The design opportunities of the biomechanical human hand and the role it plays in handheld technology

Rachel Clare Eardley
BA (Hons) and MA (Distinction)

January 2021

A thesis submitted to Cardiff Metropolitan University School of Art & Design in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)

Director of Studies: Dr Stephen Thompson Supervisors:
Professor Steve Gill and Dr Anne Roudaut

Abstract

When interacting with a smartphone, the user does not just interact with the screen-based user interface (UI) but also the physical hardware's form. This thesis looks beyond designing smartphone screen UI's as a separate entity, a common practice for many interaction designers. Instead, this research investigates combining the physical smartphone form, the screen-based UI and the biomechanical tool used to interact, that of the human hand, informing more compelling user interactions.

This research was completed through five stages using qualitative and quantitative research methods. The first questioned how the physical interaction method (touchscreen, buttons, or stylus) affected hand usage (Chapter 3). The second and third used the first stage findings to understand the effects on the smartphone movement concerning: for stage two, the size of the smartphone and grips (Chapter 4), and for the third stage, the body posture (sitting, lying down, standing) and grips (Chapter 5). Finally, for stages four and five, a collaboration with interaction designers using the gathered data developed interaction concepts that focused on types of applications (security and messaging) (Chapter 6) and the handgrips and body postures used (Chapter 7).

This research has developed insights showing the usage of four grips to interact with a smartphone. The participant's grips used, smartphones size, and body posture affected the level and angle of the smartphone's movement. With the single-handed grip, lying down body posture, and the larger-sized smartphones (iPhone 6 and 6+) produce the most movement. The least being asymmetric bimanual with a finger, standing and the smaller sized smartphones (iPhone 4s and 5). Through a collaboration with interaction designers, this research has produced 20 concepts that provide insights on new design approaches and how design can change by using the physical smartphone size, body posture, and hand grips within the design context.

Acknowledgments

Firstly, I would like to thank the participants who took part in the five studies that make up this PhD research. This research would not have been possible without your willingness to volunteer your time and feedback.

My thanks go to my PhD supervisors, Stephen Thompson, Steve Gill and Anne Roudout, who have been so supportive during this roller-coaster of a ride.

I want to thank all my work colleges over the years for the numerous jobs that I have had during the PhD (Skype, Housetrip, Ticket.com, MovieGlu, Friends Life, Somo and Bristol University). I am sure most have had a conversation with me about the PhD at varying levels of enthusiasm. I want to thank Henrique Penha, David Dinka, Peter Hornsby, Eleanor Evans, Chris Baker, Emma Tonkin and Constance Fleuriot. Special thanks go to Somo, who loaned me the smartphones for my studies and paid for me to attend CHI and DIS 2018. Finally, I will be forever grateful to Nick Hymes, Carl Uminski and Zeina Farha for your support in completing this PhD, especially during my health issues.

Thanks go to Dr Natasha Thorogood for saving my life twice, to my oncology team, first my kidney specialist Mr Francis Keeley and secondly my Thyroid specialist Dr Matthew Beasley. To Mr Valentine Akande for not giving up on me and my cancer geneticist Dr Susan Tomkins. Thank you to my family, friends and co-workers for the support and understanding as I made my way through these difficult times.

My parents have always supported and had faith in me, going over my spellings and paying for Dyslexia Institute, all in the hope that I would accomplish my dreams and not let my Dyslexia hold me back. Thanks to my big sister for putting up with me, I do so admire you – and to my nieces, who may now get their promised stain glass windows. To James, we met whilst I

have been doing this “hobby”, and you have been so understanding as I hide away during weekends working or using you as a test subject to see if an experiment would fit within a certain time frame.

Table of Contents

CHAPTER TWO: LITERATURE REVIEW 13

CHAPTER THREE: INVESTIGATING DIFFERENCES BETWEEN THE HAND AND SMARTPHONE 'INTERACTION TYPE' 33

List of Figures

List of Tables

Chapter 1: Introduction

This chapter presents an overview of the thesis and its emergence from the research questions and literature review. In addition, it presents an overview of the activities completed: qualitative and quantitative studies and design workshops. I produced three papers from this work: 2x ACM CHI and 1x ACM DIS, one poster (ACM Mobile HCI), a doctoral consortium workshop paper (ACM DIS), and a design workshop (UX Bristol 2017). This chapter also highlights the approach taken to this research and how I formed each study and establishes the research questions and professional career changes.

1.0 Motivations

Perhaps the most natural and intuitive way people interact physically with the world is through their hands. With the way the human body has influenced our understanding of mechanical technology, it is easy to think of the hand as a bio-mechanical tool - a tool we can use (disability aside) without conscious thought **(Dix 2002)**. However, Frank Wilson, in his book "The Hand", states that people rarely notice each 'skill' that the hand performs daily, not just to use interactive technology but by merely lifting the fork to our mouths so that we can eat **(F. R. Wilson 1999)**. This thesis aimed to research how we use hand-skills to interact with handheld technology. To achieve this, I looked at Napier's **(Napier 1993)** seminal work on the hand that defined grips for interacting with everyday objects (e.g., precision, power, hook and scissor grip – see section 2.2.2). Despite the previous research on the physical and connected hand (as shown in the literature review Chapter 2). UI design can often ignore the hand's natural skill. For example, current smartphone interaction design is focused solely on screen-based interaction **(Apple 2020, Apple Developer 2020 and Google 2020)**, completely ignoring the full spectrum of the hand. Importantly this research looks to close the loop between Wilson **(F. R. Wilson 1999)** and Napier's (**Napier 1993)** insights on the hand and current UI design.

Previous research has looked at smartphone movement for the single-handed grip **(Negulescu and McGrenere 2015; Noor et al. 2014; Chang et al. 2015)** and, in some contexts, dealing with the physical device **(Viet Le et al. 2016; Kim et al. 2006; Noor et al. 2014; Yoo, Yoon, and Ji 2015)**. However, there is a lack of research regarding the interactions between the hand and smartphones in various scenarios (e.g., handgrip, body posture, device size and target areas). I investigated how the hand is used in different conditions to generate knowledge to benefit UI designers. Using these findings to inspire UI designers and through design workshops, I question if considering hand usage can allow the UI designer to create more compelling UI experiences that are more usable.

I have conducted this research with the primary focus being that of the hand and not the technology or other commercial constraints that current smartphone UI designers work within. Therefore, my research is only concerned with interactions with the smartphone when held within the participant's hands, not when pocketed or resting on a table. The devices selected for study are commercially available smartphones produced during or before 2016 and are single screened devices. All participants were under 55yrs old, based in the UK and able-bodied. I did not consider any physical, mental or sight disabilities within this research. Additionally, this research focused purely on tapping as the interaction method and did not consider others, such as gesture interaction.

1.1 Research questions

This research aims to understand in a systematic way how the hand interacts with smartphones - Investigating if the smartphones' type of interaction, size or users' body posture affects how the smartphone is manipulated by the hand when operated. I then applied those findings to determine if they could be used to guide the design of new mobile UI designs.

From this, I developed the overarching research question:
1) How does the design of smartphones affect hand interaction?

1.1.1 Interaction methods

The first of the three variables (Chapter 3) were inspired by Napier **(Napier 1993)** and his research on the affordances of the hand, highlighting how the hand adapts when interacting with different objects using four grip types (power, precision, hook, and scissor). Next, I investigated how these handgrips differed between different smartphones interaction types. To this end, I selected three available commercial smartphones with differing interactions: a stylus (Sony Ericsson), button-based (BlackBerry) and touch screen (iPhone 4).

From this. I developed the research question:

2) Do the interaction methods used change the way participants use their hands to interact?

1.1.2 Size of device

Napier **(Napier 1993)** highlighted how handgrips adapt when using different sized objects to progress this research. I investigated how the movements and interactions with the smartphone compared when using four different sized devices (iPhone 4,5,6 and 6 plus) (Chapter 4). Following on from Chapter 3, I selected the touchscreen interaction as the participants used the most grips (four grips) to complete the task.

From this. I developed the research question:

3) Does the size of the handheld interactive object change the way the hand interacts?

1.1.3 Body posture

My third and final variable (Chapter 5), being inspired by Bachynskyi **(Bachynskyi et al. 2015)**, investigated how the participant's posture may alter the movement and interaction with the smartphone, comparing a participant's action when standing or lying down with one of sitting while resting. The body postures were selected to be symmetrical. Each posture used different muscles to support the arms. In each posture, the user positioned the smartphone at a particular angle, meaning that three unique combinations of posture and angle were studied overall.

From this. I developed the research question:

4) Does the participant's body posture affect how the hand interacts with the handheld interactive device?

1.1.4 UI design concepts

The final area of research that the thesis investigates is how to translate this gathered empirical research, and with the collaboration of UI designers understand if this new knowledge would allow for the creation of more compelling smartphone user interfaces.

From this. I developed the research question:
5) How can we design interactive, handheld smartphones better for the user's hand interaction?

1.2 PhD timeline

Starting in 2009, this part-time PhD has been completed jointly with me working as a professional user experience designer (UX designer) (Figure 1.1). During these years of study, several changes have occurred. First, the university changed its name from the ‘University Wales Institute Cardiff’ to ‘Cardiff Metropolitan University. Additionally, the supervisory team changed, with Dr David Dinka (then the head of user research at Skype) leaving the team and Dr Anne Roudaut of Bristol University joining.

1.2.1 Employment changes

During this period of study, I have worked as a UX designer for seven different employers. First, as an in-house UX designer for Skype and Friends Life, then freelance for early-stage start-ups such as Housetrip, Ticket.com and MovieGlu, within a technology agency for Somo and academia, firstly for Brunel University and finally as a research associate for Bristol University. I have, during this time, launched products that have enabled users to communicate across the world, helped in the securing of VC funding and led the UX design for websites, smartphone apps and system designs for international companies such as Vodafone Audi, Jardine and Moet.

1.2.2 Research topic changes

When starting the PhD and working at Skype, the research was concerned more with communication interfaces and differences between tangible vs purely screen-based interaction. However, after leaving Skype, the research topic evolved to something more personally inspired, the human hand.

The topic of the human hand had its inspiration through a conversation that I had at my first CHI (Computer-Human Interaction) conference in Vienna (2004). My then line manager, Abigail Sellen, introduced me to Bill Buxton and Yves Guard. Bill Buxton took the opportunity to educate me in the research that Guard had completed on asymmetric bi-manual interaction **(Guiard and Ferrand 1996)**. Bill Buxton demonstrated that each hand played a different role by using an imaginary ice hockey stick to hit an imaginary puck. On discovering the book 'Hand' by Frank Wilson **(F. R. Wilson 1999)**, I decided this was a research topic I would like to explore further, questioning how the hand interacted with technology.

1.3 Publications

For this PhD, I have published five academic research publications that include three full papers, one poster and one paper in the proceedings of a doctoral consortium, covering four studies and part of the literature review.

1.3.1 Related work

As an early-stage PhD student, I published part of the literature review at a doctoral consortium **(Eardley, Gill, and Thompson 2012)**.

Eardley. R., Gill. S., Thompson. S., (2012) **Investigating the biomechanical hand and its role in designing interactions**. Doctoral Symposium of ACM Conference on Designing Interactive Systems (DIS). Newcastle, UK. June 2012.

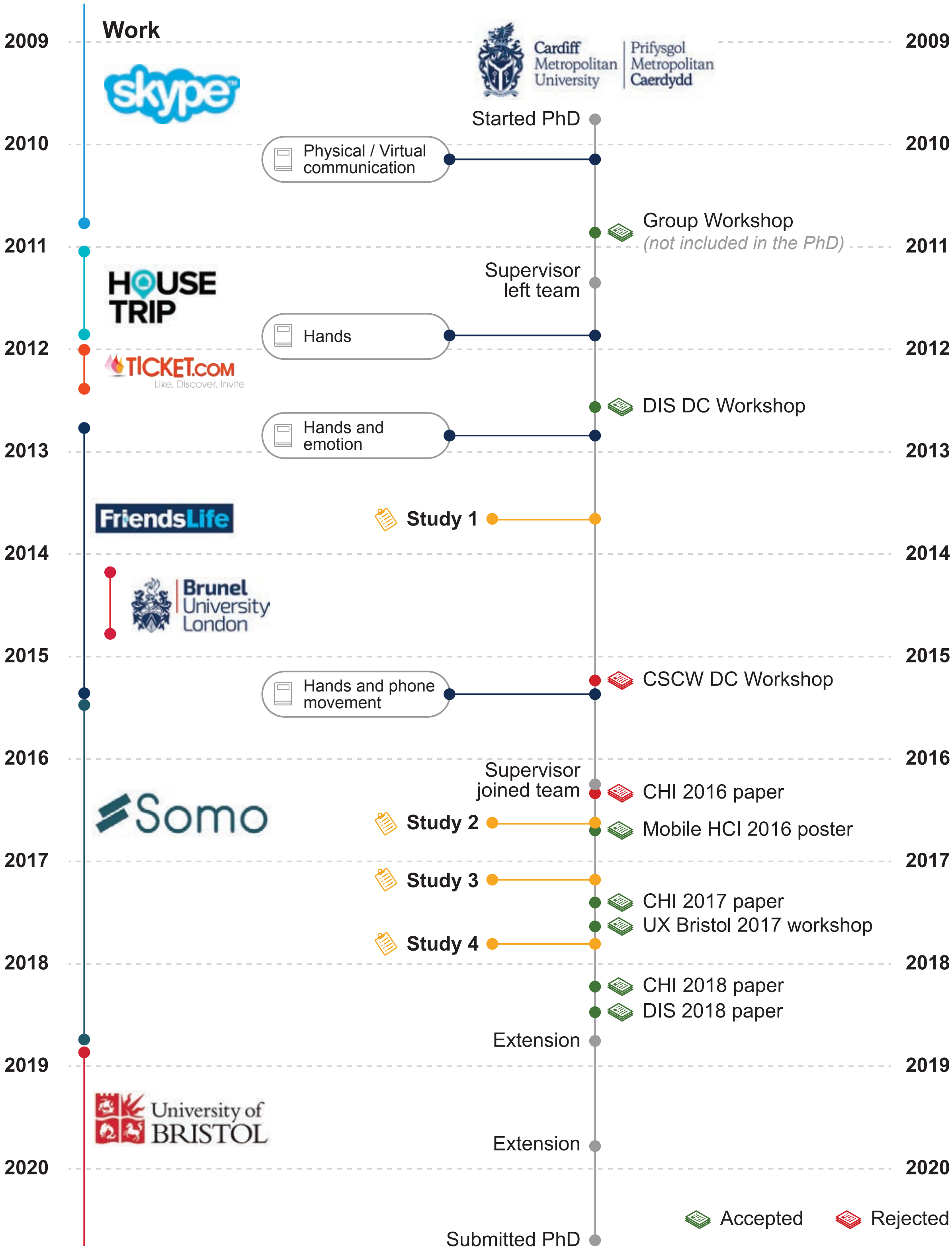


Figure 1.1. Timeline of part-time PhD

1.3.2 Study 1: Type of interaction

The research and discoveries for Study 1 have been published at Mobile HCI as a poster and contributes to chapter 3 **(Eardley et al. 2016)**.

Eardley. R., Gill. S., Roudaut. A., Thompson. S., Hare.J., (2016) **Investigating how the hand interacts with different mobile phones**. Mobile HCI 2016, Florence, Italy.

1.3.3 Study 2: Smartphone size & Study 3: Body posture

Both papers have contributed to the quantitative studies and presented in chapters 4 & 5 **(Eardley et al. 2017; 2018b)**.

Eardley. R., Roudaut. A., Gill. S.,Thompson. S., (2018) **Investigating How Smartphone Movement is Affected by Body Posture**. CHI 2018, Montréal, Canada

Eardley. R., Roudaut. A., Gill. S.,Thompson. S., (2017) **Understanding Grip Shifts: How Form Factors Impact Hand Movements on Mobile Phones**. CHI 2017, Denver, Colorado, USA

1.3.4 Study 5: Grip and body posture workshops

The design workshops from Study 5 have been published in DIS and contribute to chapter 7 and were awarded an Honorable Mention **(Eardley et al. 2018a)**.

Eardley. R., Roudaut. A., Gill. S.,Thompson. S., (2018) **Designing for Multiple Hand Grips and Body Postures within the UX of a moving Smartphone**. ACM Conference on Designing Interactive Systems (DIS). Hong Kong. June 2018.

1.4 Approach

To understand how compelling UIs are designed, it is necessary to understand how users interact with smartphones. Consequently, this research approach contained four studies that first investigated how smartphones are used with hands (Chapters 3 to 5) and secondly, how designers could use this data to design better smartphone interactions (Chapter 6). I conducted three studies investigating the impacts of type of interaction, smartphone size, and body posture on user interaction. This is shown in more detail in Table 1.1. To conclude this study, I conducted workshops with professional UI designers to apply my findings to determine if higher quality user experiences could be achieved.

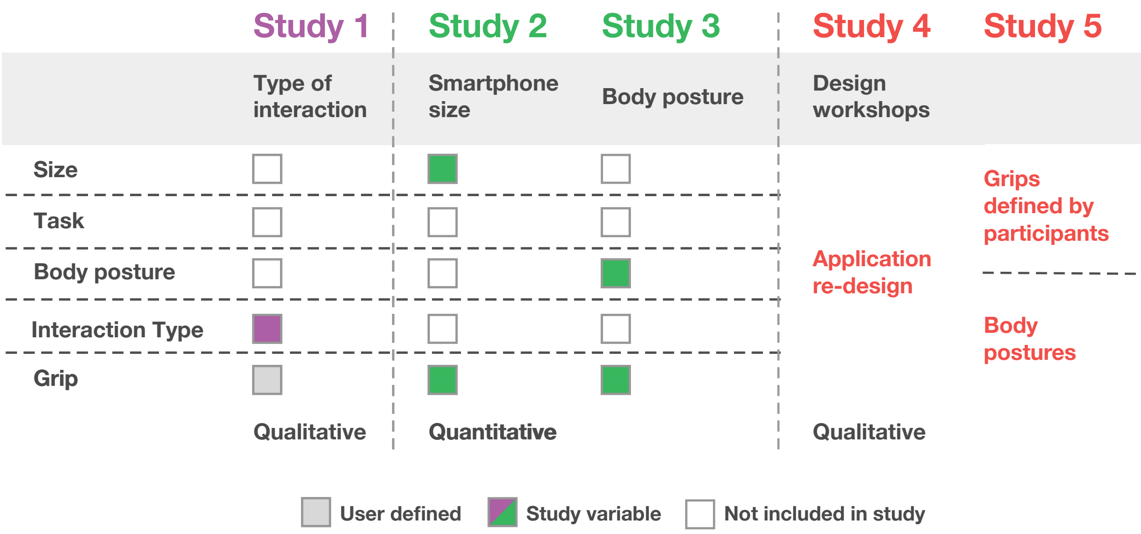


Table 1.1. Layout of approach

1.5 Methodology

This research used a mixture of qualitative and quantitative research methodologies **(Bergin 2018)** or sequential 'exploratory design' **(Creswell and Plano Clark 2011)**. First, I used qualitative research methods to conduct an observational study on how the hand interacts with a smartphone, depending on the type of phone (see Study 1, Chapter 3). I then used quantitative methods to understand the relationship between movement and smartphone size (Study 2, reported in Chapter 4) and the relationship between movement and body posture (Study 3, reported in Chapter 5). Study 4 (reported in Chapter 6) and Study 5 (reported in Chapter 7) focused on understanding how designers creatively interpreted the gathered data through qualitative design workshops.

