with any subjective ratings lower than neutral. Since the 0.5 average error count means 1 error occurs on every other trial, we also highlight the gestures higher than this threshold. Note that this is more restrict than showing trials error rate of gesture.

Residuals for *Time* is not normally distributed, so we use Tukey's Ladder of Powers transformation [143], and a factorial repeated measures ANOVA with Bonferroni corrected pairwise comparisons. When the assumption of sphericity was violated, degrees of freedom are corrected using Greenhouse-Geisser. We apply Generalized linear mixed models for *Error Count* analysis because the distribution is close to a Poisson distribution. The distribution of subjective ratings was not normal, so the Friedman test with Holm's corrected post hoc Wilcoxon signed-rank test was used for INTERACTION and ART [31, 156] was used for multi-factor analysis.

To streamline the presentation of results, details of statistical tests and significant differences are provided as tables in the appendix (Section 5.6). References are in the form "A.1: Table 1a" where A.1 refers to subsection 1 of the appendix.

Learning Effect — We are interested in practised performance, so we examine if earlier blocks were more error-prone and should be removed. A BLOCK × INTERACTION test was used. We did not find significant main effect for BLOCK on *Error Count*, so all blocks were used in subsequent analysis.

Overall Interactions

All folding interactions can be performed in less than 1.6 seconds with average ratings higher than 4 (Figure 5.7: Overall). FOLD-TOUCH had higher average error counts (0.47) than ONLY-FOLD (0.21) and TOUCH-FOLD (0.19), and ONLY-FOLD was rated the best in terms of ease, comfort, and confidence. We also found ONLY-FOLD is more social acceptable than TOUCH-FOLD (see A.1: Table 5.1 for INTERACTION main effect tests).

Only-Fold Gestures — In general, larger outward fold gestures were slower and rated lower, while a small inward fold was fast and rated highly (Figure 5.7: Only-Fold). In terms of statistical differences, INWARD gestures are 0.27s faster than OUTWARD, and SMALL magnitude gestures are 0.24s faster than LARGE magnitude ones. Folding INWARD and folding with a SMALL magnitude was rated highest in all four subjective ratings; folding with a LARGE magnitude was rated lowest in *Confidence* and *Social Acceptance* (see A.2: Table 5.2a, b for DIRECTION and MAGNITUDE main effect tests). Participants rated OUTWARD-MEDIUM and OUTWARD-LARGE more difficult, uncomfortable, and socially awkward than the other four fold gestures (see A.2: Table 5.2c for DIRECTION × MAGNITUDE interaction tests).

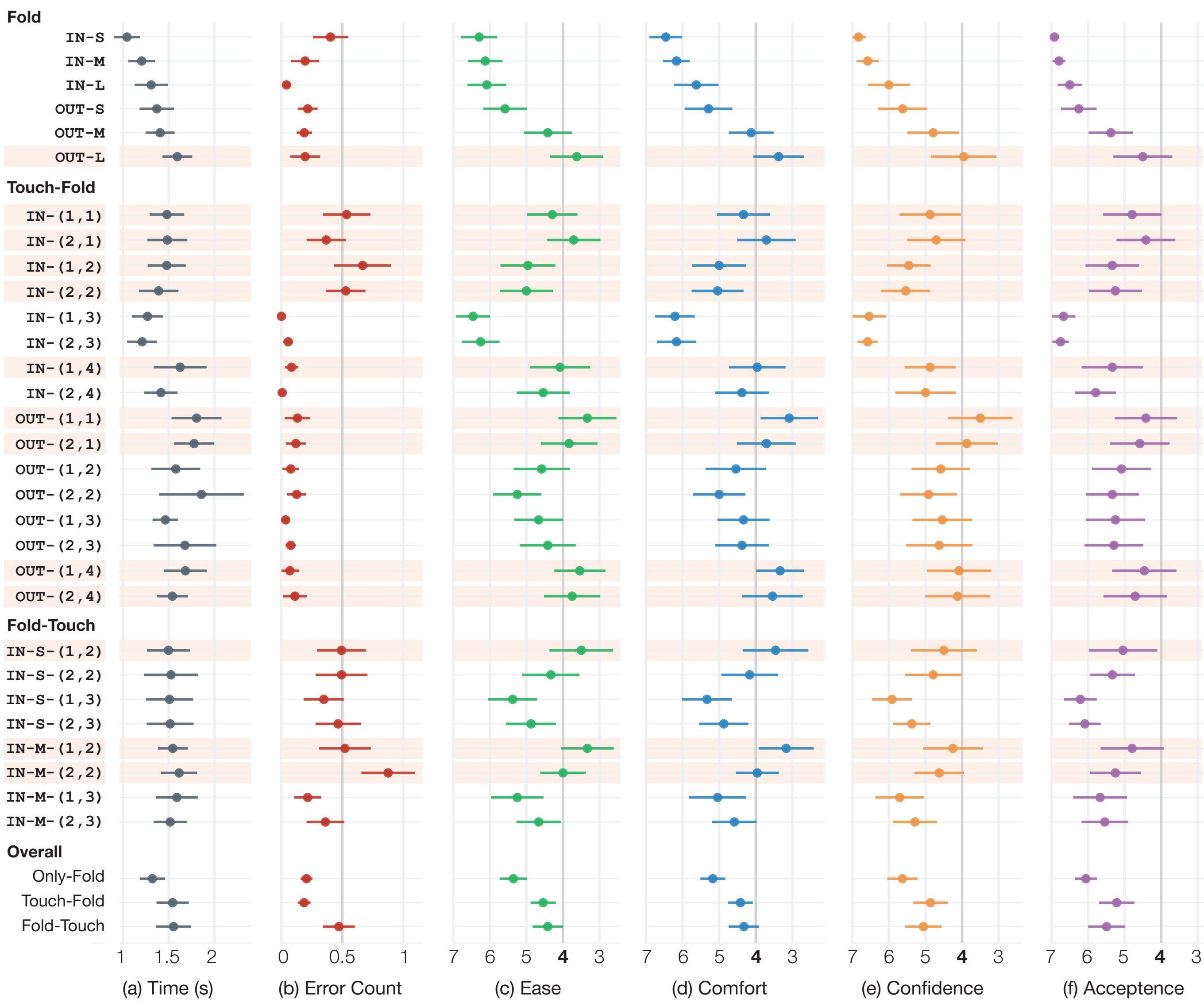

Figure 5.7: Comparison of fold gestures defined by INTERACTION, DIRECTION, MAGNITUDE, LOCATION as well as overall by INTERACTION: (a) Time; (b) Error count; (c) Ease rating; (d) Comfort rating; (e) Confidence rating; (f) Social Acceptance rating. Note: rating scales inverted to enable comparison with time and error count, left-most points in each sub-graph are better. (error bars are 95% confidence intervals)

Touch-Fold Gestures — Participants generally prefer to touch within the reachable area of the thumb and then perform a fold. Reaching locations on the back of device to fold inward are mostly rated higher than 4, but they were more error-prone (Figure 5.7: Touch-Fold). Folding INWARD is 0.25s faster than folding OUTWARD while touching the device, and also rated higher in *Ease*, *Comfort*, and *Confidence*. For LOCATIONY, touching location $(*, 3)$ is 0.24s faster than reaching location $(*, 1)$ to fold, and centre locations $((*, 2), (*, 3))$ are easier, more comfortable, and with more confidence (see A.3: Table 5.3a, b for DIRECTION and LOCATIONY main effect tests). We found INWARD-$(2, *)$ is faster than OUTWARD-$(2, *)$ and OUTWARD-$(1, *)$, and INWARD-$(1, *)$ is also faster than OUTWARD-$(2, *)$. Participants rated INWARD-$(*, 3)$ highest in *Ease*, *Comfort*, and *Social Acceptance* (see A.3: Table 5.3c, d for interaction tests).