1.5.1 Qualitative research

For the explorative Study 1 type of interaction, I wanted to understand how people used their hands to interact with current smartphones. To this end, I conducted semi-structured interviews with a task-based activity, interacting with three different types of smartphones to send a short text message. Using semi-structured interviews allows the researchers to have a defined range of topics or questions and the flexibility of expanding on those topics in greater depth during the session **(Bergin 2018; Adams 2015)**. Using a task-based activity and analysis, I observed the participants engaging with the smartphones and identified the grips used **(Stammers and Shepherd 1991)**. As the participants for the study would use smartphones one after the other, it was essential to making sure that their familiarity with the task did not affect the research goals. Once the data was collected, I categorized the grips used by the participants through Affinity Diagramming **(Harboe and Huang, 2015)** as a clustering process. I also used Affinity Diagramming to cluster the sketches in Study 4, re-designing an application and Study 5, understanding the design possibilities.

1.5.2 Quantitative research

Study 2 (smartphone size) and Study 3 (body posture) used identical research methodologies. The following research studies would then identify if the participants' smartphone activity matched or contradicted them **(Bergin, 2018)**. To statistically analyze the studies, I intended to use the standard statistical method of Analysis of Covariance (ANOVA) **(MacKenzie, 2012; Bergin, 2018)**. However, the data set also included the participants' hand sizes, and hence I selected ANCOVA, which extends the analysis of variance by including additional variables **(Rutherford, 2001)**. To understand the participants' attitudes towards the smartphone interaction (e.g., How comfortable the grip was), I created a questionnaire that used a Likert scale (Appendix B.3) **(Likert, 1932)**.

1.5.3 Ethics

I applied for and received Cardiff Metropolitan University ethical approval for all participant-based studies, including qualitative forms, interviews and design workshops (based on and off the university campus) and quantitative data collection. For the studies in Chapters 3,4,5 and 7, I recruited the participants via email. For Chapter 6, where I ran a workshop during a conference, participants could optionally join the study and have their designs photographed and analysed. All potential participants had the opportunity to review the information sheets and consent forms before conducting each study to support the potential participants in their informed decision-making. In addition, I ensured that the participants who took part in the body posture study, as presented in Chapter 5, completed activities using an air mattress to reduce discomfort when lying down.

1.6 Thesis Overview

The thesis comprises the following sections: research literature review, studies completed, and conclusions drawn.

Chapter 2 presents the related work in five parts. The first looks at HCI and its understanding of physical interaction. The second looks at the biomechanics of common types of hand usage, its tissue and bones. The third looks at how the hand is used to complete everyday tasks and which grips are used. The fourth investigates how the HCI community has researched the hand, and the fifth, how the hand interacts with handheld technology such as smartphones.

Chapters 3 to 6 present my investigations into the hand and smartphone interaction. First, chapter 3 presents my investigation into the smartphones' interaction type', in which I asked participants to use three smartphones (touchscreen, button-based and stylus-based interaction). Next, in Chapter 4, the effect of the user's grip, and the size of the smartphone, on the smartphone's tilt and rotation are investigated. Finally, Chapter 5 investigates the 'Body posture' and how different grips and the participant's body position affect the tilt or rotation of the smartphone. Using the research findings from Chapters 3, 4 and 5, I then discuss how I used the data to create 12 data cards showing the individual data for grips or body posture. I then tested these cards during two workshops that enlisted UI designers to develop UI concepts.

Through Chapters 6 and 7, I discuss my findings and their impact on smartphone design with a hardware/software approach. Finally, concluding in Chapter 8, I present the overall thesis and the future work that can be done and has emerged from this research.

Chapter 2: Literature review

Part of this chapter has been published at ACM DIS 2012 Doctoral Consortium.

In this chapter we investigate the complexity of the hand and its manifestation as a bio-mechanical tool, connected through human thought. We also explore how this bio-mechanical tool has been an inspiration for interaction within the field of Human Computer Interaction (HCI) with key methods of interaction being that of the keyboard and mouse. Finally, we look at the HCI literature on how the hand interacts with smartphones, which has informed our research.

2.0 The physical hand

Our bio-mechanical hands are complex anatomical structures, fabricated out of biological components such as *"bones, joints, muscles, arteries, veins and nerves"* **(Wood Jones 1920).** For our research, it is not necessary to comprehend all anatomical knowledge. Instead, the focus will be on those biological components that make up the hand's mechanical skills, and on examining how people control their hands, with Wood Jones, Napier and Wilson all claiming that the hand's connection to the brain is what makes the hand so essential within our daily life **(Wood Jones 1920; J. Napier 1993; Wilson 1999).** Napier declared that our hands are anatomically *"primitive"*, inheriting much of their functionality from human ancestry, with the hand's *"connection"* to the human brain bringing its sophistication **(J. Napier 1993).**

2.0.1 Bone structure and joints

The human hand has evolved into a structure that in its skeleton foundations is able to manipulate object easily. It is made up of a total of 27 bones. Eight of these make up the wrist (*'carpals'*), Five make up the palm (*'metacarpals'*) and the digits (*'phalanges'*) have two bones for the thumb and three bones for the fingers (see figure 2.2) **(Tubiana, Thomine and Mackin, 1996)**. The three bones for the fingers include the point (*'distal'*), the middle (*'middle'*) and the base (*'proximal'*) (see figure 2.2) **(Drake, Vogl, and Mitchell 2010).**

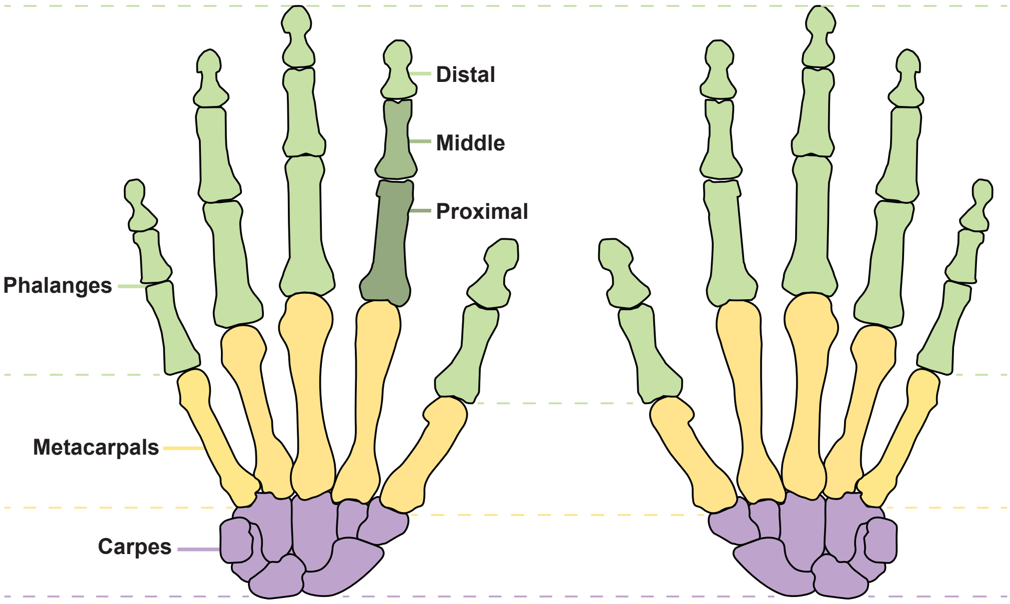


Figure 2.2: The bone structure of the human hand

Drake et al **(Drake, Vogl, and Mitchell 2010)** additionally state that where the digits (*'phalanges'*) and palm (*'metacarpals'*) connect, there is a joint (*'metacarpophalangeal'*) enabling our digits to create four distinct types of motion (*'extension', 'flexion', 'abduction' and 'adduction'*). Extension is where the digits are extended away from the palm (figure 2.3a) and flexion is where the digits are curled towards the palm (figure 2.3b). Abduction is where the digits move from the left (figure 2.3c) and adduction is where the digits move from the right (figure 2.3d).

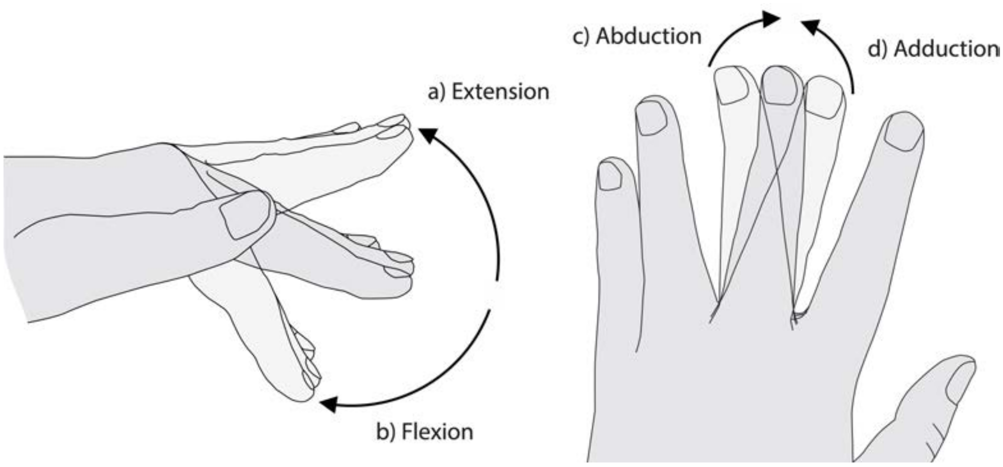


Figure 2.3: Movement of digits (Drake, Vogl and Mitchell, 2010).

Furthermore, the wrist joint allows for these same forms of movement, however, including our whole hand (see figure 2.4) **(Drake, Vogl, and Mitchell 2010)**.

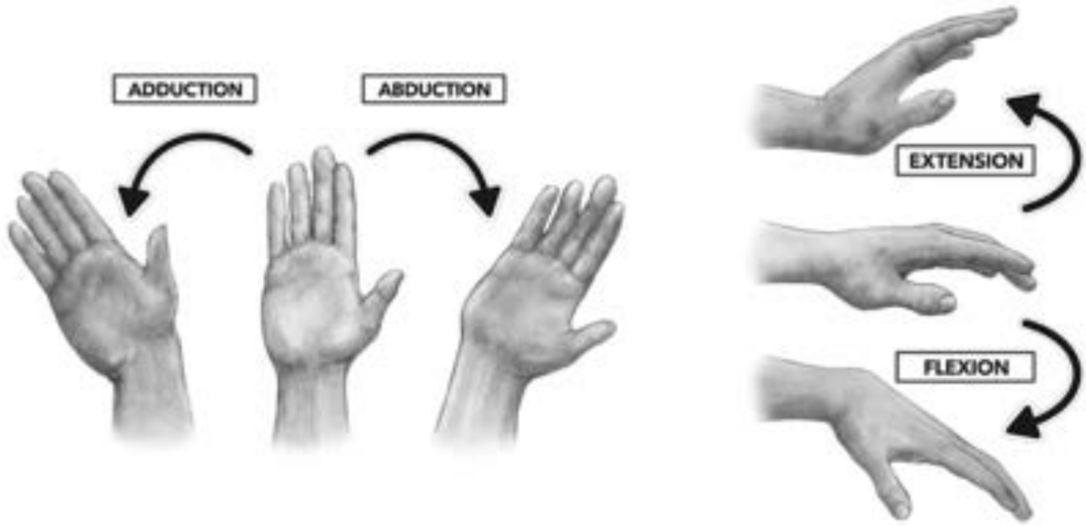


Figure 2.4: Movement of hand (Drake, Vogl and Mitchell, 2010).

2.0.2 Ligaments and muscles

The ligaments are tissues that connect the bones together. Ligaments such as those across the knuckles (‘*deep transverse metacarpal ligaments*’) are prominent within the hand and help to bind the ’*metacarpal*’ bones together and build the foundation of the palm **(Drake, Vogl, and Mitchell 2010)**. The human hand moves through muscles situated in two different locations, the hand and the forearm. The muscles located in the hand consist of six types of *‘intrinsic’* muscles. These ‘*intrinsic’* muscles enable the hand to make ‘precision movements’ with the fingers and thumb. Those muscles located in the forearm consist of nine types of *‘extrinsic’* muscles and enable the hand to perform more ‘forceful movements’ **(Drake, Vogl, and Mitchell 2010).**

2.0.3 Skin and sensors

The biological skin covering the human hand has numerous physical characteristics. The lines seen on the palms ('flexure lines') are creases in the skin that correspond to the movement of the skeletal joints of the hand **(Wood Jones, 1920).** The small ridges on the palm and fingers ('papillary ridges') are the "grasping surface of the hand" **(Wood Jones, 1920).** We should consider the *"skin as an exposed portion of the central nervous system"* as there are many complex sensors embedded in the skin **(Wood Jones, 1920).**

There are two types of sensors orientated 'outward' and 'inward' **(Paterson 2007)**. The 'outward' orientated sensors are those that permit the human to be aware of the physical surroundings. These sensors enable the human to feel "resistance, temperature, surface quality, softness, weight and more" **(Hornecker 2011)**. Hornecker also points out that touch is bi-directional as the human is unable to touch something without that something touching the human back **(Hornecker 2011)**. The 'inward' orientated sensors, as Paterson describes them, enable the human to be aware of their biomechanical body's physical position ('Proprioception') and movement ('Kinesthesis') **(Paterson 2007)**.

2.1 A connected hand

If we consider the human hand to be controlled by the human through thought, then perhaps an understanding of how the human brain connects to the hand is needed. Wood Jones argues that *"it is not the hand, which is perfect, but the whole nervous mechanism by which movements of the hand are evoked, coordinated, and controlled"* **(Wood Jones 1920)**.

2.1.1 Controlling the human hand

It is argued **(Wilson 1999)** that as a newborn the human has no control of their biomechanical tools. It is only after a number of weeks that the human develops the ability to reach towards an object and it is not until the infant can support its head that this reach obtains full accuracy, as the hand operates with 'guidance' from the infant's eyes. Wilson adds that the infant needs to develop a 'reference system' of artifacts within the material world to help establish and coordinate the hand's movements **(Wilson 1999).**

The human consciousness does not move individual muscles but controls these muscles as a physical 'movement', as it is the human brain's 'cerebral cortex' where *"Movements, not muscles, are represented"* **(Wood Jones 1920)**. Movements are described by Wood Jones as follows: *"We may say that it is a movement of which the animal has definite knowledge, a movement which it can, so to speak, see and feel itself doing, a "pictured movement" or an "action pattern" which is realized by the animal"* **(Wood Jones 1920)**. Wilson argues that this control of the hand is like that of puppeteers controlling puppets. However, instead of using strings to control the hand, humans use their biological nervous system **(Wilson 1999)**.

It is understandable then why, as with any man-made tool, the ability to control biomechanical tools is a 'skill' gained through regular practice **(Ingold 2000)**. It is with this practiced 'skill' that humans can develop the ability to use the hand without conscious thought. Humans rarely notice the 'skill' with which the hand performs daily and that the human takes for granted the ability to simply lift the fork to the mouth so that they can eat **(Wilson 1999)**. It is only when a "breakdown" occurs that the human notices this lack of 'fluidity' and needs to focus on operating these biomechanical tools **(Dix 2002)**. This learned 'skill' is based not on the anatomical human hand but on its connection to the human brain: "The skill of the hand lies in the brain and it is here that dexterity and adroitness (or clumsiness) originate" **(J. Napier 1993)**.

The human hand can perform various functions as it is cognitively connected and coordinated by the human brain. This includes mechanically manipulating the physical, sensing the material world, both hands working in partnership and gesturing to enable the human to communicate.

2.1.2 Manipulating the physical

To comprehend the hand, we first question the overall physical structure. We have what anthropologists' term *'Pentadactylism'* as our hands have five digits, this being *"the absolute bed-rock of mammalian primitiveness"* as no mammal has evolved beyond five digits **(Wood Jones 1920)**

It is argued by **(Napier, 1956)** that the human hand has two types of 'movement' *"Prehensile and non-prehensile"*. Wilson describes these types of movements as "Prehensile movements are those in which an object is held partly or wholly within the hand; non-prehensile movements are those in which the object is manipulated by the hand or fingers but not grasped" **(Wilson 1999)**.

The prehensile movement has been categorized by Napier **(J. Napier 1993)** to include four basic grips. Firstly, they identify the 'precision grip', which uses muscles located in the hand **(Drake, Vogl, and Mitchell 2010).** The human uses this 'precision grip' "when delicacy of handling and accuracy of instrumentation are essential" **(J. Napier 1993)**. The second is the 'power grip' and uses muscles within the forearm **(Drake et al 2010)**. This 'power grip' is used when the human needs to consider force. The third is the 'hook grip', which is used to carry artifacts such as a heavy bag. Finally, they identify the fourth grip, the 'scissor grip', is used when the human holds an object between their fingers**.**

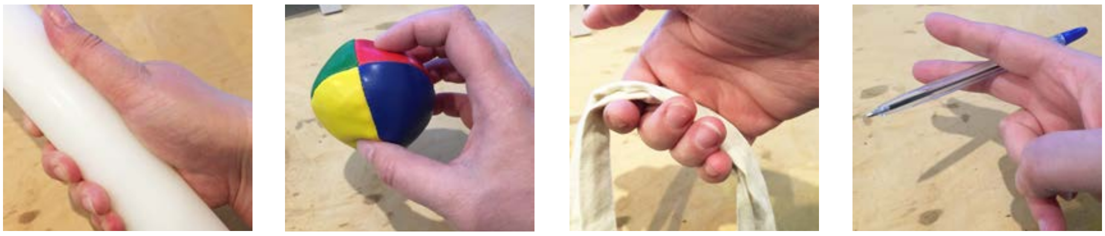


Figure 2.5: Four different grips as described by Napier. a) Power grip, b) Pinch grip, c) hook grip and d) scissor grip (Napier, 1993).

The way in which the human uses the prehensile movements is dependent on the task at hand, as it is *"a function of the activity itself and does not depend on the shape or size of the object gripped"* **(J. Napier 1993)**. It is also stated by Napier that the human has the ability to change grips to accomplish a task, and when unscrewing a lid of a jar, the human will initially use a 'power grip' to loosen the lid and untimely use a 'precision grip' to remove the lid **(J. Napier 1993)**.

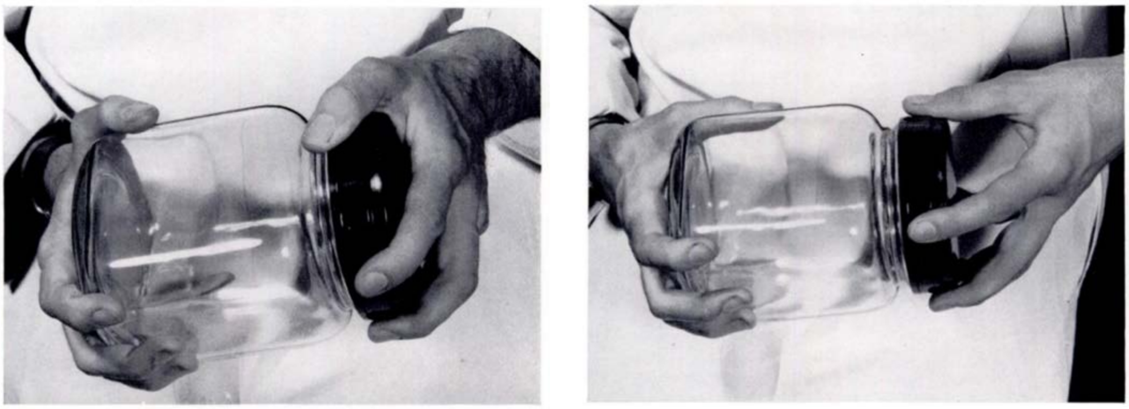


Figure 2.6: Changing grips from power to pinch grip (J. Napier 1993)**.**

2.1.3 A touch sensor

The human hand has various sensors encompassed within its anatomical structure; it is a biological tool that Napier **(J. Napier 1993)** describes as the main source of *"contact with the physical environment"*. Wood Jones **(Wood Jones 1920)** argues that the human hand is the *"dominant organ of tactile sensibility"*. Wilson **(Wilson 1999),** Wood Jones **(Wood Jones 1920)** and Hatwell et al **(Hatwell, Streri, and Gentaz 2003)** believing that the hand as a 'sense organ' enabling the gathering of information through touch. With the added benefit of being attached to the end of the human's arms, enabling the hands to operate at a distance when required **(Wilson 1999).** In fact, Klatzky et al, 1985 **(Klatzky et al, 1985)** studied how the hand can identify 100 common objects by touch and discovered that their participants could explore the object with their hands and give a correct answer within one to two seconds of contact **(Klatzky et al, 1985)**.