Fold-Touch Gestures — Folding the phone and touching the bottom section is more preferred and less error-prone. However, when considering folding magnitude is small, participants also rated reaching location $(2, 2)$ greater than neutral in all subjective ratings (Figure 5.7: Fold-Touch). For *Error Count*, *Ease*, *Comfort*, *Confidence*, and *Acceptance*, reaching location $(*, 3)$ while folding is better than location $(*, 2)$ (see A.4: Table 5.4a for LOCATIONY main effect tests). For *Ease* and *Comfort*, we also found touching location $(1, 3)$ is rated higher than location $(1, 2)$ and location $(2, 2)$, and location $(2, 3)$ is better than location $(1, 2)$ (see A.4: Table 5.4b for interaction tests).

Grasp and Manipulation Postures — The experiment facilitator observed how participants held the phone and manipulated it to perform the gestures during the experiment, recording the posture using. Fingers used for fold gestures with roughly contacted locations were drawn in sketches. We reviewed observing sketches and encoded each posture as "finger-surface-section". For example, "Index-Back-Top" means a posture where the index finger touches the back surface of the top section to perform a fold (Fig. 5.8a, b). When two fingers were used for individual touch and fold input, we described the posture in sequence, such as "Thumb-Front-Bottom & Index-Side-Top" describes a posture where thumb touches the front surface of the bottom section and the index finger folds the top section on the side of the device. A.5: Table 5.5 summarizes the most two frequently used postures.

Most gestures could be performed in similar ways. However, participants would try diverse methods for those difficult ones. For folding outward, some participants used index finger and thumb on two sections and squeezed the phone, while some participants would change the grip to hold the device on the top and use index finger to fold (Fig. 5.8c, d). The latter posture was used for touch-enhanced fold gestures, especially for touching the top left corner and folding outward. By changing the grip, there is no finger holding in the back of the device which makes folding easier. For fold-enhanced touch gestures, most participants grasped the phone tightly, folded the phone with their index finger on the back, and then reached the touch locations with their thumb. Participants with smaller hands would use another strategy because they could not reach the location while folding the device. They tended to fold the device with their index finger while holding the phone with their

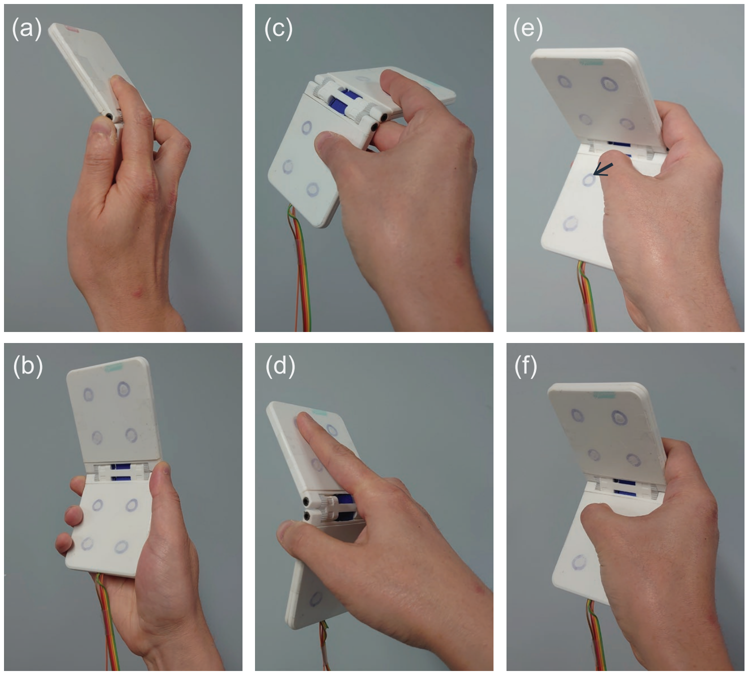

Figure 5.8: Common grasp and manipulation postures: (a, b) back and front view of index finger touches the back surface of the top section; (c, d) different ways to fold the device outward; (e, f) folding the device with thumb pressing the bottom section, and shifting thumb to the touch location.

thumb pressing the bottom section, then shift the thumb to the touch location quickly just before unfolding (Fig. 5.8e, f).

5.4 DISCUSSION

We discuss and summarize design recommendations based on experiment results.

Folding interactions

Only-fold gestures were rated the easiest and most comfortable with fewer errors. Most participants (18) preferred this type of folding interaction: *"The only-fold gestures are preferred because I do not need to worry about the touches"* [P14]. There were more errors with fold-enhanced touch gestures, likely because they require more dexterity and coordination: *"prefer fold-touch least, because I already used bigger force for folding, and it would be hard to adjust thumb to reach the touch points"* [P9]; *"For fold-touch gestures, I need to maintain the fold angle and reach the touch location. It is difficult to make it stable"* [P24]. However, some participants noted advantages for fold-enhanced touch gestures: *"I like the fold then touch because the folding can be used to bring the touch target closer"* [P12].

Overall, only-fold gestures could be used for frequent functions, while fold-enhanced touch gestures should be used cautiously or after practising.

Fold Direction

Inward folding was faster and rated higher within only-fold and touch-enhanced fold gestures. Most participants preferred an inward fold because it could be performed with the natural index finger placement while holding the phone, but a grip change was needed for an outward fold: *"For the outward direction, I need to change the grip to do the gestures. For the inward direction, I can do the gestures with posture similar to the normal holding"* [P13]. However, an outward fold can be easier when combined with a touch on the top section: *"...for top locations, would like outward fold because I just need to push a bit harder"* [P23]. Touching the back of the device and folding inward was rated more difficult and resulted in more errors. Participants expressed a need for back-touch location feedback or a larger target area: *"back-of-device folding is hard because I don't know where to touch;... an indicator to show where I touched the back will help"* [P1].

Fold Magnitude

Within only-fold gestures, a small magnitude (smaller than 45°) was faster and rated higher in all subjective ratings than a large magnitude (larger than 90°). However, some participants disliked the small magnitude because it could be hard to control: *"I do not like small angle because I could not get used to the amount of force needed and seem to fold middle angle instead. Middle and large angle are natural, ..."* [P11];*"small angle is the easier one, but I do not need to worry about the angle for a large fold"* [P6]. For fold-enhanced touch gestures, there were no significant differences between folding magnitudes, but some participants did articulate preferences in their comments: *"medium angle is harder [than small] because it needs more force to hold the angle while moving the finger to touch"* [P1] and *"Medium fold is better for the top locations, because the touch points are approaching to the thumb which is easier"* [P12]. A more relaxed threshold for small folds might maintain the ease and comfort while making it less error-prone.

Touch Location

Previous works revealed the reachable area "sweet spot" for the thumb with standard rigid phones [8, 92]. For fold gestures, touching inside the sweet spot was generally more preferred through easiness and comfort ratings. However, we found the reachable area with the thumb is smaller when coordinating with folding movements compared to reachability reported by previous works. For touch-enhanced fold gestures, the lower two touch locations were rated difficult and uncomfortable: "$(*, 3)$ *locations are better, they are the area of natural thumb placement. Do not prefer the bottom 2 since I need to stretch the index finger and thumb to perform the gestures"* [P17]. The sweet spot is even smaller when folding the phone first: *"location* $(2,3)$ *is difficult. Normally, it is easier to reach, but it is difficult to touch while folding"* [P4]; *"location* $(1,3)$ *is the easiest because the thumb placement is near and can have a good grip to perform a touch after folding. I also prefer* $(1,*)$ *than* $(2,*)$ *because I can have a grip without pulling the finger toward palm"* [P23]. Overall, preferred touch locations are largely influenced by natural finger placement while holding a phone. Reaching to locations near the thumb with folding gestures is considered easy and comfortable.

Gesture Classification

We observed participants touching the front of the top segment to do an outward only-fold gesture, or the back of the top segment to do an inward only-fold gesture. The same sort of touches could also trigger touch-enhanced fold gestures, but only-fold and touch-enhanced gestures could be differentiated with an additional interface constraint. For example, if the user presses on a widget such as a button and then folds, this would be classified as a touch-enhanced fold gesture. Otherwise, if there was no defined target under the touch, it would be an only-fold gesture. The event time between touch down and fold can also help discriminate gestures. A smaller time difference may be found in only-fold gestures since users do not need to pay attention on the touch location. More usage data is needed to test these ideas in a more advanced classifier.

Beyond Single-handed Usage

We focused on single-handed gestures, but our proposed gestures can still be performed two-handed, or even with the assistance of other body parts. For example, a user could touch the phone with their thumb, then bring the phone up to their face and press the top segment against their chin to fold. This would likely raise some social acceptability concern, but it may increase the comfort since the users would not rely solely on single hand finger dexterity to perform the gesture. Future work could investigate more creative kinds of folding interactions with flip phones.

Interface Adjustment

We showed how graphical user interface could be adjusted based on the folding angle in the reachability application (Fig. 5.1c). For other demonstrations, since folding interactions are considered as discrete and atomic gestures, we did not adjust the interface based on the participants' viewpoints. However, folding inward or outward may make the contents of the top section of the phone harder to read, and increase the difficulties to touch specific locations. Future work could investigate these readability issues and adjust the interface accordingly.

5.5 CONCLUSION

We explored single-handed folding interactions designed for a modern flip phone: only a fold, a touch-enhanced fold, and a fold-enhanced touch. An experiment examined 30 gestures by considering fold direction, fold magnitude, and touch location, with the results suggesting that these kinds of gestures can be performed quickly, and more than half of them are rated easy and comfortable even though they require finger dexterity and coordination. Demonstration applications using our prototype evaluation device show how folding interactions could be used to augment conventional flip phone input. Our work contributes a new example of how deformation gestures can be used as an input method, and using a device with capabilities similar to existing commercial phones.

5.6 APPENDIX: TABLES OF STATISTICAL TESTS

This appendix presents tables of ANOVA and post hoc statistical tests for main effects and interactions of our results (Section 5.3).

A.1: Overall Interactions

Table 5.1: Main effect

		(i) *Time*		(ii) *Error Count*		(iii) *Ease*		(iv) *Comfort*		(v) *Confidence*		(vi) *Acceptance*	
		$F_{2,46} = 6.01$, $p < .01$, $\eta^2_G = 0.07$		$\chi^2_{(2,N=24)} = 20.33$, $p < .001$		$\chi^2_{(2,N=24)} = 20.33$, $p < .001$		$\chi^2_{(2,N=24)} = 15.38$, $p < .001$		$\chi^2_{(2,N=24)} = 7.28$, $p < .05$		$\chi^2_{(2,N=24)} = 14.47$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
ONLY-FOLD	TOUCH-FOLD	-0.22	.14	0.02	.70	0.82	< .001***	0.75	< .001***	0.77	< .01**	0.84	< .01**
ONLY-FOLD	FOLD-TOUCH	-0.23	.13	-0.27	< .001***	0.93	< .001***	0.85	< .001***	0.57	< .05*	0.57	.05
TOUCH-FOLD	FOLD-TOUCH	-0.01	1	-0.28	< .001***	0.12	.53	0.1	.51	-0.2	.31	-0.27	.14

A.2: Only-Fold Gestures

Table 5.2: Main effect and interaction of a DIRECTION × MAGNITUDE statistical analysis

(a) DIRECTION

		(i) *Time*		(ii) *Ease*		(iii) *Comfort*		(iv) *Confidence*		(v) *Acceptance*	
		$F_{1,23} = 27.36$, $p < .001$, $\eta^2_G = 0.13$		$F_{1,23} = 72.86$, $p < .001$		$F_{1,23} = 87.63$, $p < .001$		$F_{1,23} = 82.78$, $p < .001$		$F_{1,23} = 80.14$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
INWARD	OUTWARD	-0.27	< .001***	1.63	< .001***	1.82	< .001***	1.68	< .001***	1.36	< .001***

(b) ANGLE

		(i) *Time*		(ii) *Ease*		(iii) *Comfort*		(iv) *Confidence*		(v) *Acceptance*	
		$F_{1.33,30.63} = 16.79$, $p < .001$, $\eta^2_G = 0.08$		$F_{2,46} = 16.09$, $p < .001$		$F_{2,46} = 20.80$, $p < .001$		$F_{2,46} = 22.98$, $p < .001$		$F_{2,46} = 24.18$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
SMALL	MEDIUM	-0.1	.36	0.67	< .01**	0.73	< .001***	0.54	< .001***	0.5	1
SMALL	LARGE	-0.24	< .01**	1.09	< .001***	1.38	< .001***	1.25	< .001***	1.08	< .001***
MEDIUM	LARGE	-0.14	.28	0.42	.06	0.65	< .05*	0.71	< .01**	0.58	< .05*

(c) DIRECTION × ANGLE

(i) *Ease*	(ii) *Comfort*	(iii) *Confidence*	(iv) *Acceptance*
$F_{2,46} = 8.60$, $p < .001$	$F_{2,46} = 3.51$, $p < .05$	$F_{2,46} = 5.56$, $p < .01$	$F_{2,46} = 11.81$, $p < .001$