When exploring an object, the participant will as argued by Lederman and Klatzky **(Lederman and Klatzky 1990)** complete a two-stage sequence, the first is a "grasp-and-lift" action and the second is termed an exploratory procedure **(Lederman and Klatzky 1990)**. Lederman and Klatzky **(Lederman and Klatzky 1987)** and Hatwell et al **(Hatwell, Streri, and Gentaz 2003)** describes these "exploratory procedures" **(Lederman and Klatzky 1987)** as ways the human can assess material characteristics of physical artifacts. A brushing of fingers across the surface ('lateral motion') informs texture. Pushing the fingers into the artifact ('pressure') informs hardness. Holding the artifact freely within the hand ('unsupported holding') informs weight. Gripping an artifact within the hand ('enclosure') informs approximate shape. Others such as placing the hand on the artifact ('static contact') informs temperature and using the finger to trace the artifacts edge ('contour following') informs the size and shape; both procedures also enable the human to gain a broad understanding for the size, shape and texture of the artifact **(Lederman and Klatzky 1987** and **Hatwell, Streri, and Gentaz 2003).**

This perception of touch **(Lederman and Klatzky 1987)** was investigated further by Klatzky et al, **(Klatzky et al, 1987)** exploring the identification of objects with and without vision. Using haptic exploration alone, showed that hardness and texture were easily defined, however, vision was needed to ease the definition of the objects shape **(Klatzky et al, 1987)**.

2.1.4 Left and right hand

The human hand, as Wilson **(Wilson 1999)** argues, has a number of symbolic implications, none quite so much as left and right-handedness. Napier **(J. Napier 1993)** presents that historically *"In most cultural groups the left hand is regarded as both unclean and unworthy"*, with Wilson **(Wilson 1999)**, Napier **(J. Napier 1993)** and Wood Jones **(Wood Jones 1920)** all stating that, within the Western World's education system, people who had a natural dominance for their left hand, were historically forced to use their right. This hand dominance, as Wilson **(Wilson 1999)** argues, is a uniquely human behavior and set at the early stages of life, ranging from right-dominant, ambidextrous to left-dominant.

It is argued by Guiard **(Guiard 1987)** that it is important to not only focus on the human hands' dominance, but on how the hands work individually and in partnership, stating that the *"human's most skilled manual activities involve two hands playing different roles"*. Guiard **(Guiard 1987)** believes there are two types of activities in which the human hands do this. Firstly, there are activities in which the hands work together but in different roles ('bimanual asymmetric') and secondly, activities in which the hands work together and play similar roles ('bimanual symmetric'). It is in this bimanual partnership that Wilson **(Wilson 1999)** argues that the non-dominant hand plays a supportive role for the dominant hand.

2.2 Human Computer Interaction and the hand

With the hand as arguably a perfectly evolutionally designed tool, used to physically interacting with the object around us as discussed in Section 2.1 and Section 2.2, we question how the hands' skill as described by Wilson **(Wilson 1999)** is used within the HCI literature.

2.2.1 Physical interaction

Understanding the natural affordance of the hand in terms of physical interaction has been investigated by Ishii et al, **(Ishii and Ullmer 1997)** who questioned how to combine physical interaction with modern computer technology. This had its origins in 1967 when English et al **(English, Engelbart, and Berman 1967)** created and compared three devices that participants used to select text (see Figure 2.7). Their observations about the hand showed that participants' usage of the three devices (Light pen, Joystick and Mouse) depended on how the device fitted within their hand (its size and its range of movement). English et al stated that *“large-motion capability of arm and wrist can coordinate with the fine-motion capability of the fingers”*.

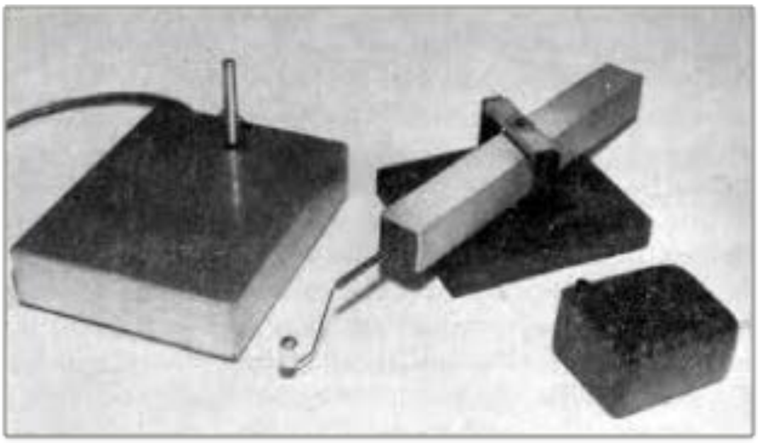


Figure 2.7: The three devices used Joystick, Light Pen, and mouse (English, Engelbart and Berman, 1967)

To further understand the size of objects and how they correspond with the size of human hand, we should look at the Industrial Designer Henry Dreyfuss **(Dreyfuss 1960)** and his work on the measurement of man. Dreyfuss **(Dreyfuss 1960)** created a lexicon defining the sizing of the human body, including the human hand (See figure 2.8) and the sizing for mechanical controls (e.g. keypads, rotary knobs, push buttons and joysticks) **(Tilley 2002)**.

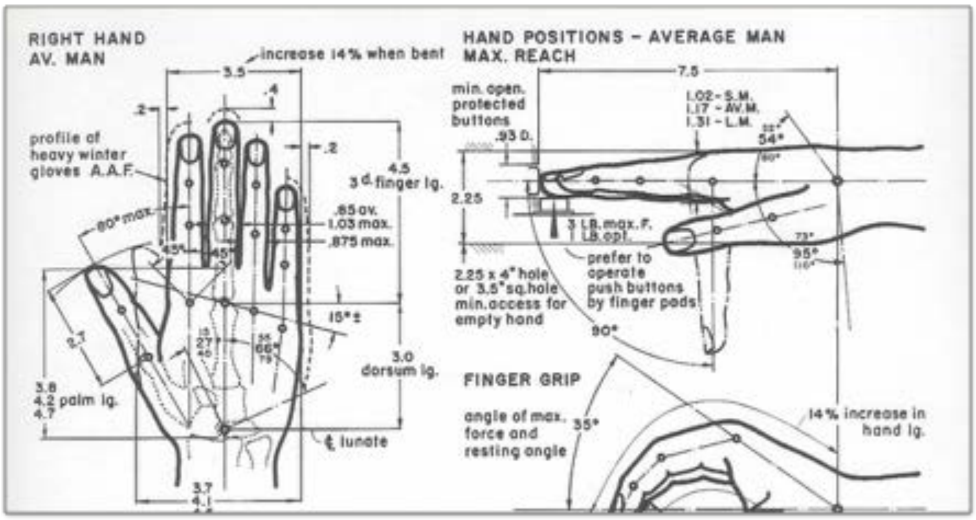


Figure 2.8: Measurements of the hand (Dreyfuss 1960).

This work used the human hand's mechanical structural measurements *'anthropometrics'* and its range of movement *'ergonomics'* as tools to empower the design of physical devices **(Dreyfuss 1955)**. The work presented measurements that included the amount of pressure the hand can exert, the reach of the arm or even statistically the number of left-handed indviduals. Dreyfuss **(Dreyfuss 1955)** argued that knowing these details will help designers to understand the best physical positioning for buttons or mechanical levers. On the positioning of physical buttons, consideration should be made on how the functional layout is defined. Card et al **(Card, Moran, and Newell 1983)** stated that the speed of the finger press is essential when designing these interaction elements. One such layout is that of the telephone number keypad. To define what worked best, Deininger **(Deininger 1960)** tested numerous layouts (See figure 2.9). The layout that won was the one that allowed for the greatest speed offset with the least human error.

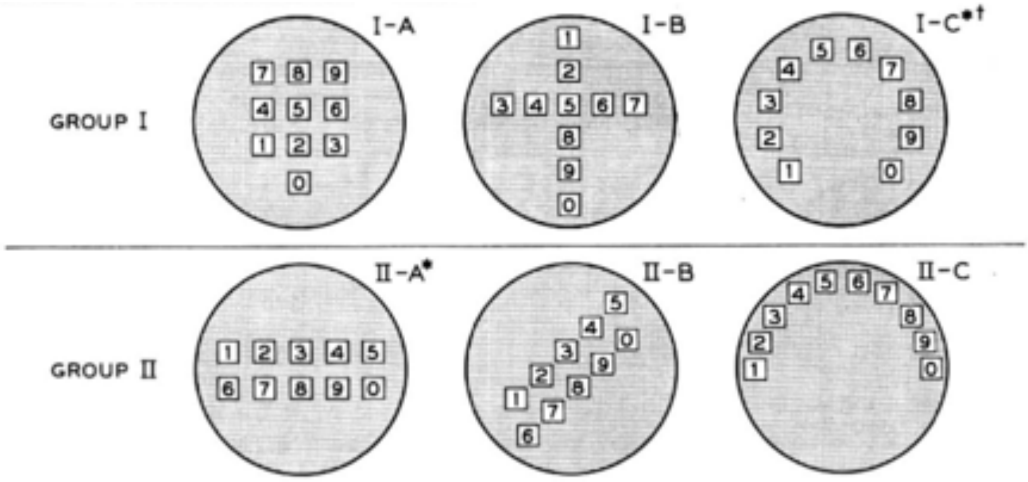


Figure 2.9: Examples of the button layouts used (Deininger 1960).

Investigating how the pen and the hand could be merged to create better interactions is an area that Hinckley et al **(Hinckley et al. 2010)** researched. Their research *"Pen + Touch = New Tools"* takes many interaction clues from the human 'naturally' interacting with paper and seeing what range of interaction adding a pen would make.

2.2.2 Sensory Interaction

Design researchers such as Hemmert **(Hemmert et al. 2010)**, have attempted to utilize the hand's sensors with handheld objects such as mobile phones, creating a form of subtle communication, through the physical shifting of weight and the changing of shape. This physical change communicates, through the human hand, information such as the mobile phone's battery life **(Hemmert et al. 2010)**. There have also been attempts to create a more compelling digital world interaction within the commercial game industry through the development of handheld vibration feedback devices such as the Nintendo switch **(Nintendo 2020)**.

Touch screen devices such as the Apple IPhone have become popular. This is understandable given the flexibility that a screen and a soft key interface provide. However, these touch screen devices have a disadvantage, in that they exclude tactile feedback. Both Hoggan et al **(Hoggan, Brewster, and**

Johnston 2008) and Harrison et al **(Harrison and Hudson 2009)** have attempted to solve this by providing the user with different types of tactile feedback. Hoggan et al **(Hoggan, Brewster, and Johnston 2008)** attached actuators to mobile devices. By comparison, Harrison et al **(Harrison and Hudson 2009)** adapted a screen by adding tactile feedback through dynamically inflated buttons.

Other forms of sensory interactive technologies have been developed to allow the human to sense tactility from within the virtual world. Paterson **(Paterson 2007)** states that this area of research termed 'Haptic' means *"the sense of touch in all its forms"*. Researchers such as Burdea et al **(Burdea *et al.*, 1991)** attempted to achieve 'Haptic' feedback through mechanical technologies such as actuators in gloves that vibrated when an object was manipulated within the virtual world. Iwata **(Iwata 2008)** describes another type of haptic interaction, which uses mechanical structures and servomotors to emulate force feedback through the hand from a virtual object.

2.2.3 Gesture Interaction

The hand's natural range of motion has enabled many researchers to develop interaction techniques through gesture. These interaction methods include both surfaces based and 'in air' gestures.

Surface technology such as touchscreen interaction (tabletops, tablets and mobile phones) uses direct manipulation techniques, where the hand connects with the screen. Morris et al **(Morris, Wobbrock, and Wilson 2010)** attempted to create a lexicon of interaction methods through participant input, asking the participants to demonstrate a gesture that they would perform to complete a task. These surface gestures include both one and two-handed interaction. Others such as Wu et al **(Wu and Balakrishnan 2003)** have investigated how the use of the whole hand could create new gestures. Buxton et al **(Buxton and Myers 1986)** has researched two-handed interaction techniques, questioning how the human uses of one or two hands compare in manipulating content on a screen. The results of this research as presented by Buxton et al **(Buxton and Myers 1986)** showed that parallel two-handed input worked best.

'In air' gestures, as argued by Wachs et al **(Wachs et al. 2011),** have improved in recent years with vision-based systems advancing in power and quality, enabling HCI researchers to develop gesture systems that have greater accuracy and responsiveness. With this advance in vision technology systems such as 'SixthSence' can enable the hands of the human to be tracked through a wearable camera, when the human performs a variety of gestures that the computer recognizes, corresponding tasks are performed. One example is the human making the shape of a box with their hands which tells the 'SixthSence' system to take a photograph **(Mistry and Maes 2009)**.

2.3 Smartphone interaction and the hand

From my understanding on how the biological hand grips physical objects as discussed in Section 2.2 and how the hands play a crucial role within HCI interaction as discussed in Section 2.3, I next questioned how these hand interactions with the physical objects influence the usage of so called 'handheld' technology devices such as a smartphone.

2.3.1 Grip type detection

For touchscreen smartphones, research by Wimmer et al **(Wimmer and Boring 2009)** and Kim et al **(Kim et al. 2006)**, proposed to detect the type of grip the individual used when completing specific tasks. The results of this detection were intended to support researchers to develop a smartphone UI that would adapt accordingly to the type of grip used. Wimmer et al **(Wimmer and Boring 2009)** sought to identify how the smartphone's sensory technology might potentially differentiate between six hand grips that had been defined by the researchers. Similarly, Kim et al **(Kim et al. 2006)**, used capacitive touch sensors around the smartphone to define where the hands touched the smartphone for a defined set of tasks (e.g. SMS, camera, phone call or gameplay).

In order to detect screen orientation, Cheng et al **(Cheng et al. 2012)** again used sensors around the smartphone to detect grips and help to define if the smartphone is being used in either landscape or portrait. Shirazi et al **(Shirazi et al. 2013)** used in-built sensors to investigate if smartphone participants used the landscape or portrait orientation for a list of applications (e.g. YouTube, Facebook, SMS or google maps). What the study **(Shirazi et al. 2013)** found is that there is a difference depending on the application type, with video viewing applications such as YouTube, being predominately landscape and text-based applications like Facebook being predominately portrait.

2.3.2 Hand interaction

The gripping of smart phones has been investigated in a number of ways. The first of these involved the mathematical modeling of the human hand and understanding of the limited reach of the thumb, for a static single-handed grip **(Bergstrom-Lehtovirta and Oulasvirta 2014)**. Using this limitation of the smartphone and hand interaction, researchers Negulescu et al **(Negulescu and McGrenere, 2015)**, Noor et al **(Noor et al. 2014)** and Chang et al **(Chang *et al.*, 2015)** questioned if estimating the pre-touch of the thumb to the screen could improve user interaction. Noor et al **(Noor et al. 2014)** focused on the capacitive sensors and through the small shifting of the smartphone in the hand, identifying the thumb's intended target area. Looking at larger smartphones, Chang et al **(Chang *et al.*, 2015)** used the internal gyroscope to identify the tilt and rotation of the smartphone. They developed a number of concepts to help the user reach with their thumb to the intended target area when using the larger smartphones. It is this tilting and movement of the smartphone that Negulescu et al **(Negulescu and McGrenere, 2015)** has called 'Grip change'.

Researches have also proposed screen-based sensor technology to create adaptive UIs that update depending on where fingers are placed around the device **(Hinckley et al. 2016; Le et al. 2019)**. Looking at different grips, Azkenot and Zhai **(Azenkot and Zhai 2012)** investigated three different types of hand interaction. They asked participants to use either two thumbs, one thumb or one finger in a qwerty keyboard touchscreen typing task. Through these three types of interaction, Azenkot et al **(Azenkot and Zhai 2012)** examined the resulting typing speed and accuracy. What they found is that the fastest and least accurate was two thumbs, with one thumb being the slowest but having the most accuracy. Looking further at accuracy for the static single-handed grip, Perry et al **(Perry and Hourcade, 2008),** showed through a tapping task that the dominant hand is faster and more accurate than the non-dominant hand.

Other researchers have looked at tablet devices and how UI elements could be adapted to depend on the type of grip used **(Cheng *et al.*, 2012)**. These works are of less relevance since larger devices are bound to enable different insights and the researchers were focusing on the keyboard interactions, rather than the full user journey to task completion.

2.3.3 Back of device interaction

The back of the smartphone is where the fingers are positioned during gripping. It is this positioning that researchers have investigated through video analysis and sensors **(Kim *et al.*, 2006; Yoo, Yoon and Ji, 2015; Viet Le *et al.*, 2016; Taheri et al. 2020, Le et al. 2018)**. Viet Le et al **(Viet Le *et al.*, 2016)** and Kim et al **(Kim et al. 2006)** questioned how the activities (e.g. Typing a message and watching a video) might alter the grip and therefore the finger positioning on the back of the smartphone. In related work, Yoo et al **(Yoo, Yoon and Ji, 2015)** focused on the index finger and its location when placed on the back of the smartphone. What these researchers are questioning is if the back of device finger placement can be a form of secondary interaction.

Figure 2.10: Fingers gripping the back of the device (Viet Le et al., 2016)

Looking further into this secondary interaction is Seipp et al **(Seipp and Devlin, 2014)** and Wobbrock et al **(Wobbrock, Myers and Aung, 2008)** who have explored how the fingers on the back of the device can use interaction techniques such as gesture.

2.3.4 Physical body posture

Through an observational study on college students' body postures while using a smartphone (e.g. neck, elbow position), Gold et al **(Gold *et al.*, 2012)** discovered statistical gender differences between neck, wrist and shoulder positions. Looking at detailed muscle usage, Bachynskyi et al **(Bachynskyi et al. 2015)** investigated how individuals' body postures change depending on the touchscreen device that they use (Smartphone, tablet, tabletop, wall display). This research highlighted that distinctive body postures use a distinctive set of muscles. Specifically, for smartphone interaction, Bachynskyi et al **(Bachynskyi et al. 2015)** discovered that this muscle usage relates to differing grips. When sitting, a two-handed grip uses the lower back, upper back and shoulder muscles on the arm of the dominant hand. However, the single-handed grip uses just the upper back and back shoulder muscles of the dominant hand (see figure2.11).

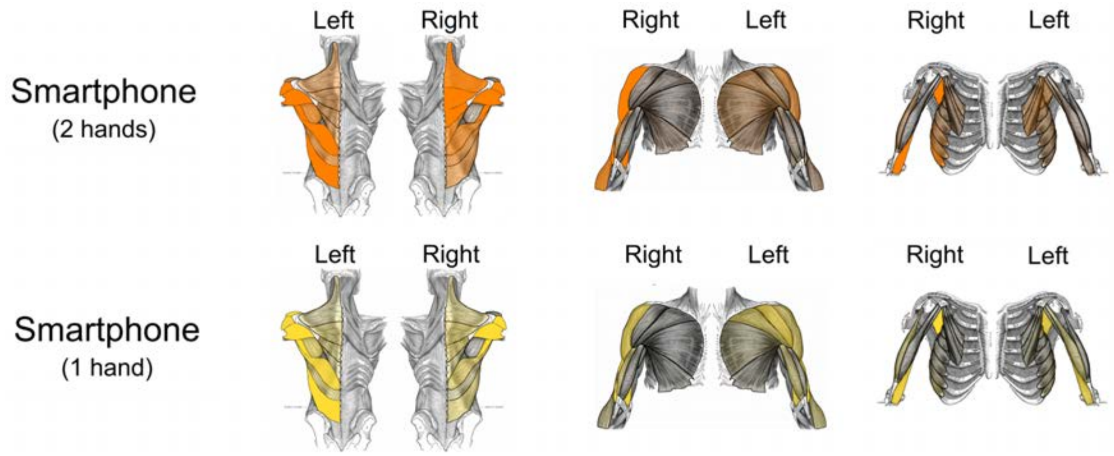


Figure 2.11: Bachynskyi et al's defined muscles usage for smartphone interaction in a sitting position (Bachynskyi et al., 2015).

For specific body postures such as walking, the movement can, as Goel et al **(Goel, Findlater and Wobbrock, 2012)** state, affect the individual's smartphone typing speed and accuracy. By using inbuilt smartphone accelerometers and the data that they provide, Goel et al **(Goel, Findlater and Wobbrock, 2012)** were able to compensate for this movement and improved typing speed and accuracy for body postures, sitting and walking. Both Negulescu et al **(Negulescu and McGrenere, 2015)**. and Kim et al **(Kim and Chae, 2012)** investigated single-handed interaction in multiple body postures. Negulescu et al **(Negulescu and McGrenere, 2015)** using the smartphone's internal accelerometer and gyroscope to predict where the individuals would touch the screen, taking readings as the individual's tilt and shift the device so that they can reach the desired touch area. They were studying these movements and the data provided for body postures, sitting, standing and walking. Related research by Kim et al **(Kim and Chae, 2012)** focused on comparing the differences between the thumb's biomechanical joint movement and musculature pressures for three different body postures (sitting, sitting at a table and standing).

2.4 Conclusion

In this PhD research I question how the design of handheld interactive devices can affect hand interaction, first by understanding the human hand and secondly the current HCI interaction methods that focus on hand interaction.

When we look at the hand we must consider Napier's **(J. Napier 1993)** belief that understanding the human hand and its physical qualities could potentially enable better-designed objects, arguing that if the object is designed to require with great force then it should be designed so that the hand can utilize the power grip **(J. Napier 1993)**. It comes into question how we currently use this understanding of the human hand to design digital products and if we can make this experience more compelling.

What the related studies in HCI and smartphone interaction have done is highlight the ways in which people can use multiple grips to interact with the smartphone, the range of reach available when using static grips, as well as the accuracy that individuals have when interacting with action items. What these approaches do not take into account is the natural role the hand plays when interacting with the smartphone, or how the hands movement helps or hinders participants during complex tasks. Additionally, there is no true understanding of any difference that may occur due to the smartphone's interaction method (button vs touchscreen), the size of the device or how a user is bodily positioned when interacting with the smartphone.

I believe that investigating the hand's natural transitions **(J. Napier 1993; Wilson 1999)** or movements is critical because movement in between direct interactions is actually key to the interactions themselves, as each movement sets up the conditions for the next interaction. To this end, I have taken a systematic look at the hands / smartphone interaction and compared the use of multiple grips. Finally, I question what would be possible if the 'designer', as defined in the design community, focused on developing technologies for the affordances of the biomechanical hand rather than that of creating task-based technology?

Chapter 3: Investigating differences between the hand and smartphone interaction type

Findings described in this chapter were published in the proceedings of Mobile HCI 2016 and CHI 2017 (See Appendix A.1 for Mobile HCI poster).

In this chapter I start my investigation into how people use their hands to interact with smartphones and if the physical interaction method affects this hand interaction.

Research question for this chapter:

Do the interaction methods change the way participants use their hands to interact?

3.0 Introduction

This chapter investigates the affordances of the physical interaction between the human hand and handheld smartphones. Video observational analysis was used to determine: (1) How participants grip the smartphone when completing a common task (such as sending a text message); (2) If the smartphone's physical interaction type affects these grips (touchscreen, button-based keyboard and stylus); (3) What coping mechanisms the participants use to complete the task (e.g., reaching movements).

My findings show that participants use a range of five grips to interact, that these grips differed for each phone type and that participants changed their grips as they completed the task. I also observed participants manoeuvring the devices through horizontal and vertical tilts, showing that the hand is used for more than just interacting with on-screen action items. Understanding this hand interaction and the context within which it is used will enable interaction designers to understand how to improve smartphone UI design.

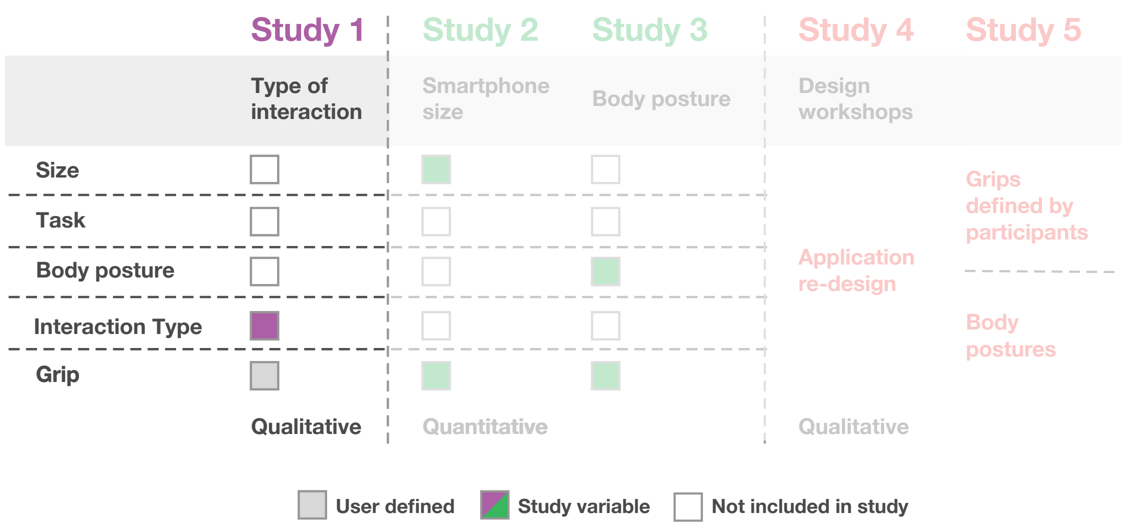


Table 3.1: Variables of study 1 design

3.1 Experimental Design

This study does not measure the efficiency or usability of the selected smartphones' interaction **(Card, Moran and Newell, 1983)**. It instead focuses on investigating how the physical affordances of the smartphone affect the dominant and non-dominant hand's interaction.

I recruited 18 participants for a study run at a university research lab over a series of one-to-one sessions. The participants used three similar-sized commercially available smartphones (see table 3.2 for sizes) that used three different types of physical interaction (touchscreen, button-based keyboard and stylus). The participants completed the same task with each smartphone: sending a pre-defined text message using UK QWERTY based keyboards. Each participant completed the task seated and resting their arms on the table to minimise the impact of whole-body movement on smartphone usage. Participants were given the freedom to choose the most comfortable smartphone grip and, if desired, change the grip during the task. While the smartphone had a stylus and a keyboard, participants used the stylus as the sole interaction mechanism.

3.1.1 Participants

The 18 participants were recruited through an email campaign sent to students and staff at the university. This email asked volunteers to attend a 40-minute session at the university and presented information about the study. Additionally, the email stated that potential participants should show their interest by completing an online questionnaire. This questionnaire asked the potential participants their hand dominance (right or left), glove size (XS, S, M, L, XL), current smartphone and gender.

I had a total of 23 responses through this recruitment method. However, one potential participant did not respond when contacted, and three potential participants did not show for their session. Once all 18 participants attended their sessions, the final potential participant was contacted, thanked for their interest and told that the study had been completed.

For the 18 participants who took part, there was a 50% gender split, and their ages ranged from 18 to 31. 16.6% of the participants were left-handed, a greater proportion than the estimated 12.24% within the UK **(Mcmanus, 2009)**. Two participants had reduced flexibility of their hands due to past injuries that included a broken wrist and finger. Three participants stated that they had greater flexibility than the average person, including one double-jointed participant.

The participant's hand measurements are illustrated in Figure 3.1:

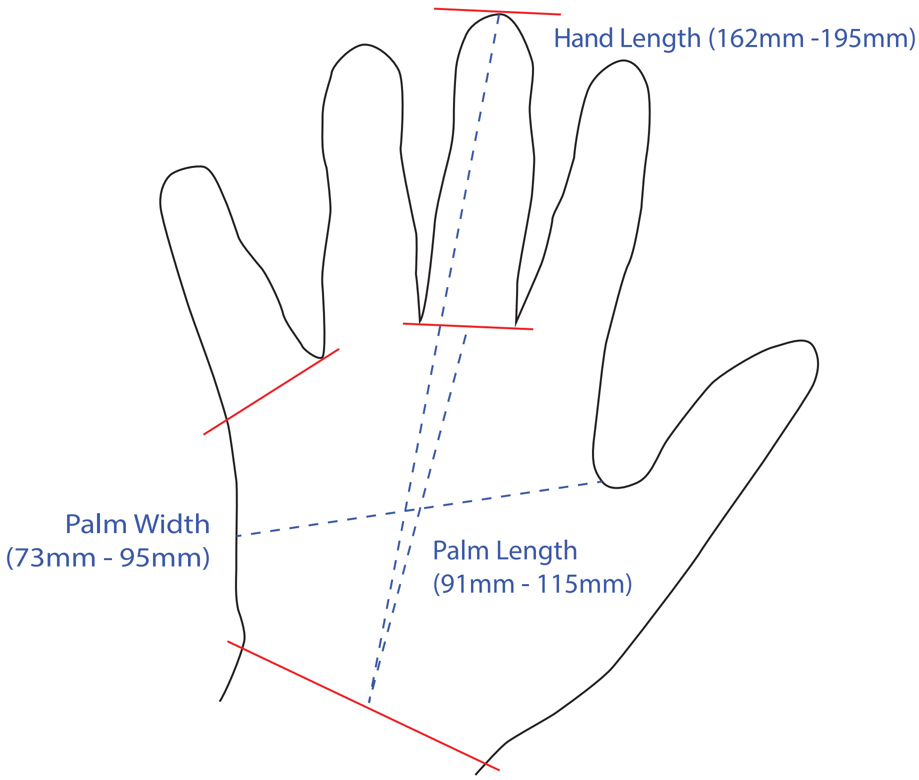


Figure 3.1: Participants' hand measurements

All participants owned smartphones and had owned their current smartphone from three months to four years, 16 of these being based around a touchscreen and two around a button-based keyboard. In addition, 10 of the participants had modified their smartphones by adding an external casing. Each participant was asked about their top three smartphone activities. Out of the 18 participants, the three most popular activities were texting, making a phone call and accessing the internet. 18 participants had used a touchscreen device, 14 a button-based device and 1 participant had familiarity with a stylus-based smartphone. However, nine participants had used a stylus with either a tablet or Nintendo DS device.

3.1.2 Apparatus

For this study, I used three smartphones (Sony Ericsson, Blackberry Bold and iPhone 4), an A5 card with pre-defined interactions that the participants needed to follow, three synchronized cameras that video recorded the sessions and an external audio device to capture sound. Additionally, I used a remote video monitoring station (operated by a secondary researcher) to control and focus the three cameras on the participants' hands and smartphones. The secondary researcher recorded the session from this remote station, and all digital data was saved.

Smartphones

The participants were asked to use three smartphones of varying vintage. They were selected due to their similarities in size and differences in physical interaction methods. The models selected were the Sony Ericsson P1i for 'stylus', the Blackberry 9780 Bold for 'button-based keyboard' and the iPhone 4 for 'touchscreen' (Figure 3.2 & Table 3.2). All three smartphones were pre-owned and on loan for the study. None of the smartphones had SIM cards installed or were connected to WiFi, cutting out any disturbances from external sources that may have disturbed the participant from completing their task. In addition, all security measures had been removed, for example, PIN codes, and the smartphones were charged and wiped down between each participant session.

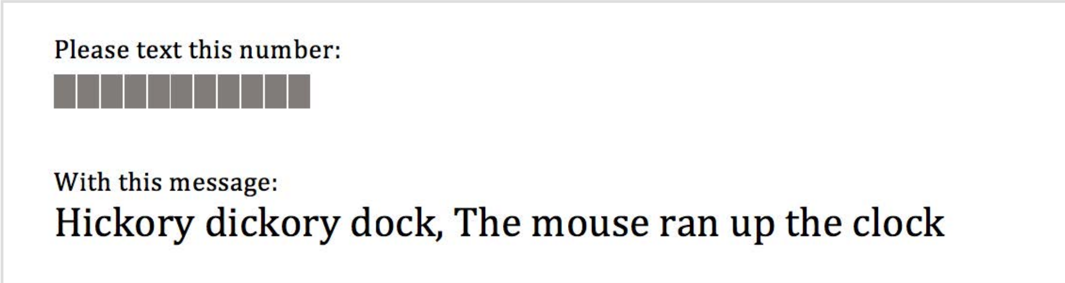
	Height	Width	Depth
Sony Ericsson P1i	106 mm	55 mm	17 mm
Blackberry bold	109 mm	60 mm	14.1 mm
iPhone 4	115.2 mm	58.6 mm	9.3 mm

Table 3.2: Sizes of the smartphones used during the sessions

Figure 3.2: The smartphones used during the sessions (Sony Ericsson, Blackberry and iPhone 4)

Printed A5 Card

The participants were presented with a white A5 card with printed black text using large bold font (Figure 3.3) placed in front of the participant on the table. This A5 card displayed instructions, the first line of a nursery rhyme and a telephone number that the participants needed to text.



Please text this number:

With this message:

Hickory dickory dock, The mouse ran up the clock

Figure 3.3: The A5 card with the text message and phone number

Recording devices

Three wall-mounted synchronous cameras and a microphone recorded the participant sessions. The three cameras were remotely controlled from the monitoring station and focused on the smartphone and the participant's hands. Three angles were captured: the first over the participant's shoulder, the second the right-hand side of the smartphone/participant's hands, and the third, the back of the smartphone/participant's hands (Figure 3.4). In addition, a microphone was placed between the moderator and participant, picking up any verbal content.

Figure 3.4: The three angles captured by the three cameras

3.1.3 Study procedure

The study was broken down into four parts. The first introduced the potential participant to the research and obtained consent. The second, a semi-structured interview, asked further questions about the participants’ phone usage. The third part measured the participants’ hand sizes, and the fourth had the participants interact with the smartphones.

Introduction interviews

Following the recruitment questionnaire, I asked the participants for further information about their current smartphone and confirmed the top three activities completed with their device. I asked additional questions such as the length of time they had owned their smartphone and if they had made any alterations, e.g., using a case. I also asked if they had any feedback on their smartphone usage and other interactive devices they may have used.

At this point, I asked several questions about the participants' hands. Firstly, I confirmed which of their hands were dominant. Secondly, I asked if they had any medical conditions that reduced their hands' flexibility (e.g., Arthritis) or if they had anything that made their hand movement more flexible (e.g., Double jointedness).

The participants were then asked to stand up and place their hands flat on the table. Next, the dimensions of participants' hands (hand length, palm length, palm width) were measured with a ruler (See figure 3.1).

Smartphone interaction

I initially explained to the participants that they would need to send a text message to a pre-defined number using three types of smartphones (Figure 3.2) and introduced the A5 card (Figure 3.3). I selected the activity of texting as this was the top application used by all potential participants when completing the recruitment questionnaire.

At the beginning of each smartphone session, I asked the participants about their familiarity with the smartphone’s physical interaction (touchscreen, button-based keyboard and stylus) and if they had used any devices with similar interaction methods. Next, each participant was given a short time to get acquainted with the smartphone's user interface. Finally, the smartphone was reset to the home screen, and the task began.

The participants completed each task one at a time. First, the smartphones were handed to the participants in a randomised order using the 'Latin Square' method, removing interference between the test conditions **(Grant, 1948; MacKenzie, 2012)**. Then, for each smartphone, the participants completed a four-stage task. Firstly, the participant picked up the smartphone from the table and then navigated the home screen and opened the texting application. Secondly and thirdly, the participants used the keyboard and either duplicated the pre-defined text message or entered the pre-defined phone number from the A5 card. Fourthly, once the phone number and text message had both been entered into one of the three smartphones, the participant then sent the text message (Figure 3.5).

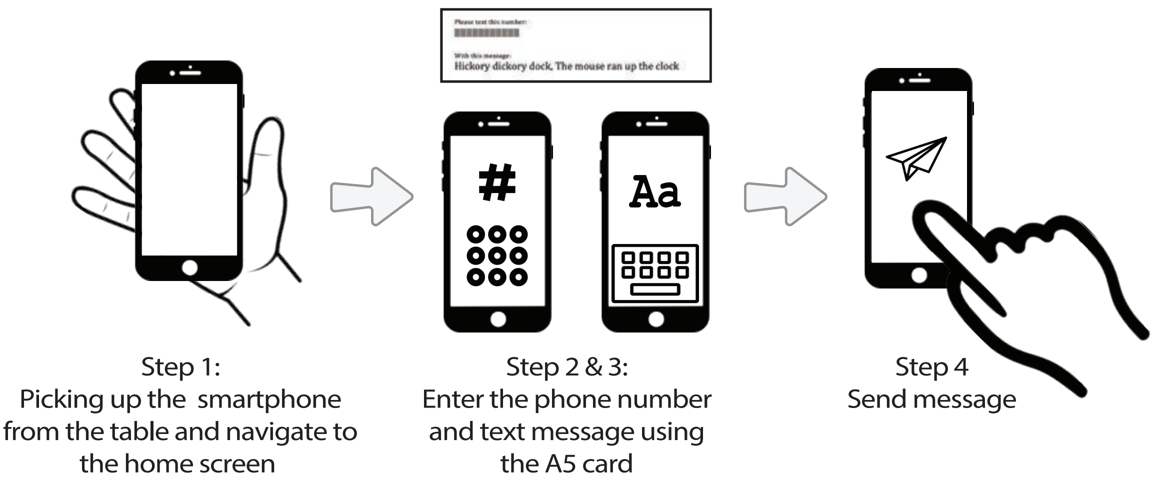


Figure 3.5: Storyboard showing the participants completing the 4-stage task

3.2 Data collection and analysis

I recorded a total of 68.07 minutes of video data for all 18 participants using the three types of smartphones. For the iPhone, all participants completed the task in a total of 14.03 minutes, the participants taking between 0.23 to 1.50 minutes. The 18 participants took a total of 32.39 minutes when using the Blackberry, with individual participants taking 0.32 to 4.15 minutes. The Sony Ericsson had participants taking 21.25 minutes, with individual participants completing the task in between 0.41 to 2.26 minutes. During the study, all 18 participants completed the task for all smartphones.

The data collection for this study, that of the video data has been analyzed, and this analysis took three distinct stages; (1) Analysis of the video and the identification of key interactions; (2) Printing out these key interactions into grips used (3) Printing out these key interactions into interaction types.

3.2.1 Stage 1: Key moments identified and printed

The videos of the 18 participant sessions were analysed, and 148 'key moments' were identified within the video data and time stamped. These 'key moments' are defined as a change of handgrip, physical contact to interact with the smartphone and movement of the hands to reach interaction areas on the smartphones.

To record these 'key moments,' video still images were collected from all three synchronous cameras and printed on paper. These printouts also contained participant information such as the video time stamp, participant number, whether the participants were right or left-handed and if the participants were male or female. Additionally, a short text description was added to help identify how the participant interacted with the smartphone during that 'key moment' (figure 3.6 and Appendix A.2).