A.3:Touch-Fold Gestures

Table 5.3: Main effect and interaction of a DIRECTION × LOCATIONX × LOCATIONY statistical test

(a) DIRECTION

		(i) *Time*		(ii) *Ease*		(iii) *Comfort*		(iv) *Confidence*		(v) *Acceptance*	
		$F_{1,23} = 16.10$, $p < .001$, $\eta^2_G = 0.06$		$F_{1,23} = 21.86$, $p < .001$		$F_{1,23} = 28.15$, $p < .001$		$F_{1,23} = 62.69$, $p < .001$		$F_{1,23} = 17.14$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
INWARD	OUTWARD	-0.25	< .001***	0.74	< .001***	0.86	< .001***	1.17	< .001***	0.65	< .001***

(b) LOCATIONY

		(i) *Time*		(ii) *Ease*		(iii) *Comfort*		(iv) *Confidence*		(v) *Acceptance*	
		$F_{2.13,48.97} = 5.99$, $p < .01$, $\eta^2_G = 0.03$		$F_{3,69} = 24.53$, $p < .001$		$F_{3,69} = 23.36$, $p < .001$		$F_{3,69} = 16.44$, $p < .001$		$F_{3,69} = 18.30$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
$(*,1)$	$(*,2)$	0.06	1	-1.16	< .001***	-1.19	< .001***	-0.88	< .001***	-0.7	< .01**
$(*,1)$	$(*,3)$	0.24	< .05*	-1.66	< .001***	-1.56	< .001***	-1.33	< .001***	-1.44	< .001***
$(*,1)$	$(*,4)$	0.07	1	-0.19	.99	-0.09	.95	-0.28	.59	-0.52	.08
$(*,2)$	$(*,3)$	0.18	.36	-0.5	.09	-0.37	.17	-0.45	.27	-0.74	< .001***
$(*,2)$	$(*,4)$	0.01	1	0.97	< .001***	1.1	< .001***	0.6	< .01**	0.18	.78
$(*,3)$	$(*,4)$	-0.17	.12	1.47	< .001***	1.47	< .001***	1.05	< .001***	0.92	< .001***

(c) DIRECTION × LOCATIONX

		(i) *Time*	
		$F_{1,23} = 7.02$, $p < .05$ $\eta^2_G = .01$	
comparisons		*diff (s)*	*p-value*
INWARD-$(1,*)$	OUTWARD-$(2,*)$	-0.25	< .05*
INWARD-$(2,*)$	OUTWARD-$(1,*)$	-0.26	< .01**
INWARD-$(2,*)$	OUTWARD-$(2,*)$	-0.34	< .001***

(d) DIRECTION × LOCATIONY

		(i) *Ease*		(ii) *Comfort*		(iii) *Acceptance*	
		$F_{3,69} = 5.93$, $p < .001$		$F_{3,69} = 4.85$, $p < .01$		$F_{3,69} = 4.67$, $p < .01$	
comparisons		*diff (s)*	*p-value*	*diff (s)*	*p-value*	*diff (s)*	*p-value*
INWARD-$(*,3)$	ALL OTHERS	> 1.37	< .001***	> 1.17	< .01**	> 1.15	< .001***

A.4: Fold-Touch Gestures

Table 5.4: Main effect and interaction of a MAGNITUDE × LOCATIONX × LOCATIONY statistical test

(a) LOCATIONY

		(i) *Error Count*		(ii) *Ease*		(iii) *Comfort*		(iv) *Confidence*		(v) *Acceptance*	
		$\chi^2_{(1,N=24)} = 7.16$, $p < .01$ $\eta^2_G = 0.06$		$F_{1,23} = 32.61$, $p < .001$		$F_{1,23} = 35.24$, $p < .001$		$F_{1,23} = 23.23$, $p < .001$		$F_{1,23} = 13.54$, $p < .001$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*	*diff*	*p-value*
$(*, 3)$	$(*, 2)$	-0.25	< .05*	1.25	< .001***	1.27	< .001***	1.03	< .001***	0.78	< .001***

(b) LOCATIONX × LOCATIONY

		(i) *Ease*		(ii) *Comfort*	
		$F_{1,23} = 9.29$, $p < .01$,		$F_{1,23} = 10.95$, $p < .01$	
comparisons		*diff (s)*	*p-value*	*diff*	*p-value*
$(1, 3)$	$(1, 2)$	1.89	< .001***	1.88	< .001***
$(1, 3)$	$(2, 2)$	1.14	< .001***	1.13	< .01**
$(2, 3)$	$(1, 2)$	1.35	< .001***	1.42	< .001***

A.5: Grasp and Manipulation Postures

Table 5.5: Top 2 posture for each fold gesture.

Interaction	Gesture	First Frequent Posture	Count	Second Frequent Posture	Count
FOLD	IN-S	Index-Back-Top	21	Index-Back-Top & Thumb-Front-Bottom	3
	IN-M	Index-Back-Top	19	Index-Back-Top & Thumb-Front-Bottom	5
	IN-L	Index-Back-Top	18	Index-Back-Top & Thumb-Front-Bottom	6
	OUT-S	Index-Side-Top	9	Thumb-Front-Top	7
	OUT-M	Index-Side-Top & Thumb-Front-Bottom	7	Index-Front-Top (hand on top of the phone)	6
	OUT-L	Index-Side-Top & Thumb-Front-Bottom	9	Index-Front-Top (hand on top of the phone)	8
TOUCH-FOLD	IN-1,1	Index-Back-Top	24		
	IN-2,1	Index-Back-Top	24		
	IN-1,2	Index-Back-Top	24		
	IN-2,2	Index-Back-Top	24		
	IN-1,3	Thumb-Front-Bottom & Index-Back-Top	24		
	IN-2,3	Thumb-Front-Bottom & Index-Back-Top	24		
	IN-1,4	Thumb-Front-Bottom & Index-Back-Top	23	Little-Front-Bottom & Index, Thumb-Side-Top	1
	IN-2,4	Thumb-Front-Bottom & Index-Back-Top	24		
	OUT-1,1	Thumb-Front-Top	13	Index-Front-Top (hand on top of the phone)	9
	OUT-2,1	Thumb-Front-Top	16	Index-Front-Top (hand on top of the phone)	6
	OUT-1,2	Thumb-Front-Top	20	Index-Front-Top (hand on top of the phone)	2
	OUT-2,2	Thumb-Front-Top	21	Index-Front-Top (hand on top of the phone)	1
	OUT-1,3	Thumb-Front-Bottom & Index-Side-Top	24		
	OUT-2,3	Thumb-Front-Bottom & Index-Side-Top	24		
	OUT-1,4	Thumb-Front-Bottom & Index-Side-Top	23	Little-Front-Bottom & Index, Thumb-Side-Top	1
	OUT-2,4	Thumb-Front-Bottom & Index-Side-Top	24		
FOLD-TOUCH	IN-S-1,2	Index-Back-Top & Thumb-Front-Top	19	Index-Back-Top & Thumb-Front-Top*	3
	IN-S-2,2	Index-Back-Top & Thumb-Front-Top	22	Index-Back-Top & Thumb-Front-Top*	2
	IN-S-1,3	Index-Back-Top & Thumb-Front-Bottom	19	Index-Back-Top & Thumb-Front-Bottom*	4
	IN-S-2,3	Index-Back-Top & Thumb-Front-Bottom	21	Index-Back-Top & Thumb-Front-Bottom*	3
	IN-M-1,2	Index-Back-Top & Thumb-Front-Top	18	Index-Back-Top & Thumb-Front-Top*	3
	IN-M-2,2	Index-Back-Top & Thumb-Front-Top	23	Index-Back-Top & Thumb-Front-Top*	1
	IN-M-1,3	Index-Back-Top & Thumb-Front-Bottom	19	Index-Back-Top & Thumb-Front-Bottom*	4
	IN-M-2,3	Index-Back-Top & Thumb-Front-Bottom	20	Index-Back-Top & Thumb-Front-Bottom*	4