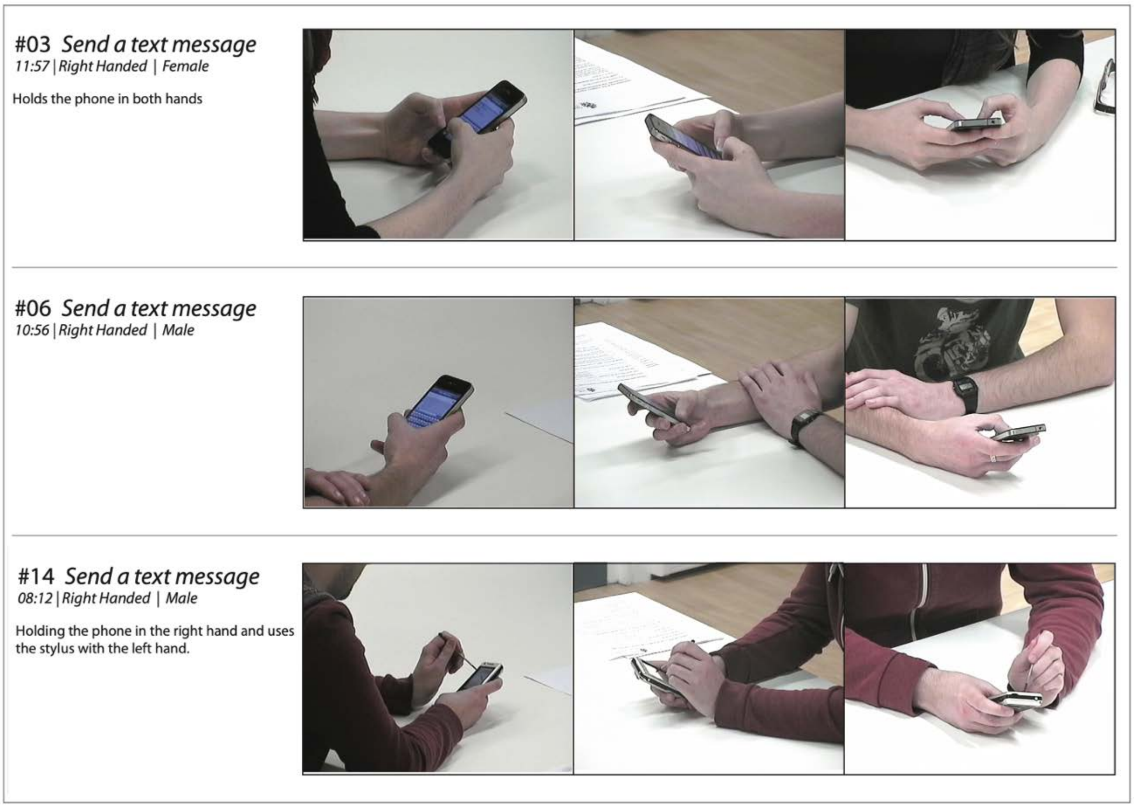


Figure 3.6: An example of a 'Key moment' printout for participants 03, 06 and 14.

3.2.2 Stage 2: Printouts themed to identify grips used

My next step was to use the 'key moment' printouts to situate the different types of grips used by the participants for all three smartphones. This was done using Affinity diagramming to categorize the printouts. Finally, the printouts were placed on the floor of a large space and physically sorted into the corresponding grip themes through an iterative process (please see figure 3.7).

Figure 3.7: Printouts placed into grips used by the participants

3.2.3 Stage 3: Identifying 'key moments' of movement

Using the time-stamped printouts of the identified 'key moments', I investigated the collected video data further. I found that for these 'key moments', the participants reached with their digits to contact the required interaction area. Shifting the grip that they were using enabled them to manoeuvre the smartphone into position for easy reach. Figure 3.8 shows an example of this movement where the grasping hand moves the smartphone into a position.

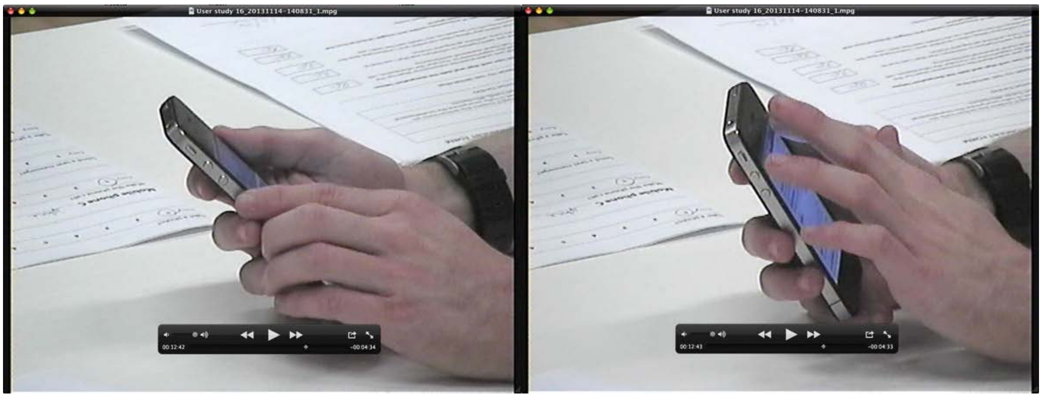


Figure 3.8: An example of a 'Key moment' identified within the video analysis (Smartphone movement)

To understand the reaching or shifting movements of the hands and smartphone, I visually represented by tracing still images obtained from the video data. The still images showed the hands at the extreme ends of the movement (Figure 3.9). The colour red represented the starting position and blue the end position. The traced lined drawings were then set in position using static content in the background of the still images.

Figure 3.9: An example of the traced outline of the still images (red the starting position and blue the end position).

During the video data analysis, it was noted that the participants pressed down on the smartphone to make a selection; the smartphones moved due to the pressure of the digit. However, these results were discarded because they were not considered reaching or shifting movements but rather a natural reaction to pressure.

3.3 Results

The study brought to my attention two areas for consideration. First, the participants used numerous grips and changed grips to complete the task. Secondly, the observations highlighted that the participants made slight movements as a coping mechanism to reach key areas. The study brought two areas for consideration to my attention. Firstly, when completing the task, the participants used numerous grips and changed grips when needed. Secondly, the observations highlighted that participants made slight movements as a coping mechanism to reach key action items on the smartphone.

Overall, I found no difference in the observed movement or hand grips for participants gender or age. However, with only 13yrs between participants ages, this may need further investigation with a more extensive age range. Additionally, as the study was completed through observations via video footage, it was not possible to identify if the hand size affected the movements of the smartphone, and further quantitative research will be needed. Unfortunately, each of the smartphones had different screen-based UI’s. Although I did time the speed at which a participant completed the defined task, the length of time spent appeared to be based on the participants’ familiarity with the smartphone’s UI rather than the time spent on the data input.

3.3.1 Type of handgrip

I observed that the participants used five specific grips: Symmetric bimanual (Figure 3.10a); asymmetric bimanual with the thumb (Figure 3.10b); single-handed (Figure 3.10c); asymmetric bimanual with the finger (Figure 3.10d) and asymmetric bimanual with the stylus (Figure 3.10e). Perhaps unsurprisingly, there is a strong correlation between the type of grip(s) used and smartphone interaction style.

Figure 3.10: Different hand grips used by the 18 participants during the sessions

For the different interaction styles, four grips were used by the touchscreen device, three grips were used for the button-based device, and the stylus device used just one grip.

Touchscreen interaction

When interacting with the touchscreen smartphone, the 18 participants used four grips (6 x Symmetric bimanual, 8 x asymmetric bimanual with the thumb, 4 x single-handed and 3 x asymmetric bimanual with the finger). In addition, 15 participants completed the task with just one grip, whereas three participants switched between using two grips (Figure 3.11).

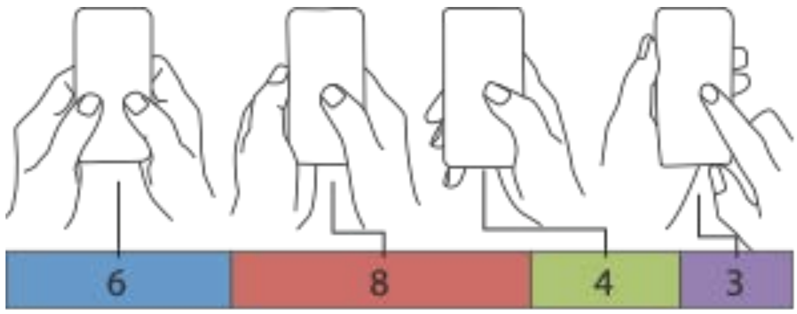


Figure 3.11: Grips used for the touchscreen smartphone

Button-based interaction

The button-based smartphone had 18 participants using a range of three grips (8 x Symmetric bimanual, 12 x asymmetric bimanual with the thumb and 3 x single-handed). In addition, 14 participants used just one grip to complete the task, three switched and used two grips, and one participant used three grips (Figure 3.12).

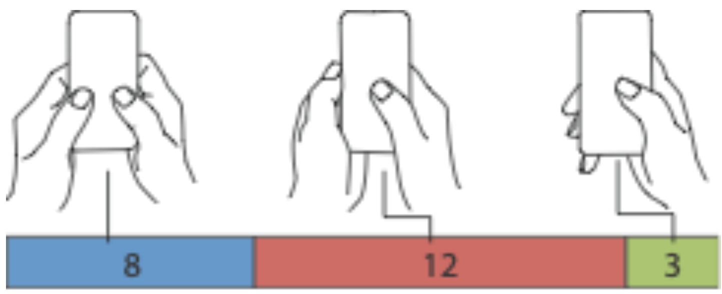


Figure 3.12: Grips used for the button-based smartphone

Stylus-based interaction

The stylus-based smartphone was the most constrained interaction wise, and consequently, all 18 participants used just one grip (asymmetric bimanual with the stylus) (Figure 3.13).

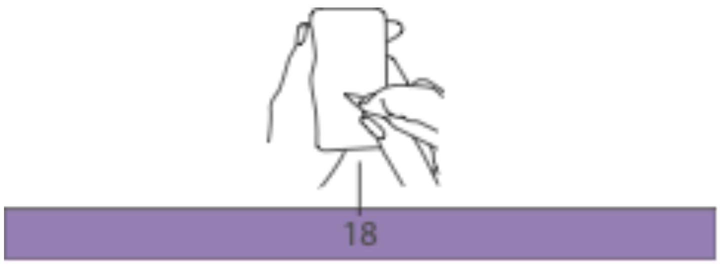


Figure 3.13: Grips used for the Stylus based smartphone

3.3.2 Reach Movements

All 18 participants were observed moving the smartphone during the task. In addition, 17 participants moved the touchscreen device, 16 did so with the button-based keyboard interaction, and 14 used the stylus-based interaction. As previously stated, the participants used five different grips to interact with the smartphones during the task (Figure 3.10). Each of the grips required the participant to make small movements with the smartphone to reach the action items.

Symmetric bimanual

A total of 10 participants used the symmetric bimanual interaction (six touchscreens and eight button-based keyboards), grasping the smartphone in both hands and using both thumbs to interact (Figure 3.10a).

Through observation, I found that the reach movements for the symmetric bimanual grip occurred when the participants alternated between thumbs to type on the keyboard (Figure 3.14). This interaction occurred for both touchscreen and button-based keyboard interaction.

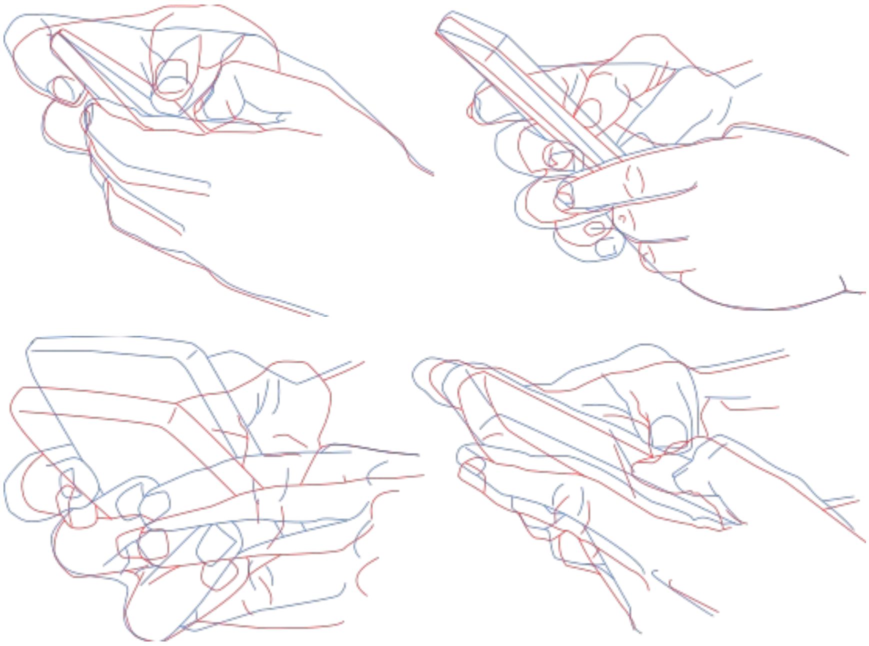


Figure 3.14: Reach movement for the grip symmetric bimanual (iPhone 4 and Blackberry Bold)

One participant used the touchscreen smartphone rotated at a 90-degree angle to better access the keyboard. I excluded this horizontal holding of the smartphone for two reasons. Firstly, it was an outlier, with there being only one case. Secondly, as stated in the literature (see section 2.1.2), Napier **(J. Napier 1993)** defines the grips based on intent, not the shape or size of the object. The intent, in this case, was to use two thumbs to input data via the keyboard.

Asymmetric bimanual with the thumb

14 participants were observed using the asymmetric bimanual with thumb interaction (eight touchscreen and 12 button-based keyboard), grasping the smartphone in both hands and using one thumb to interact (Figure 3.10a).

I observed that both the dominant and non-dominant hands gripped both the touchscreen and button-based keyboard devices for each participant who used the asymmetric bimanual with the thumb method. In addition, the non-dominant hands were observed supporting the smartphone either by using the index finger on the side or with the whole hand cupping the device (Figure 3.15). In both instances, the hands manoeuvred the smartphone so that the dominant hand's thumb had greater access to the target area.

The movements of the touchscreen and button-based keyboard smartphones occurred when the participants changed approach, from typing on the keyboard to selecting the next step or mode. Additionally, the movement was observed when the dominant hand's thumb advanced around the keyboard. What differed between the two smartphones was the size of the interactive area. The touchscreen smartphone showed more obvious movements as its interactive area covered most of the smartphones' front.

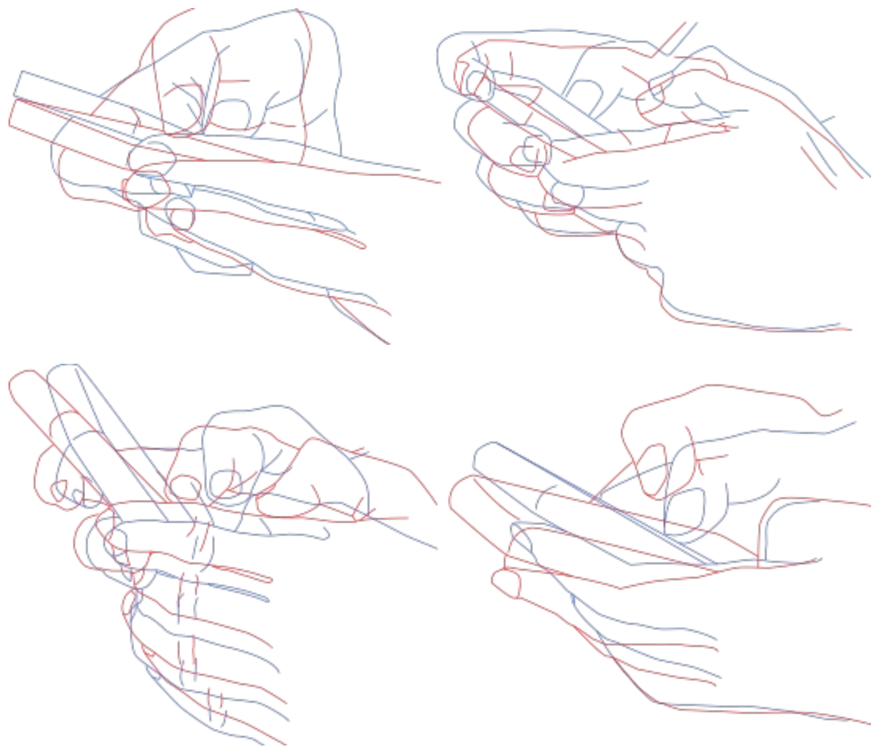


Figure 3.15: Reach movement for the asymmetric bimanual grip with the thumb (iPhone 4 and Blackberry Bold)

Single-handed

Four participants used only their dominant hand to hold and interact with the smartphones (four touchscreen and three button-based keyboard). When using single-handed interaction, participants held the smartphone in their dominant hand and used their little finger to anchor the bottom of the phone (Figure 3.10c).

The majority of single-handed movements occurred when the participant moved their thumb around the keyboard by lifting the phone with the little finger (Figure 3.16) to access the lower part of the keyboard better. Next, participants tilted the smartphone: in the case of the touchscreen, this was done so that the thumb could reach the top of the phone, while for the button-based smartphone, this was done so that they could reach the upper part of the keyboard (Figure 3.16).

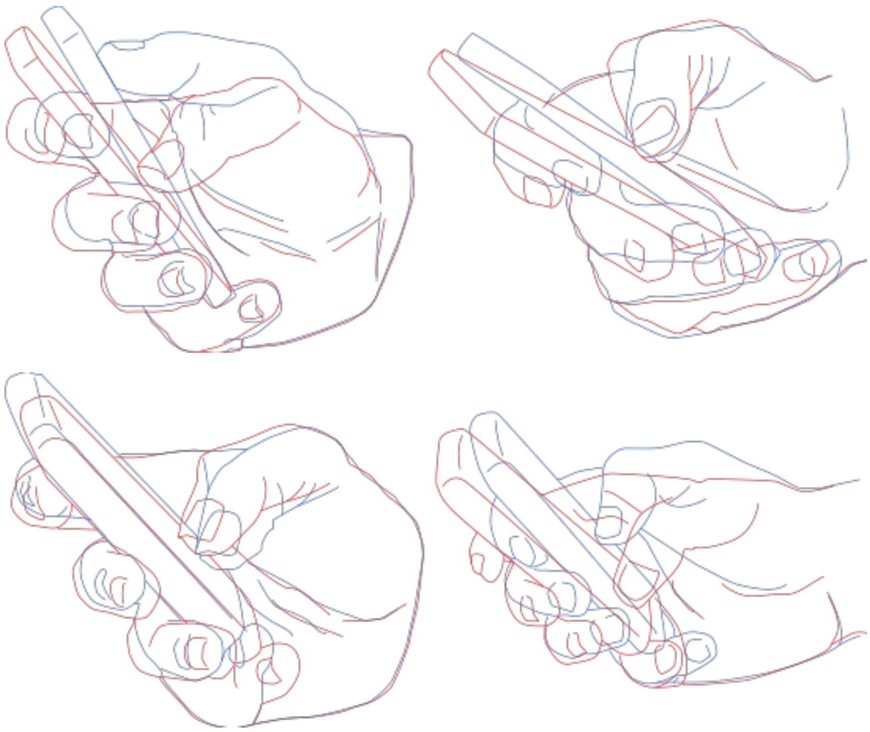


Figure 3.16: Reach movement for the grip single-handed with the thumb (iPhone 4 and Blackberry Bold)

Asymmetric bimanual with the finger

Out of the 18 participants, three used asymmetric bimanual with the finger while interacting with the touchscreen smartphone. They were grasping the smartphone in the non-dominant hand and interacting with the index finger of their dominant hand (Figure 3.10d).

I observed that two-finger movement types occurred with the asymmetric bimanual grip with the finger method. Firstly, the dominant hand's finger moved towards the screen, while the smartphone, held in the non-dominant hand, did not move (Figure 3.17). Secondly, the non-dominant hand aided interaction by moving the smartphone towards the dominant hand's index finger (Figure 3.17).

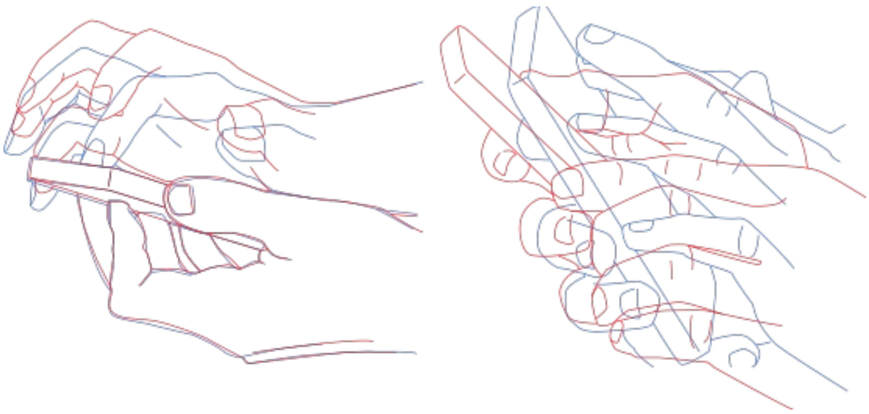


Figure 3.17: Reach movement for the grip asymmetric bimanual with the finger (iPhone 4)

Asymmetric with a stylus

I specifically asked all 18 participants to use the stylus with the stylus-based smartphone. I found that the asymmetric bimanual with the stylus interaction method (Figure 3.10e) was similar to that of the finger-based asymmetric bimanual method, so the participants' movements were unsurprisingly similar.

Participants manoeuvered the stylus-based smartphone in two ways: the first method was to grip the smartphone in the non-dominant hand and assist interaction by moving the smartphone towards the stylus held in the dominant hand (Figure 3.18). In the second method, the participants kept the smartphone stationary and only moved the stylus (Figure 3.18).

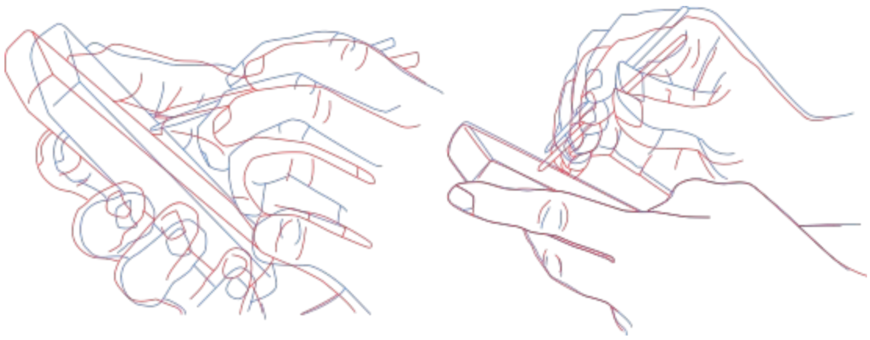


Figure 3.18: Reach movement for the grip asymmetric bimanual with the stylus (Sony Ericsson)

3.4 Insights

I have found five basic grips that the participants used to interact with the three different interaction types of smartphones (figure 3.2). I found that these grips change depending on the smartphone's physical interaction method (figure 3.11, figure 3.12 and figure 3.13). I also found that the hand adapts to the smartphone interaction type and the context in which it is being used (e.g., menu selection or typing on the keyboard through a combination of grips). This study has also shown that as a coping mechanism, the hand manoeuvers the smartphone to reach action items, not within reach.

3.4.1 Coping mechanisms

If I look closer at the way in which the participants moved the smartphone, I can gather several insights to understand the participants' issues when interacting with the three different interaction types.

Insight 1: Side-to-side movement

When typing on a screen-based keyboard, participants move the smartphone from side to side to gain better access to the keyboard (Figure 3.15).

Insight 2: Tilting vertically for better reach

Participants tended to tilt the smartphone vertically to enable navigation options from the top bar.

Insight 3: Twisting both horizontally and vertically for better reach

When participants reached across the smartphone to select an action item opposite their dominant hand's thumb (single-handed and asymmetric bimanual with a thumb), the smartphone is twisted both vertically and horizontally (Figure 3.15 and Figure 3.16).

Insight 4: Both Stylus and smartphone move

The smartphone tilts and moves towards the stylus when selecting an action item. The dominant hand holding the stylus appears to move in sync with the non-dominant hand holding the smartphone (Figure 3.18).

3.5 Conclusion

Through this controlled study, I have observed that the interaction methods (e.g., touchscreen, stylus and keyboard) provided by each smartphone type change the way participants use their hands to interact. A total of five individual grips were identified as being used consistently by the participants. The most common grips used for the button-based keyboard and touchscreen interaction were the symmetric bimanual and asymmetric bimanual with the thumb. The six participants who changed grips responded in response to context, using one grip to select a menu item and then changing to another to input data through a keyboard. Due to their seated body posture, all participants had their forearms placed on the table. This placement enabled the participants to use a rolling motion of their wrists that helped them manoeuvre the device.

I observed a horizontal side-to-side tilt being used with the symmetric bimanual method (Figure 3.14), Participants employing the asymmetric bimanual with the thumb method also used side-to-side movement but added a horizontal twisting motion (Figure 3.15). Using the single-handed interaction method exploited similar movements but with greater emphasis (Figure 3.16). The asymmetric bimanual with a finger (Figure 3.17) and asymmetric bimanual with a stylus method (Figure 3.18) had similar movements. However, each used a twisting motion that manoeuvred the smartphone towards the dominant hand.

To progress this research, I next explore the coping mechanism reach movement and investigate what other external factors may affect this movement. To do this, I begin by comparing the size of a smartphone, questioning if interacting with larger smartphones produces the same type of reach movements or if they are exaggerated (Chapter 4). Secondly, I investigate the participant's body posture and see how this may alter the reach movements, comparing a participant's actions when standing with their actions when lying down (Chapter 5).

Chapter 4: Investigating differences with the smartphone size

Part of this chapter has been published at ACM CHI 2017.

In this chapter, I investigate how the physical size of the smartphone affects hand interaction using the four user-defined grips, as presented in Chapter 3.

The research question for this chapter:
Does the size of the handheld interactive object change the way the hand interacts?

4.0 Introduction

This chapter investigates the external physical factors of the smartphone size through a quantitative study. Including (1) Understanding how the smartphone's size affects interaction design. (2) How the four user-defined grips (Chapter 3) affect the tilt/rotation of the smartphone, (3) What the participants' perceptions are of different smartphone sizes during the interaction.

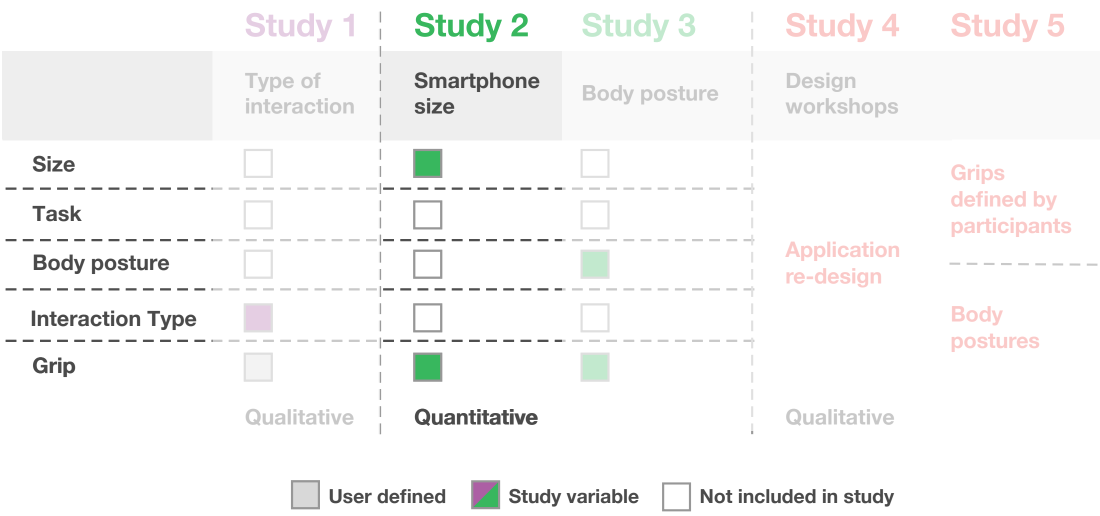


Table 4.1: Variables of study 2 design

For this quantitative study, I fixed the posture and interaction style and varied the size (iPhone 4,5,6 and 6+), varied the grip as defined in chapter 3 (Single-handed, Symmetric bimanual, Asymmetric bimanual with thumb and Asymmetric bimanual with finger) and the position of widgets through a dual pointing task (Table 4.1). The results showed that the tilt and rotation of the smartphone were different with each grip type and phone size. I believe that understanding the changeability of ‘hand interaction’, and the context in which it is used will enable designers to improve mobile device design.

To demonstrate how designers can use these findings, I conclude this chapter by proposing three designs. This final exercise is intended to provoke discussion around the current approach to smartphone design.

4.1 Experimental Design

This second study explores how the 'smartphone size' affects the participant-defined grips and the tilt/rotation of the smartphone observed in the initial' interaction type' study. I wanted to empirically look at how smartphone size and the handgrips from the 'interaction type' study affected smartphone movements. By doing so, I extended the research from Chapter 3 and expanded on other published research. For example, Yu-Cheng Lin **(Lin, 2013)** questioned if different sized smartphones affect participants' fatigue with different sized hands, while Bergstrom-Lehtovirta and Oulasvirta **(Bergstrom-Lehtovirta and Oulasvirta, 2014)** researched the reachable area of the static thumb. From this, I understand that the size of the smartphone will affect how participants can reach action items on the smartphone screen. Both Negulescu et al. **(Negulescu and McGrenere, 2015)** and Chang et al. **(Chang et al., 2015)** investigate the tilt and rotation of the smartphone that occurs when a user attempts to interact with action items in hard-to-reach locations. Their research focuses on one grip and one size of the smartphone; however, their results made me question the differences in movement resulting from different smartphone sizes.

To progress the 'smartphones size' study and understand fully how the hand interacts with different sized smartphones, I focused firstly on the observations of the initial 'interaction type' study and secondly on the findings in the literature review, to create a number of hypotheses based on the movements of the smartphone and hand interaction.

4.1.1 Hypotheses

The hypotheses are based on objective measurements around the variable, smartphone size (quantity of smartphone movement performed by the hand in the different axes) and subjective experience (users’ perception of security and comfort). I focused on four sized smartphones (iPhone 4,5,6 and 6 Plus) to have a trackable set for a controlled experiment.

H1: The larger the phone, the larger the phone movement. A larger phone might be more difficult for the user to reach target areas with the hand, and thus the users will have to tilt the phone to stretch across the screen to the targets, especially those placed at the extremities of the screen.

H2: The amount of movement of the phone will differ according to the handgrip. Single-handed (S) will have the most movement, followed by Asymmetric with a thumb (AT), Symmetric bimanual (B) and Asymmetric with a finger (AF). I postulated that the more the hand needs to stretch and exert physically, the more the phone will be moved and tilted.

H3: The amount of phone movement will differ according to Target Position (more movements for targets further away). Target 1’s starting location and the direction users need to shift their hand to reach Target 2 will affect the degree of phone movement. For example, Target Positions 2,3,5 and 7 require the hand to reach away from the dominant hand’s location, whereas Target Positions 1,4,6, and 8 require less reach by the participant’s dominant hand.

H4: The amount of directional movement will change with grip and target Position. B will have more side-to-side Gamma (y-axis) movements, which will be opposite to that of other grips. I should observe greater Beta (x-axis) movement differences between S and AT (i.e., the movement needed to bring the phone to the thumb, the converse of AF where the finger will move to the phone).

H5: The amount of directional movement will change with phone size and Target Position. I expect to see opposite movements depending on the orientation of the targets. These movements should increase with phone size.

H6: Phone size and grips requiring the participant to make smaller phone movements to complete the task will be subjectively preferred and found more comfortable and secure. I assume that configurations implying fewer movements will mean less effort for the users and thus that they will prefer these configurations.

4.2 Study variables

I carried out a controlled experiment using a quantitative research methodology. First, to answer these hypotheses, including such participant activities as a tapping task via a smartphone app and two questionnaires that recorded the participant information and, secondly, participant opinions on the study variables.

To ensure scientific rigor, this study, focused on smartphone size, continued with the five variables that focused on interaction type and characterisation (Chapter 3). For an overview, please see table 4.1. The variables for this following study included: firstly, a task (via a custom-built app); secondly, the interaction method (touchscreen smartphone); thirdly, the four grips that had been discovered in the ‘interaction type’ study (Chapter 3) and fourthly, smartphones size using four different smartphone sizes.

4.2.1 Smartphone size

Following on from the theoretical understanding **(Napier, 1993)** of the human hand as discussed in the literature review (Chapter 2.2). I set a variable of different sized smartphones, questioning if there was a difference in the way the human hand interacted. To keep consistency, I made sure that all smartphones were from one manufacture, Apple. Ensuring that the touchscreen smartphone used in the ‘interaction type’ study allowed the application to be consistent throughout. I selected the iPhone 4, 5, 6 and 6 Plus from this range.

4.2.2 Task

To control the position of the finger movements and analyze how these positions impacted the phones’ movement, I chose a pointing task, pointing consecutively at two targets on a screen. The target positions had eight combinations, as shown in Figure 4.1 (see application design for more details Chapter 4.5).

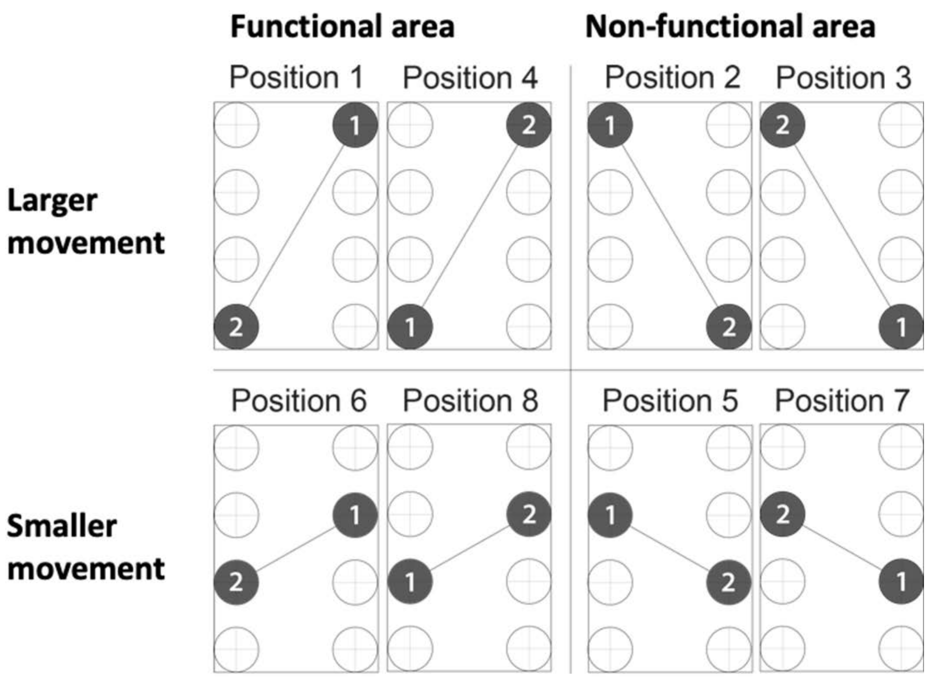


Figure 4.1. Possible target positions

4.2.3 Interaction type

For this study, I decided that only the touchscreen interaction method should be used, dropping the stylus and keyboard smartphones. This was done for two reasons: the touchscreen smartphone was the only smartphone observed in the 'interaction type' study to use all four different hand grips. In contrast, the other two interaction types (button-based and stylus) only used three or just one handgrip. The second reason was that this allowed me to reduce the number of independent variables within the study, allowing for a more compelling and balanced experimental design.

4.2.4 Grips

The four hand grips in which the participants were asked to use for this study are those which participants were observed to use on the touchscreen smartphone during the 'interaction type' study presented in Chapter 3 (Symmetric bimanual, Asymmetric with a thumb, Single-handed and Asymmetric with a finger).

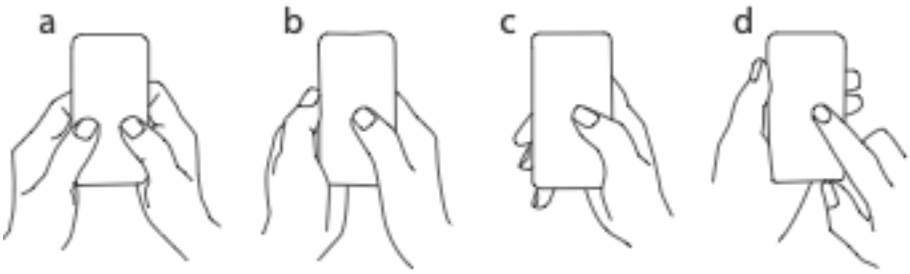


Figure 4.2. The four grips: a) Symmetric bimanual, b) Asymmetric with a thumb, c) Single-handed and d) Asymmetric with a finger

4.3 Apparatus used

The apparatus used for this study included online questions, the smartphones, the cameras and two software applications that recorded the sessions. In addition, a touchscreen tablet was used to collect participants' feedback and the physical furniture placed in the environment.

4.3.1 Online recruitment questionnaire

An online questionnaire was created through Google forms and used to recruit participants. You can see the questions asked in this recruitment questionnaire in Appendices B.1. Through this questionnaire, potential participants inputted the information about their hand dominance, current smartphone (Type, Length of ownership), and smartphone usage (Locations used and Applications used).

4.3.2 Smartphones

As I selected the touchscreen interaction method and to maintain consistency with the ‘interaction type’ study, as stated in 4.2.1 Smartphone Size, the research continued to use the same range of touchscreen smartphones. The smartphones used WiFi to connect to the internet during the study and were the iPhone 4, 5, 6 and 6 Plus (Figure 4.3).

Figure 4.3: The smartphones used.

	Height	**Width**	**Depth**
iPhone 4	115.2mm	58.6mm	9.3mm
iPhone 5	123.8mm	58.6mm	7.6mm
iPhone 6	138.1mm	67mm	6.9mm
iPhone 6 plus	158.1mm	77.8mm	7.1mm

Table 4.2: Measurements of the smartphones used.

4.3.3 Room furnishings

A desk and chair were used to keep consistency with the ‘interaction type’ study for the body posture sitting at a table.

4.3.4 Cameras and recording software

The sessions were recorded using two cameras, the Logitech C920 USB HD Pro Webcams and were connected to a MacBook Pro through a USB connection.

Figure 4.4: Cameras used during the two studies.

To record the images and sound provided by the cameras, I used two forms of software. The ‘HeadsUp’ camera viewing application by Keisi L.L.C **(Keisi L.L.C., 2020)** showed both synchronised cameras on the MacBook Pro screen. I captured the MacBook Pro screen with the application Silverback 2 by Clearleft **(Silverback, 2015)**.

4.3.5 Participants' feedback questionnaire

I used a touchscreen tablet running a Google form to gather feedback during the sessions. This form had two parts; the first was an admin section where the grips used and the smartphone size was inputted by the researcher (Appendices B.2). The second was a participant section that enabled them to rate the study variables (see Appendices B.3). The ratings were completed using a Likert scale **(Likert, 1932)** to rate the grips.