* Thumb shifts from hinge to touch location.

6 DISCUSSION

In the previous three chapters, we explored various forms of single-handed physical phone interaction utilizing finger dexterity. In this chapter, we first discuss the meaning of using dynamic grips in the context of our work, and how we can use it in interaction design, especially for future phone form factors. Second, we describe the difficulties we faced when testing these new kinds of interactions, and we sketch out a technical solution in the form of an augmented reality prototyping system to overcome current hardware limitations. Last, we address the participants sampling limitation of our user studies.

6.1 DYNAMIC GRIP AND REACHABILITY

In this thesis, our focus on dexterity also pushed the boundary of using a static grip to interact with a phone, encouraging users to sometimes use dynamic grips instead. Human hands are prehensile which means we are capable of using our hands to seize or grasp objects. Thus, there are two main types of hand movement, prehensile and non-prehensile movement. Prehensile movement is an action that involves holding an object firmly within the hand, which is the same as using the hand to grip or grasp an object. In contrast, a non-prehensile movement is an action without gripping or grasping to manipulate an object, typically by pushing or lifting. Here, we further describe different prehensile postures that detail finger position and placement to grip a phone, and discuss possibilities to use more gripping gestures and changing between those grips for physical phone interaction.

Power Grip and Precision Grip

Napier [95] identified two basic prehensile movement of the hand to achieve the *stability* of holding object:

- Power grip: fingers and palm clamp around the object with the force applied by the thumb to the object and the palm.
- Precision grip: one or more fingers and the opposing thumb pinch the object.

Within a power grip or a precision grip, the grasping posture can be influenced by the shape and the size of the object, finger placement, and which areas the fingers touch the object. Pheasant [102] describes a taxonomy of hand functions (Figure 6.1(a)), and shows how a power grip and precision grip can be further split into detailed categories by the shape of the held object (e.g. cylindrical grip, spherical grip, disc grip) or the finger placement (e.g.

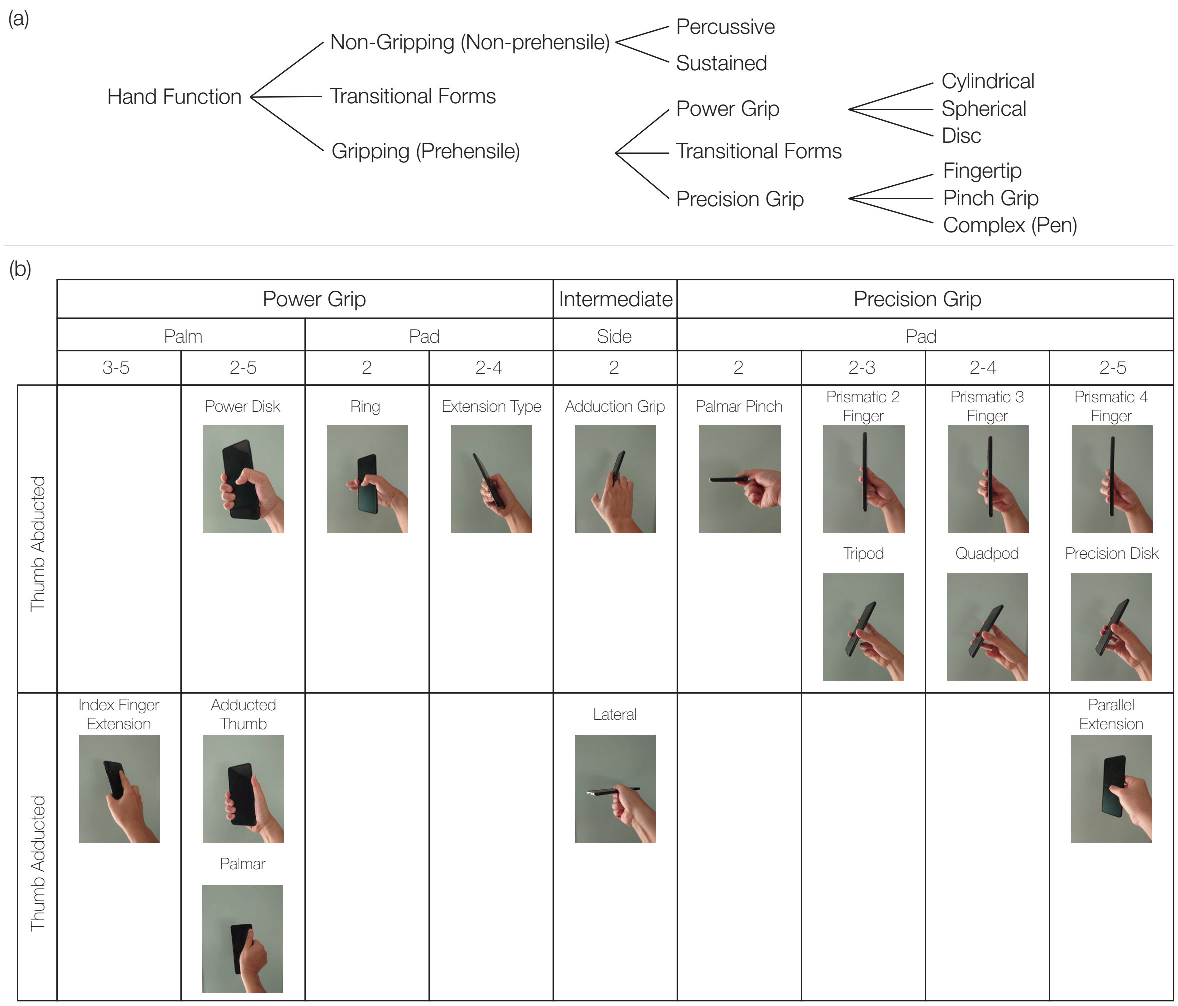

Figure 6.1: Taxonomies of hand functions: (a) full taxonomy (modified from Pheasant [102]); (b) GRASP Taxonomy of postures for holding a phone (modified from Feix et al. [32]).

pinch grip, key grip, complex grip). More recently, Feix et al. [32] propose "The GRASP Taxonomy" by analyzing grasps from 22 taxonomy literature. 33 different single-handed postures are derived from grips (power grip, precision grip, or intermediate grip), location where the holding force applied to (palm, finger pad, or finger side), a functional unit of fingers, and position of the thumb (abducted or adducted).

From those 33 grasps, we examine the possible ones for grasping a phone and demonstrate the 16 postures in Figure 6.1(b) with the same taxonomy. For example, the most frequent grasps would be "Adducted Thumb", which users hold the phone with palm in the back, thumb on the dominant side, while other fingers on the other side. Users may change to use "Extension Type" grape while typing, which uses the palm and four fingers on the back of the phone as support while tapping with the thumb on the front. These two grasps can both be categorized as power grips, but people also use precision or intermediate grips as well, such as grasping a phone using a "Lateral" posture when turning it to a landscape orientation, or using a "Precision Disk" posture to tilt the device.

Static Grip and Dynamic Grip

In our scope definition in chapter 1, we describe interactions in two categories, static grip or dynamic grip, with the main difference whether users change the grip while interacting with the phone or not. A static grip can be either a power grip or a precision grip, such as grasping a phone with an "Adducted Thumb" posture and turning the phone screen away and then back [115], or bringing a phone to the mouth horizontally with a "Precision Disk" posture [158]. Dynamic grips can be performed by switching within power grips or precision grips, or changing between these two categories of grips. We describe how users perform physical interactions in our work with the category of grip and the grasp postures shown in Figure 6.1(b).

In chapter 3, participants used dynamic grips to perform four dexterous manipulations. Shifting starts with an "Adducted Thumb" posture, then uses a "Tripod" or a "Quadpod" posture to walk up or down a phone. Spinning includes grasps that hold the device with the thumb on the front and other fingers on the back (an "Extension Type" posture), pinch the device with thumb, index finger, and middle finger (a "Prismatic 2 Finger" posture), and pinch the phone with thumb and index finger to spin it (a "Palmar Pinch" posture). Rotating includes grasps that hold the phone normally (an "Adducted Thumb" posture), tilt the device with a "Precision Disk" posture, and support the phone with palm to regrasp (an "Extension Type" posture). Flipping includes grasps that hold the device with fingers (a "Prismatic 4 Finger" posture), pinch the phone with thumb and index finger (a "Palmar Pinch" posture), and clamp the phone with index and middle finger to flip it (an "Adduction Grip" posture).

In chapter 4, participants used a static grip or dynamic grip to tap or flick on the side of a phone according to gesture locations. To perform a thumb tap or flick, a static grip with an "Adducted Thumb" posture is used. To reach the top-right locations, some participants would use dynamic grips to shift the phone first. To perform an index finger tap, most participants used dynamic grips that changed from an "Adducted Thumb" posture to a "Precision Disk" posture to reach the top-left locations.

In chapter 5, folding gestures can also be performed with a static grip or dynamic grip. An inward fold uses a static "Index Finger Extension" posture with the index finger in the back of the device. For an outward fold, participants used dynamic grips that change from an "Adducted Thumb" posture to an "Extension Type" posture, and pushed the top section with the thumb or index finger. To perform touch-fold or fold-touch gestures, more grasps are included, such as a "Prismatic 4 Finger" posture or a "Precision Disk" posture.

Overall, our results show that users can loosen their grip and change between different grasps to perform different dexterous manipulations. However, our proposed interactions only utilized some grip postures in the GRASP Taxonomy. With the combination of 16 postures shown in Figure 6.1(b), we could further expand the input vocabulary by providing more physical phone interactions.

Reachability

In previous works [8, 74, 162], the reachability of fingers is measured by asking users to extend their finger to a maximum reaching area while maintaining the same grip. In our scope definition (Figure 1.1), we can describe such methods as the boundary between static grip and dynamic grip. However, the reachability results of these related works may be less representative when we consider using dynamic grips. This raises one research question: *How can the reachability of fingers be defined when users are allowed to change grips?*

In chapter 4, we conduct a reachability study without constraining the participants' grip. Subjective ratings from participants are the main measurements to determine if a location is reachable or not. We also calculate a grip stability metric by comparing the difference between grips before and after reaching, and use it as an objective measure for the easiness to reach specific locations. One main limitation of our method is that we did not consider the effort and movement to change between grips. Other measurements such as stability of phones [28] and finger movement may be better at capturing the nuances of reachability.

6.2 PROTOTYPING SYSTEM

In this thesis, we focus on the human factors of physical phone interaction. To fully understand the performance of these interactions, it is necessary to build evaluation devices. The methods we used to create evaluation devices for each project can serve as another aspect of our research into physical phone interactions. We used three different approaches: (1) using a current phone device, (2) adding extra sensors on a current device, and (3) building a mockup to simulate a future phone device. Figure 6.2 shows the three evaluation devices we created for our proposed interactions.

Difficulties

From our experience designing and evaluating physical interactions, and from our analysis of related work surveyed earlier, we can identify difficulties in prototyping with current phones. To evaluate dexterous gestures, we directly used a current phone device because dexterous gestures can be recognized based on the built-in IMU data. However, using a current phone

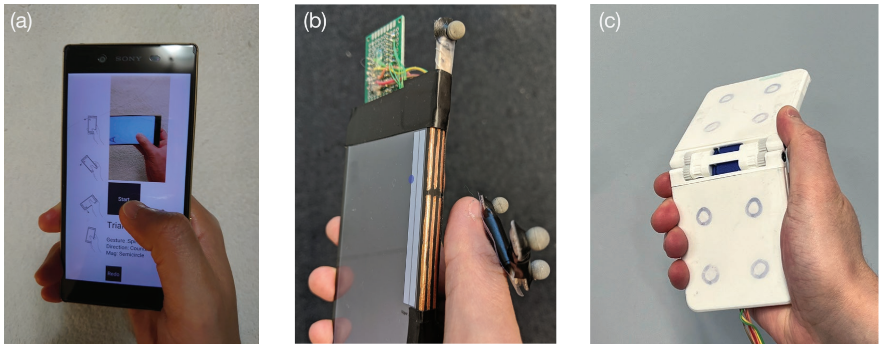

Figure 6.2: Three approaches to create evaluation devices: (a) using a current phone device for dexterous gestures; (b) adding extra sensors on a current device for side touch input; and (c) building a mockup to simulate a future phone device for folding interactions.

limits physical interaction techniques in terms of sensing, displays, and shapes, such our explorations of side touch input and folding interactions. Augmenting a current phone with external hardware introduces challenges related to electronics size, mounting, and placement, as well as wire routing, battery, and system complexity to process events and forward them to the user interface code. For the side touch input project, due to the limited space of the side of a phone, we could not directly enable 2D capacitive sensing which would change the geometric profile of the side. We combined capacitive sensing with optical motion tracking instead, which increased the complexity of our prototype. Furthermore, to explore alternate form factors, complex mechatronic techniques, knowledge, and facilities are needed. To enable double-acting folds, we built a hardware sensing prototype to explore our proposed folding interactions. Because an angle sensor cannot fit inside our designed hinge, the folding angle was determined from the orientation difference between two IMU sensors.