4.4 Custom application

A custom application on the smartphone had to be designed and built to run the empirical study. A key part of the research gathering process, this custom application had seven high-level requirements. (1) Ability to work on the selected smartphones operating system; (2) Enable a consistent experience for all selected mobile phone sizes; (3) Guide the participants through the required mobile phone research task; (4) Measure and record through timestamps the x,y screen coordinates, the location of the participants' taps; (5) Measure and record through timestamps the mobile phones inbuilt accelerometer and gyroscope, the mobile phones Alpha, Beta and Gamma axis; (6) An administration page that enables the moderator to specify the research variables being used; (7) The capacity to extract the gathered data and save within a spreadsheet.

4.4.1 Technical solution

The custom application needed to run on a number of different smartphones, and due to the team's technical ability, I decided to build the custom application using canvas HTML. This website technology would allow the custom application to run on any smartphone as long as a web browser was installed. Additionally, canvas HTML allowed the custom application to utilize 'responsive' web technology, allowing interactive elements to be positioned on the smartphone screen using percentages as measurements, keeping the user experience consistent for the four different-sized smartphones.

The custom application tracked the participants’ interaction in two ways. Firstly, it enabled tracking of the smartphones’ movements through the inbuilt accelerometer and gyroscope. Secondly, it permitted tracking of the participants’ physical interaction by recording their button presses to ensure they performed the task correctly. In addition, through an administration page, the moderator selected the smartphone type and the grips presented.

I initially tried to run the custom application using the iPhones’ default web browser Safari in full-screen mode during testing. However, after a few taps, I discovered that this produced performance issues and the application slowed down until it was unusable. I tried two things to fix this issue; the first was to check that the custom application was working correctly and the second was to see if there was an issue with the web browser. Finally, after some testing, I found a new web browser to run the custom application smoothly in full screen browsing. This was the web browser ‘Frameless’ by Jay Stakelon **(Stakelon, 2015)**.

4.4.2 Application design

The custom application had two modes. The first allowed the moderator to set the individual session variables and recover the data once the session was complete. The second mode guided the participants through the tasks that needed to be completed by showing them the required grip and letting them know where to tap.

Moderator mode

The moderator mode had two parts (Figure 4.5). The first allowed the moderator to set up the study variables by inputting the participant number, selecting the order of grips and stating which sized smartphone was being used. The second provided the data gathered for the moderator to extract and save it to a spreadsheet.

The participants only knew about the second and understood through the previous discussion that when this data appeared, the task was complete. The smartphone was to be handed back to the moderator.

Participant mode

Through the custom application, the participants could view and interact with three screen types (Figure 4.6). The first showed which of the four grips the participants should use. The second acted as a neutral screen and was shown between the tapping screens to separate the different tapping tasks. The third showed the targets that the participants needed to tap. Here they tapped ‘1’ and then ‘2’. Once the ‘1’ had been successfully tapped, its colouring changed to a light grey. Errors

Figure 4.5: Screen shots of the moderator view of the custom-built application Moderator mode for a) smartphone size study configuration. b) collection of the raw data captured from the research.

triggered a discordant sound, while successful interactions rewarded a more harmonious sound. The size of the targets was 14mm in diameter, as advised for finger input by Holz and Baudisch **(Holz and Baudisch, 2010)**.

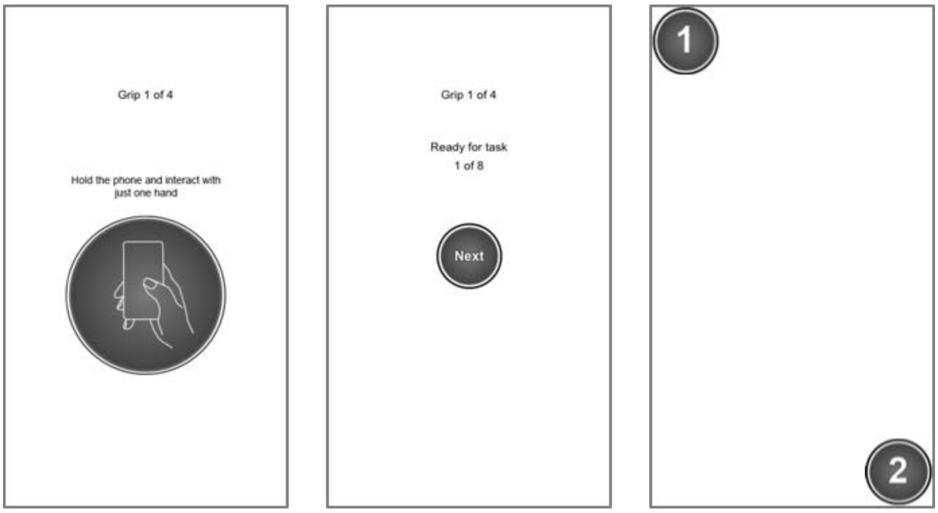


Figure 4.6: Screen shots of the participant view of the custom-built application a) specifying grip to use and b) Pre-task screen c) targets to tap – in this case, 1 and then 2.

The moderator part of the application controlled the order of the four grips, and the tapping targets were generated randomly through the custom-built application. The eight target positions were based on research by Bergstrom-Lehtovirta et al. **(Bergstrom-Lehtovirta and Oulasvirta, 2014)**, in which they modelled the functional area of the thumb. As a result, from this research, I identified four target positions within the functional area of the thumb and four targets that were opposite and not within the functional area of the thumb (non-functional area). Please see figure 4.1. To understand if the distance of the tapping targets affected the smartphone’s movement, I additionally looked at tapping targets that were situated at larger and smaller distances.

4.5 Participant sessions

The participant sessions were broken down into seven parts. (1) Explain the experiment to the participants and sign a consent form. (2) Discussing unclear information from the recruitment questionnaire. (3) Taking the participant’s hand measurements. (4) Adopting the body posture of sitting at the table (5) Provide preset smartphones to the participant to complete the task. (6) Participants complete a questionnaire based on their experience with those activities (7) Repeat parts four, five, and six until the study was completed (All four sized smartphones).

4.5.1 Participant hand measurements

Each participant was asked to place their hands on a gridded A3 sheet of paper, and then the moderator used a pencil to trace around both hands. Next, the participant's left hand was broken down into units and measured. These units were: Overall hand length, Palm length, Palm width, Thumb length and Finger length (Please see figure 4.7 for the location of these measurements). These measurements were used in the final data analysis of the study.

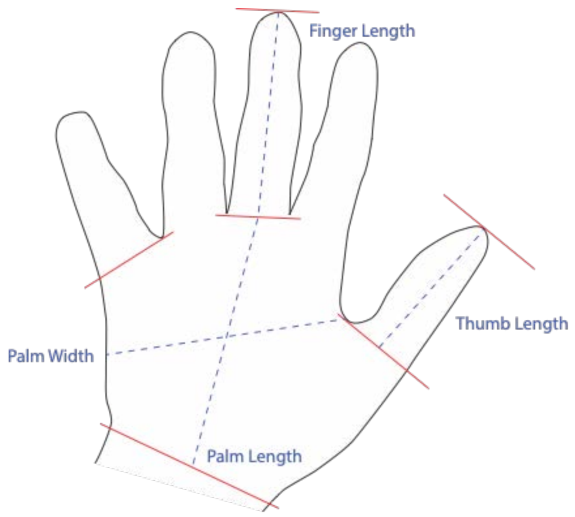


Figure 4.7: Image of hand measurements taken.

4.5.2 Task questionnaire

Once the tasks were accomplished for an individual smartphone, the participants were asked to complete a questionnaire using a "Likert scale" ranging from 1 to 7 **(Likert, 1932)**. The participant was asked to grade each grip by answering three associated questions: 'How comfortable'; 'How secure (risk of the device being dropped)' and 'How popular (user preference for a particular condition of the study)' the handgrip was for the completion of the assigned task. To find out more information about the post-task questionnaire, see Appendix B.3.

4.6 Participants

For the study, I had sixteen right-handed participants (seven males and nine females), aged between 18yrs to 50yrs, take part. All of the participants recruited had used a touchscreen smartphone for between 1 month to 3yrs. Their smartphone use broke down to Six iOS devices, one Windows device and nine Android devices. In addition, 12 of the participants had added an external casing to the smartphone. Their smartphone sizes ranged from W:58.6mm, H:121.55mm, D:6.8mm to W:78.6mm, H:159.3mm, D:11.6mm, the smallest smartphone being the Samsung Galaxy mini and Apple iPhone 5s, while the largest smartphones were the Nexus 6p and Apple iPhone 6+.

The top locations in which the participants reported using their smartphones were: Transport (Bus, Train, Walking), Work/University (Breaks, Lectures) and at Home. Social media (Instagram, Facebook, Snapchat), Messaging (Text, WhatsApp), General internet usage and Calls were identified as the main applications used by the participants. The participants' hands ranged in size: Overall hand length: 165-205mm, Palm length: 81-117mm, Palm width: 78-95mm, Thumb length: 55-73mm and Finger length: 74-92mm.

4.7 Data gathering

I gathered four types of data, (1) The video recording by the two synchronized cameras and (2) the feedback questionnaire as described in Chapter 4.3, (3) the hand measurements as described in Chapter 4.6 and (4) the data gathered from the custom application as described in Chapter 4.5.

4.7.1 Video data

The video data was reviewed and used to: (1) Record the time it took the participants to complete all the tasks (2) Identify any possible issues that the participants had while completing the study (3) review and understand any tapping errors that had occurred during the study, which the custom application may have missed and (4) Using the video stills as a method of capturing visual data characterising hand/smartphone movement.

Figure 4.8: An example of the video data

4.7.2 Participant feedback questionnaire

As described in 4.6.2, the results for the feedback questionnaire were processed and added to the master excel spreadsheet.

4.7.3 Data from custom application

The data gathered from the custom application used for the study resulted in three independent variables; (1) The hand grips (Symmetric bimanual, Asymmetric bimanual with finger, Asymmetric bimanual with thumb and single-handed), all of which were drawn from the ‘interaction type” study (2) target positions (Eight different combinations of target positions as shown in Chapter 4.5) and (3) Four different sized smartphones (iPhone 4,5,6 and 6 Plus). All combinations were carried out using the body posture of sitting at a table.

Error checking for custom application

The goal was to understand phone movement when selecting the targets rather than measuring pointing precision (which is why the tapping task had to be completed before the trial could continue). Nevertheless, it was essential to check that participants finished the task without complications, so I first looked at errors.

The errors that occurred as the participants completed the task were captured in two ways: (1) Through manual analysis of the video record to identify when more than one tap had occurred, and (2) through inbuilt analytics that registered when identified taps missed the target area.

I defined *errors* as events when a participant required more than one attempt to select a target, either because a target was missed or because the software did not register the interaction. Dropping the phone was also logged as an error. The analytic measurement showed that the error rate was particularly elevated for two participants, especially for the single-handed grip of the iPhone 6 and the larger iPhone 6+, where it became even more pronounced. This corroborated the qualitative observer judgements of the video. These participants also rotated the phone to such a degree that the web app triggered the landscape-viewing mode. I decided to exclude these data sets as clear outliers from the phone movement analysis.

4.8 Analysis of the data

Once I had completed the participant-based sessions, I analysed the data collected by adding the independent studies data to a master excel spreadsheets (Appendix B.4). The data added into the master excel spreadsheet included the data collected from (1) The feedback questionnaires, (2) participant hand measurements and (3) the custom-built application.

The post-study questionnaire was analysed using the Analysis of Covariance (ANCOVA) on the sum of the absolute values of the accelerometer movements on each axis **(Rutherford, 2001)**. ANCOVA extends the analysis of variance by including additional variables (covariates) that influences the dependent variables; - here, the size of participants’ hands. To generate a unique covariate using the four hand measurements (palm width & palm length, thumb length and middle finger length), I used a Principal Component Analysis to reduce the number of dimensions. This created a hand size score metric, which is a good indicator of the general hand size. The variances were also not significantly different from each other, thus showing that the assumption of homogeneity of covariance holds. I used a p-value below 0.05 as the threshold to define significance in the rest of the analysis.

Using the data from the master excel sheet, I ran a Shapiro-Walk test **(Shapiro and Wilk, 1965)**. Here I confirmed that for ‘smartphone size’, the assumption of normality was met ($p<0.001$).

I conducted a within-subject experiment **(Charness, Gneezy and Kuhn, 2012)** where all the participants tested all three independent variables:

Phone Size (four different sizes detailed in apparatus), Hand Grip (four different types: Symmetric bimanual, Asymmetric bimanual with a finger, Asymmetric bimanual with thumb and single-handed), and Target Position (eight different combinations of Target Positions shown in Figure 4.1). In total I had 4 sizes x 4 grips x 8 target positions = 128 double-tapping tasks = 8 mins 51 secs of motion collected.

4.9 Overall movements

I performed an Analysis of Covariance (ANCOVA) on the sum of the absolute values of the accelerometer movements on each axis. ANCOVA is an extension of the analysis of variance (ANOVA) that includes additional continuous variables (covariates) that may influence the dependent variables. For example, the size of participants’ hands is an essential factor that can affect the results.

Due to the fact I took four different measures of the hand (Palm width, Palm length, Thumb length and middle finger length), I first performed a Principal Component Analysis in order to reduce the number of dimensions (and consequently the number of factors considered through the ANCOVA). This type of analysis produces a general score (or a component), in this case, the hand size score, which is arguably a better indicator of general hand size than any of the four measures taken individually. Furthermore, I found that the variances were not significantly different from each other, thus showing that the assumption of homogeneity of covariance holds.

I then proceeded to do the ANCOVA. I found a main effect for phone Size ($F_{3,1791}=49.135$, $p<0.05$), Grip ($F_{3,1791}=275.165$, $p<0.05$), and Target Position ($F_{7,1791}=109.371$, $p<0.05$). I also found an effect for interaction Size x Grip ($F_{9,1791}=7.159$, $p<0.05$), Size x Target ($F_{21,1791}=2.237$, $p<0.05$), and Grip x Position ($F_{21,1791}=14.567$, $p<0.05$). Finally, I performed

Post-Hoc comparisons using Least Significant Difference (LSD). Figure 4.9 shows the estimated means, i.e. the hypothetical means unbiased by the hand size scores after correction by the ANCOVA.

I found that both the grip and the phone size had a strong effect on phone movements. In a significant manner, the single grip (S) produced the most movements, followed by Asymmetric with a thumb (AT), Bimanual (B) and Asymmetric with a finger (AF). This validates Hypothesis H2 as I successfully predicted the order of the phones’ movement based on data from the initial study. In addition, I found significant differences linked to device size. The two smallest phones provoked smaller movements compared to the two largest ones, although there were no significant differences between the two smallest and two largest. This validates Hypothesis H1, which predicted that larger phones would require larger phone movements.

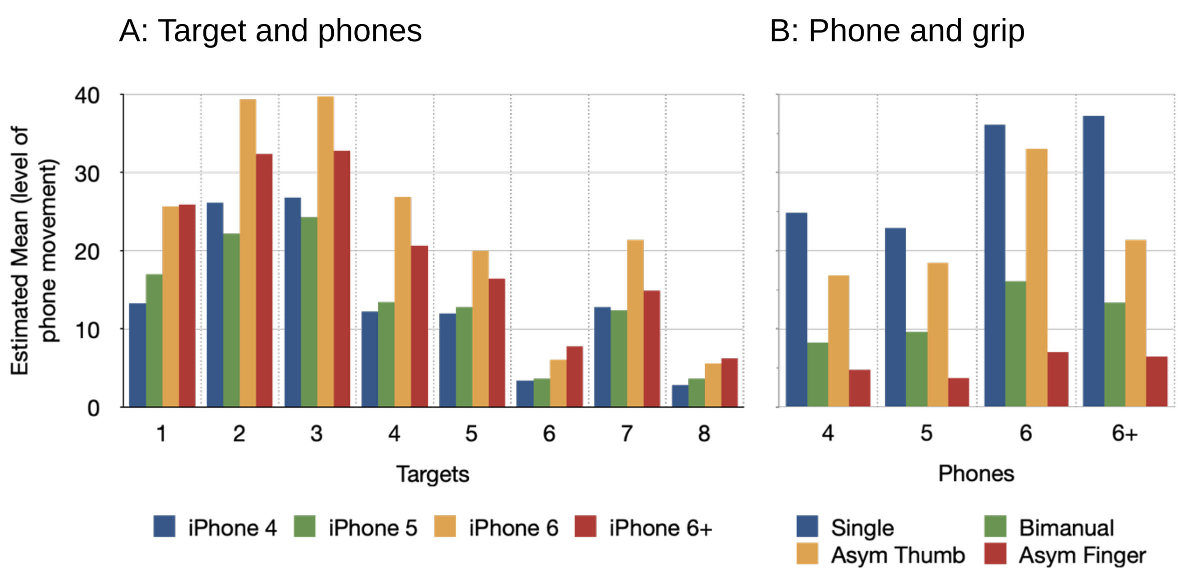


Figure 4.9: Overall level of phone movement for the interaction between the different factors studied.

Target	Phones			
	4	5	6	6+
1	13.30	16.98	25.68	25.91
2	26.18	22.18	39.34	32.39
3	26.77	24.30	39.80	32.79
4	12.23	13.39	26.84	20.68
5	12.00	12.79	20.02	16.46
6	3.39	3.64	6.04	7.77
7	12.79	12.41	21.38	14.88
8	2.80	3.64	5.54	6.20

Table 4.3: Estimated mean of phone movement for the interaction between the different factors studied (Targets and Phone).

Grips	Phones			
	4	5	6	6+
S	24.85	22.88	36.14	37.28
B	8.26	9.63	16.08	13.38
AT	16.84	18.46	33.03	21.38
AF	4.79	3.70	7.06	6.50

Table 4.4: Estimated mean of phone movement for the interaction between the different factors studied (Grips and Phone).

I found that the Functional Area Smaller Movement Positions 6 and 8 produced fewer movements, followed by the Non-functional area Smaller Movement Positions 5 and 7, then Functional Area Larger Movement Positions 1 and 4 and finally the Non-functional Area Larger Movement Positions 2 and 3 (Figure 4.9). These results are all significant except for Positions 5, 7 and 4. Positions 6 and 8 (centre of the screen) may be the more stable because they require a smaller amplitude of movement from the finger and are also within the 'functional area of the thumb' described by Bergstrom-Lehtovirta et al. **(Bergstrom-Lehtovirta and Oulasvirta, 2014)**. Positions 5 and 7 also require small movements but are not in the functional area of the thumb, which might explain why they require more movement than 6 and 8. Positions 1 and 4 require larger movement and are again in the functional area of the thumb, while Positions 2 and 3 are not. A similar trend was found when phone size was examined individually. Thus, I found that hypotheses H3 and H4 were validated. Firstly, the data shows that the amount of movement of the phone will differ depending on the distance between the target positions. Secondly, they demonstrate that the location and consequently the direction the hand needs to shift in order to tap influences the phone's movement. Having validated the hypotheses related to the general amount of movement, I refined the analysis to consider the direction of the movements in allowing us to test the next hypothesis.

4.10 Directional movements

In preparing data for the ANCOVA in this next phase, I followed an identical process to assess overall movements. I focused this time on the movements around each axis of the mobile phone: Alpha (z-axis), Beta (x-axis) and Gamma (y-axis).

For Alpha (rotation around Z) I found a main effect for Target Position ($F_{7,1791}$=12.475, p<0.05). I also found an effect for interaction Size x Position ($F_{21,1791}$=2.383, p<0.05), and Grip x Position ($F_{21,1791}$=9.976, p<0.05). For Beta (rotation around X) I found a main effect for Target Position ($F_{7,1791}$=216.906, p<0.05). I also found an effect for interaction Size x Position ($F_{21,1791}$=5.078, p<0.05) and Grip x Position ($F_{21,1791}$=21.697, p<0.05). For Gamma I found a main effect for Target Position $F_{7,1791}$=213.614, p<0.05). I also found an effect for interaction Size x Position ($F_{21,1791}$=5.351, p<0.05), and Grip x Position ($F_{21,1791}$=67.990, p<0.05). as before I used Least Significant Difference (LSD) for performing Post-Hoc comparaisons.