These difficulties may lead to a longer period to implement an evaluation device or a less externally valid prototype.

Previous Prototyping Systems

Rapid prototyping is a process of quickly creating and simulating the future state of an object and its behaviour, for the purpose of validating it with designers, developers, and users. This enables more unconstrained design iterations, and allows designers to generate more variations, and evaluate for early feedback and performance to improve the final design. There are some examples of prototyping systems related to phones, where the method has been used to examine physical interfaces, touch events, gesture design, and accessibility design.

A prototyping system can be used to change how a current phone works, like improving the user interface. Choo et al. [19] prototype and simulate how existing content of a phone appears for cataract-impaired users. The system includes tracking a real phone with fiducial markers through a depth camera to detect touch events, the gripping posture, and finger placement. It displays a virtual phone with the interface to be tested combined with a background scene and the visual impairment simulated by filtering everything in augmented reality. The system and tracking system are limited to current phone factors.

Custom or exotic hardware can be combined in a prototyping system to simulate phone interactions for exploration and testing. Midas [119] creates a system to design, fabricate, and define custom capacitive touch events to prototype interactive objects. The capacitive sensing layout is automatically generated based on the desired shape and touch area. An interactive object can be created by attaching printed copper foils onto target objects and connecting them with capacitive sensors. With the touch events detected by sensors and interactions defined by designers, Midas supports off-screen inputs, such as scrolling with a slider on the back of the device, and tapping a widget on the bezel. These types of prototyping systems use special hardware implementations for simulating specific interactions which are complex and not general. In addition, the characteristics of the hardware likely affect users preference and performance.

Some researchers focus on software to simulate and prototype different interfaces without physical objects. Eventhurdle [67] presents a gesture authoring tool to allow designers to prototype gestural interactions. The authoring tool supports motion gestures with sensors and touch gestures utilizing standard touch screens. The relevant sensor data of gestures is visualized in a conceptual two-dimensional plane for designers to visually define and modify gestures. Goguey et al. [37] develop a storyboard-based modelling tool to prototype touch interfaces and predict user performance. Combining visual design and a predictive model, the system enables a designer to construct an interaction sequence by dragging and dropping touch actions, such as tapping, pointing, or scaling, and visualize prediction times in different scenarios or phone form factors such as screen size. Vanderdonckt and Khaddam [64, 146] create a visual tool for prototyping foldable graphical user interfaces and simulate them with 3D rendering on a monitor. The system includes prototyping the foldable device, like defining surfaces and hinge locations, prototyping software user interfaces, such as listing graphical components and events, mapping the UI prototypes onto a defined device, and 3D rendering the interfaces to enable interactions. Prototyping with software can avoid constraints such as form factor and hardware functions and rapid designing and refining is possible. However, this comes at the cost of losing the feel and behaviour related to a real physical object for designers and study participants during the prototyping process.

Augmenting passive or simple objects to simulate display and input can be used to prototype interactions with future phone factors. Displayobjects [1] proposes an interface prototyping system with passive device models made of styrofoam, paper, or cardboard. The system tracks the model and a user's finger with a Vicon motion tracking system and projects a corresponding user

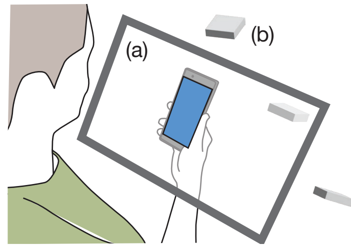

Figure 6.3: The high level concept for the proposed AR prototyping system: (a) see-through display window with corresponding phone content; (b) three depth cameras for markerless tracking.

interface onto the model to simulate realtime interactions. Using a similar approach, Paddle [108] tracks the topology of a Rubik's Magic puzzle toy and projects interfaces onto the passive object's reconfigurable tiles. With the exception of the last example, these systems prototype rigid physical interactions. Issues such as projection slip and occlusion, and invasive motion tracking markers, introduce new kinds of potential confounds for the design and evaluation of physical interactions.

Physical Interaction Prototyping System

We are inspired by approaches used in DisplayObjects [1] and Paddle [108], which simulated future interactions using passive mock-ups with projection. As future work, we propose an AR prototyping system which combines tracking and a virtual display to simulate future device capabilities, and explore physical interactions without hardware limitations. Figure 6.3 is a conceptual sketch of the system design which combines depth cameras and a display window.

DisplayObjects [1] projects content onto 3D mockups. The mockup position and orientation and the user's finger are tracked by a Vicon motion capture system to enable realtime interactions. By using markerless tracking, it is possible to generalize their proof-of-concept demonstration and enable much more diverse prototypes. The Iterative Closest Point (ICP) framework is often used to register 3D models with a point cloud captured from a depth camera [9, 17, 117] by minimizing the point-to-point or point-to-plane distance between model and scene. More recently, Stoiber et al. [135] enable 3D textureless tracking by calculating region-based correspondence between multiple sparse viewpoint models and depth contour images. The results are accurate and highly efficient. Integrating the system with a see-through display style of AR [79, 152] can avoid projection slip and enable opaque augmented content.

We did some in-depth investigation and implementation tests for markerless tracking of simple passive 3D objects held in one hand. To track precise phone poses and finger placement, we set up multiple depth cameras and captured point clouds of the scene. We used Azure Kinect [171] since the provided high quality, depth data in close range and they have a time sync

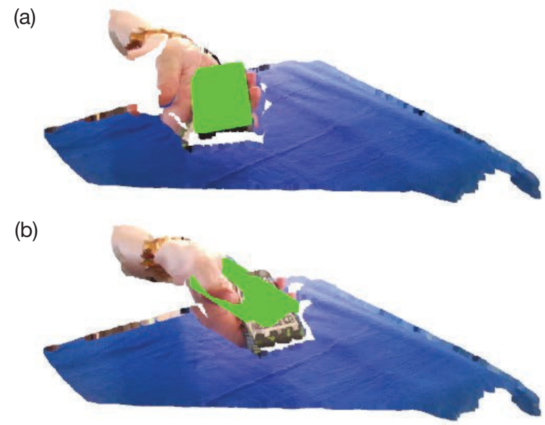

Figure 6.4: Results of 3D model pose estimation with a single depth camera: (a) without occlusion; (b) with finger occlusion. The pose estimation of 3D model is represented by the green point cloud.

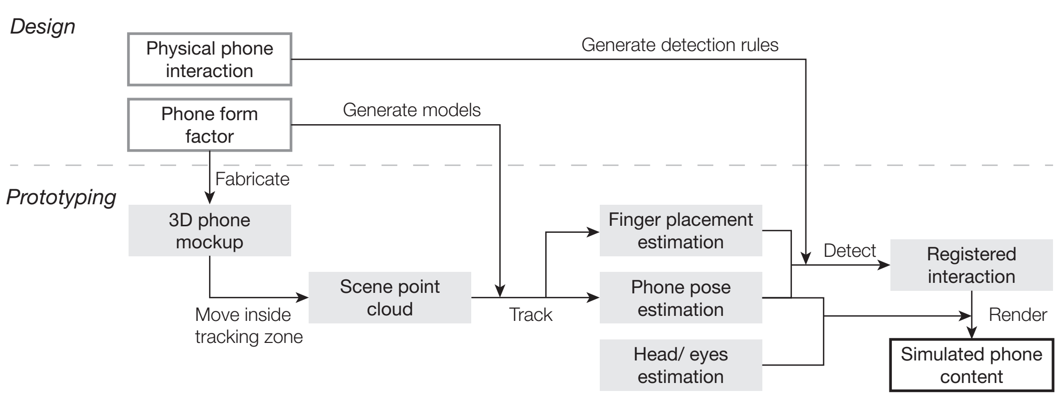

Figure 6.5: The flow of proposed prototyping system.

feature to coordinate capture across multiple cameras. However, we found stitching multiple point clouds to be error-prone because of the noise and a massive viewpoint difference between cameras we could not reliably remove. We further tested 3D model pose detection with a single depth camera with the ICP framework. We found the pose estimation could be less accurate with large occlusion areas caused by the user's hand, and too time intensive for interactive framerates with higher point cloud resolution (Figure 6.4). More challenges need to be addressed to implement our proposed system, such as detecting precise touch events and its location, tracking the user's head and eyes in front of the display to create realistic 3D mapping in the AR system, and the mounting of a virtual camera to make the simulated phone believable when the distance between mockup and display is quite small. However, we believe this prototyping system supporting rigid or deformable objects could contribute to enable interaction design and evaluation without hardware implementations. We show the possible evaluation flow of physical phone manipulation interaction design using our proposed system in figure 6.5.

6.3 participants sampling

In our user studies, we recruited 12 to 24 participants through on-campus flyers and word-of-mouth. These sizes of participants enable us to roughly compare between conditions and confirm our hypothesis. However, the calculated effect size was small which showed that our results may be less meaningful due to the number of participants. Large-scale experiments can be conducted to further evaluate our proposed interactions. Another limitation of our studies is the diversity of recruited participants. Since we recruited participants within university, the average age of our participants were comparably young. Broader demographics of participants could be recruited to better investigate the gesture performance in different groups of users.

7 CONCLUSION

In this thesis, we explore new forms of physical interactions which we define as input methods triggered by physical contact with a phone or direct physical manipulation of the phone when interacting with the phone content. We focus on interactions which would be performed with dynamic grips where users need to loosen their grip and change between grasp postures using their finger dexterity. We study different kinds of dexterous physical interactions to achieve our high-level research objective:

Investigate the performance and user preference of new forms of single-handed physical phone interactions that utilize finger dexterity, and explore the possible applications.

In this final chapter, we provide a summary of work by revisiting proposed research questions, and make our final thoughts.

SUMMARY

We investigate three physical interactions with finger dexterity by understanding the human factor, creating the prototypes, and building the demonstration applications (Figure 1.1, 1.2).

In chapter 3, we explored a new form of physical phone interactions called dexterous gestures which use fine motor skills of fingers to manipulate the device in-hand. We defined a gesture design space consisting of shifting, spinning, rotating, and flipping manipulations, with tilting used as a baseline.

- *Do people already loosen their grip and perform dexterous manipulations with their phones?*

  A formative study showed that all manipulations except flipping had been previously performed by participants.

- *How well can users perform different types of dexterous gestures and what are their perceptions and preferences? Can users improve their ability to perform dexterous gestures after one-week practice?*

  A performance experiment showed that rotating was fast and the most preferred gesture while a full flip was rated lowest. A one-week experiment further showed that speed and willingness to adopt dexterous gestures improve after practising, and that there is little difference in using the gestures while sitting or standing.

- *Can dexterous gestures be reliably detected using only current built-in sensors of phones? What applications are there for dexterous gestures?*

A prototype system using a heuristic recognizer demonstrated that most spinning, rotating, and flipping gestures can be recognized reliably on standard phones with 91.2% average accuracy, which illustrates how this style of gestures could be used in real applications. We can use dexterous gestures for global commands or within-app interactions, such as opening a camera app, invoking assistance tools, dismissing an alarm, or declining an incoming call.

Our exploration shows how human dexterity can be harnessed for new forms of phone interaction.

In chapter 4, we explored the potential of an expanded one-handed two-dimensional touch input space along the side of a phone.

- *What is the preference regarding comfort, and grip stability when reaching different phone side locations with different fingers? Which fingers and which side area is most suited for side touch input?*

  A first study shows that virtually every location around the phone can be comfortably reached with at least one finger. We find side locations include middle to top-right for the thumb and top-left for the index are good candidates for primary side touch interaction.

- *How well can different kinds of taps and flicks be performed on the side when two dimensional sensing is possible?*

  Two subsequent studies evaluate the performance and preference for side taps and flicks, showing that taps and flicks with the thumb have great potential, but the index is less suitable except for simple in-frequent input.

We hope our investigation of side touch input provides ideas and evidence to inspire hardware designers to consider this alternative to physical side buttons: harnessing the expressive potential of smooth, touch-sensitive sides on a phone.

In chapter 5, we explored single-handed folding interactions designed for a modern flip phone: only a fold, a touch-enhanced fold, and a fold-enhanced touch.

- *How well can users perform different types of folding interactions, what are their preferences, and how do they change the grip to perform them with modern flip phones?*

  An experiment examined 30 gestures by considering fold direction, fold magnitude, and touch location, with the results suggesting that these kinds of gestures can be performed quickly, and more than half of them are rated easy and comfortable even though they require finger dexterity and coordination.

- *What applications are suitable for folding interactions?*

> Demonstration applications using our prototype evaluation device, such as editing texts, browsing maps, or improving reachability, show how folding interactions could be used to augment conventional flip phone input.

Our work contributes a new example of how deformation gestures can be used as an input method, and using a device with capabilities similar to existing commercial phones.

FINAL WORD

It has been about 20 years since the first smartphone launched. Smartphones largely reshape how we gather information and interact with people. In our experiments, most participants use their phone for at least one hour per day. People are familiar with their phone in terms of physical handling and manipulation. With such familiarity, it is possible to leverage more dexterous physical abilities of users when designing new forms of phone interaction. We show people can perform such gestures and we demonstrate how they can integrate into practical applications. Although our explorations are limited compared to the full scope of physical interaction, we believe our results can provide insights for researchers and designers to further create more expressive interactions, and users can harness their finger dexterity and use it in new and creative ways. We hope that our work sheds light on the design of future phone form factors and interactions.

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