4.10.1 Effect of phone size and Target Positions

The size of smartphones influenced all types of rotational movement (Figure 4.10). The Alpha movement was affected least, while the Gamma movement was affected the most. The Post-Hoc statistical test illustrates the effect that the phone size and target position have with the alpha (z-axis) movement;

this movement increasing with the phone size, i.e., the movement is significantly different between target positions 1 and 4. This corresponds to the longest amplitude of movement, with all phone sizes excluding the

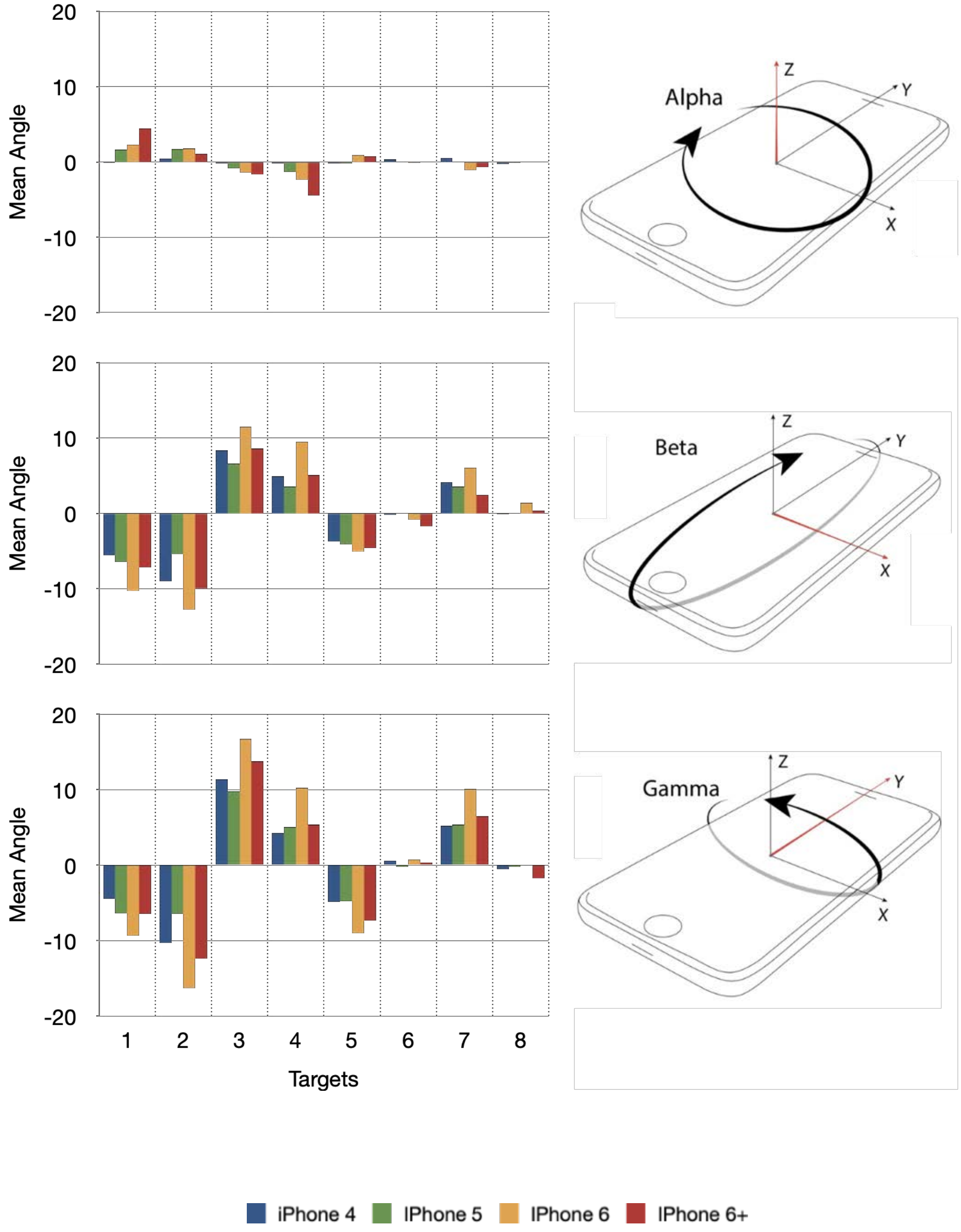


Figure 4.10: Estimated extent of phone movement for the four different grips in the Alpha (z-axis), Beta (x-axis) and Gamma (y-axis) axes for interaction between phone sizes

smallest (iPhone 4). This partially validates Hypothesis H5, which predicted that phone size would change rotational movements around the Alpha (z-axis). I speculate that this is due to the fact that participants rotate the phones in their hands, shifting the grip in order to reach the target. This happened less with smaller phones because a change of grip was enough to complete the task without rotating the phone.

Phones	Target							
	1	2	3	4	5	6	7	8
Alpha								
iPhone 4	-0.14	0.43	-0.20	-0.20	-0.21	0.36	0.52	-0.30
IPhone 5	1.64	1.70	-0.84	-1.29	-0.20	0.07	0.00	-0.09
IPhone 6	2.29	1.84	-1.36	-2.36	0.95	-0.09	-1.10	0.12
IPhone 6+	4.48	1.07	-1.61	-4.45	0.79	0.07	-0.71	0.02
Beta								
iPhone 4	-5.55	-9.04	8.38	4.91	-3.71	-0.18	4.13	-0.14
IPhone 5	-6.43	-5.39	6.66	3.54	-4.13	0.02	3.59	0.05
IPhone 6	-10.27	-12.73	11.55	9.48	-5.11	-0.86	6.05	1.38
IPhone 6+	-7.16	-9.98	8.66	5.07	-4.61	-1.71	2.46	0.38
Gamma								
iPhone 4	-4.46	-10.29	11.38	4.27	-4.89	0.61	5.21	-0.57
IPhone 5	-6.38	-6.48	9.80	5.07	-4.75	-0.20	5.36	-0.25
IPhone 6	-9.34	-16.30	16.71	10.25	-9.00	0.77	10.11	0.11
IPhone 6+	-6.48	-12.34	13.77	5.38	-7.36	0.38	6.52	-1.77

Table 4.5: Estimated extent of phone movement for the four different grips in the Alpha (z-axis), Beta (x-axis) and Gamma (y-axis) axes for interaction between phone sizes

The trend is very similar along the Beta and Gamma axes of all four phones. There are, however, some significant differences between specific Target Positions. For example, I found that the iPhone 6 had a larger Beta movement with Target Positions 1,2,3 and 4 (the Target Positions with the greatest distance). In addition, I found significant differences for the Gamma axis of the iPhone 6 and Target Positions 1,2,3,4 and 7, as well as for the iPhone 5 and Target Position 2.

I expected the iPhone 6, the second-largest phone, to produce significantly greater movement than the iPhone 4 and 5. I also expected this larger movement to be activated by the target positions 1,2,3 and 4 as they had the

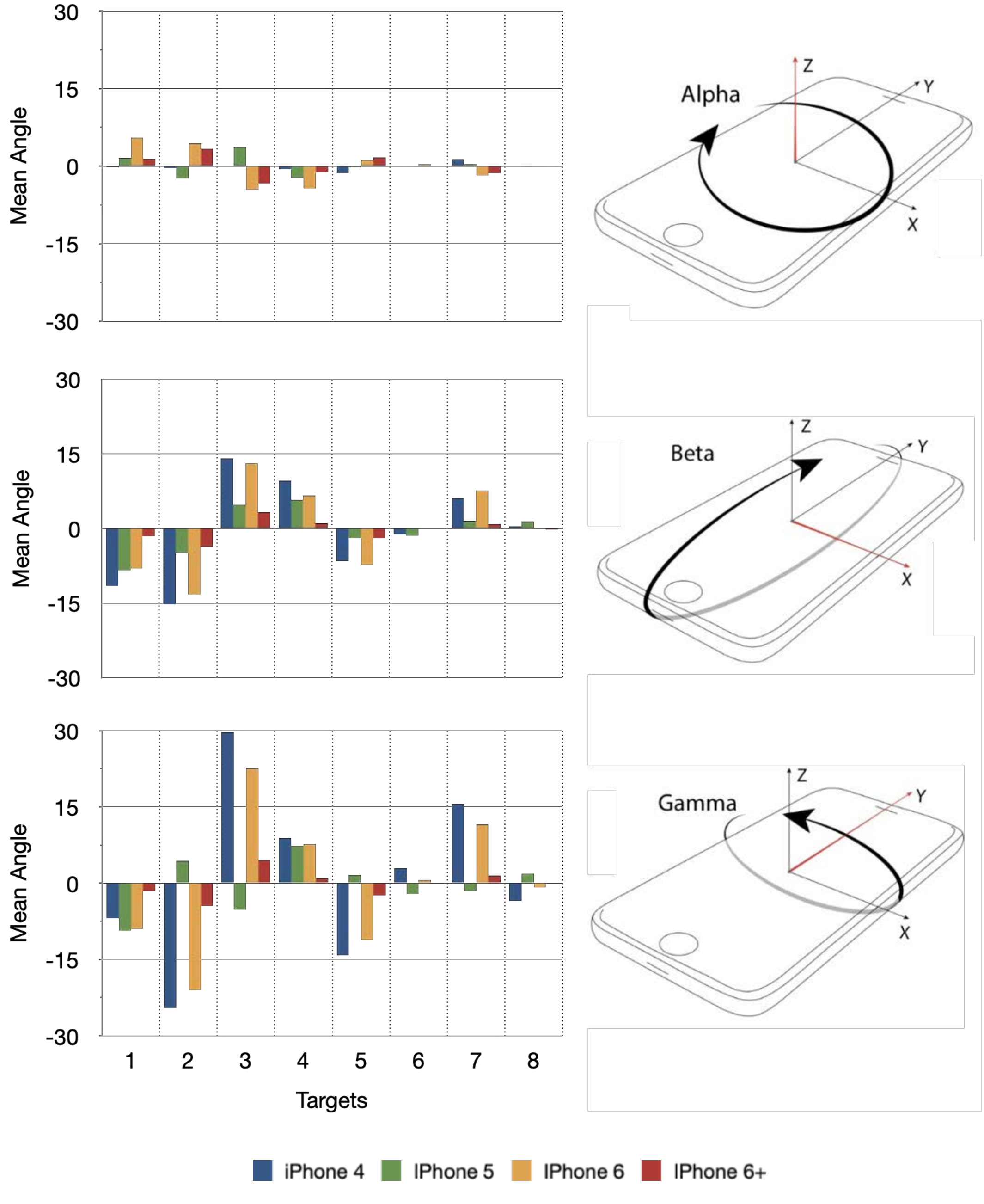


Figure 4.11: Estimated extent of phone movement for the four different grips in the Alpha (z-axis), Beta (x-axis), and Gamma (y-axis) axes for interaction.

greatest distance between the targets and by target position 7, which, although had a smaller distance between the targets, also went against the ‘functional area of the thumb’ and so required participants to reach across the phone.

Grips	Target							
	1	2	3	4	5	6	7	8
Alpha								
S	-0.20	-0.29	0.13	-0.59	-1.34	-0.11	1.30	0.00
B	1.54	-2.41	3.77	-2.29	-0.18	0.09	0.43	-0.12
AT	5.52	4.39	-4.54	-4.23	1.16	0.36	-1.79	-0.13
AF	1.41	3.34	-3.36	-1.18	1.68	0.07	-1.25	0
Beta								
S	-11.45	-15.20	14.05	9.63	-6.48	-1.21	6.13	0.45
B	-8.39	-4.93	4.82	5.73	-1.87	-1.41	1.52	1.48
AT	-8.00	-13.30	13.07	6.64	-7.27	-0.04	7.61	-0.09
AF	-1.57	-3.71	3.30	1.00	-1.93	-0.07	0.98	-0.18
Gamma								
S	-6.93	-24.45	29.70	8.88	-14.16	2.91	15.57	-3.46
B	-9.27	4.37	-5.18	7.36	1.64	-2.09	-1.48	1.89
AT	-8.91	-20.93	22.63	7.70	-11.09	0.71	11.64	-0.82
AF	-1.55	-4.41	4.52	1.04	-2.39	0.02	1.46	-0.09

Table 4.6: Estimated extent of phone movement for the four different grips in the Alpha (z-axis), Beta (x-axis), and Gamma (y-axis) axes for interaction.

4.10.2 Effect of grip and Target Positions

The Post-Hoc statistical test illustrated that the directional movements differed significantly depending on the Target Position and Grip, thus corroborating my Hypothesis H5. I noticed that the level of movement in the Alpha, Beta and Gamma axes increased, with the Gamma increase being the greatest. The exception here is AF, which appeared to show only a marginal increase in Gamma rotation. Without going into too much detail about each individual Target Position comparison, I can state that there were few significant differences between Target Positions involving small amounts of movement (5,6,7 and 8). This was except for targets 5 and 7 with the Gamma axis and Beta axis values of grips S and AT, which were larger.

However, I found more significant differences for the Target Positions involving larger movements (1,2,3 and 4). In particular, the Alpha rotations were comparatively high for AT and very low for S. I believe this is due to the non-dominant hand acting in support of the dominant hand by manoeuvring the phone closer to the thumb’s position. Interestingly, the direction of rotation also appears to change depending on the grip, with AF and AT having rotations opposite to B for Target Positions 2 and 3. I believe that this is due to the usage of both thumbs and the direction of the movement between the targets.

For the Beta axis rotations, the largest movements were attributed to the S and AT and were significantly higher than those of B and AF, while the direction of movement was similar for all targets. This suggested that participants used the same movement each time to acquire the target, i.e., rocking the phone toward them. For the Gamma rotation, there was again a significant difference between S and AT vs B and AF. Figure 4.11 also illustrates the difference between B and AF, where one can see an opposite movement direction. I believe that this is again due to the B grip where both thumbs are employed to interact with the phone. Users were found to have used a rocking motion along the Gamma axis - i.e., instead of bringing the phone to the finger or thumb, they rocked the phone in the opposite direction to reach the target (see Figure 3.13).

Through the Post-Hoc analysis, I observed a strong difference for the combined Gamma and Beta values between conditions where the thumb was used to point (S and AT) and the condition where the index finger was used (AF). The amplitude of movements is significantly statistically different for S and AT, which could simply be due to the fact that the AF grip allows the user to move their hand and arm more freely, thus bringing the finger to the correct position, which necessitates less phone movement (as observed in the initial study). Conversely, S and AT grips constrict the hand more, forcing participants to move the phone substantially further to bring it into contact with the thumb.

4.11 Post questionnaire

Using a similar analysis to that described above, I found a main effect for Q1 (Secure) on Phone Size ($F_{3,1791}$=16.536, p<0.05) and Grip ($F_{3,1791}$=192.056, p<0.05) and Grip x Size ($F_{9,1791}$=30.728, p<0.05); Q2 (comfort) on Phone Size ($F_{3,1791}$=13.101, p<0.05) and Grip ($F_{3,1791}$=81.297, p<0.05) and Grip x Size ($F_{9,1791}$=32.606, p<0.05); Q3 (popularity) on Phone Size ($F_{3,1791}$=5.960, p<0.05) and Grip ($F_{3,1791}$=62.346, p<0.05) and grip x size ($F_{9,1791}$=24.996, p<0.05).

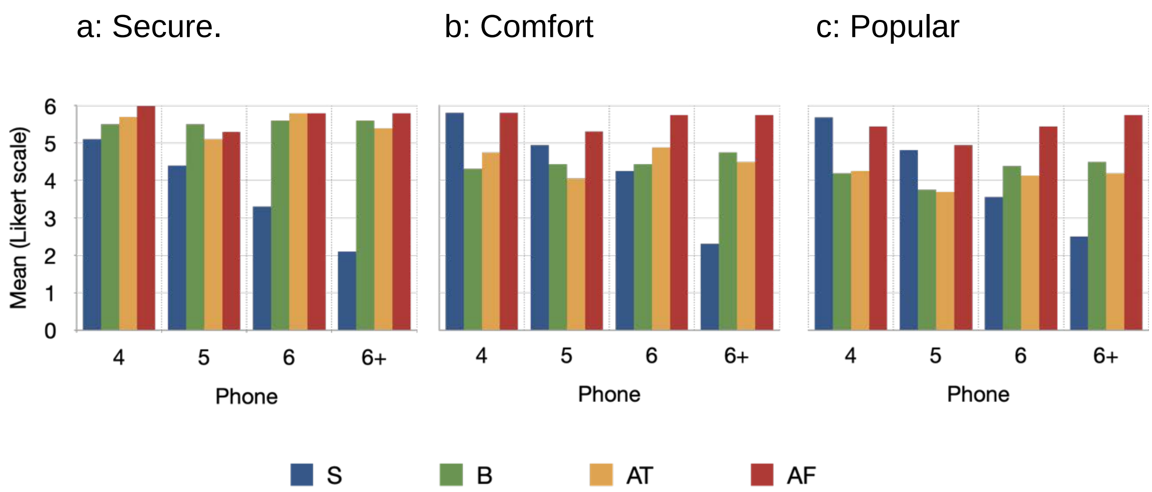


Figure 4.12: Questionnaire Results: a) Security of the grip b) Comfort of the grip and c) Popularity of the grip for this task

A: Single-handed									
Targets		1	2	3	4	5	6	7	8
iPhone 4	X	9.7	15.1	15.1	9.5	6.6	1.7	8.9	1.5
	Y	6.2	23.0	27.1	7.6	12.1	3.4	12.1	3.4
	Z	4.7	7.7	6.2	3.5	4.7	1.6	5.6	1.6
iPhone 5	X	11.5	14.1	12.9	8.1	7.6	1.5	5.9	1.7
	Y	9.9	15.5	22.4	8.6	11.1	2.4	13.1	2.6
	Z	4.7	9.4	4.9	4.3	3.8	1.6	3.3	1.9
iPhone 6	X	19.4	22.7	18.2	18.6	10.1	3.1	10.0	2.6
	Y	10.7	32.8	36.9	12.4	17.4	4.9	23.1	4.0
	Z	5.3	6.4	5.7	7.1	5.2	2.6	8.5	1.4
iPhone 6+	X	17.7	18.0	17.0	18.0	6.6	5.7	5.7	4.0
	Y	13.9	30.6	35.8	14.7	16.9	8.2	17.4	6.9
	Z	12.5	9.5	8.4	11.9	4.8	4.7	3.9	3.4
B: Symmetric Bimanual									
Targets		1	2	3	4	5	6	7	8
iPhone 4	X	6.0	4.5	4.1	5.2	1.8	1.3	1.4	0.8
	Y	6.9	5.6	4.9	5.2	2.1	1.4	1.4	1.1
	Z	2.3	1.6	4.1	1.8	0.9	0.6	0.6	0.4
iPhone 5	X	6.7	3.2	4.9	3.6	2.0	1.4	1.2	2.2
	Y	8.5	6.2	4.5	5.6	2.3	2.4	2.6	1.9
	Z	2.9	3.9	3.6	3.0	1.1	0.9	1.6	0.7
iPhone 6	X	11.6	7.1	6.8	11.0	2.2	2.1	2.1	3.3
	Y	12.7	8.4	9.6	14.3	3.4	3.0	2.6	4.1
	Z	3.1	4.9	6.4	4.9	1.6	1.1	1.6	0.6
iPhone 6+	X	9.8	7.8	6.4	5.1	3.4	2.7	2.1	2.4
	Y	11.1	7.4	6.9	7.7	2.4	3.9	2.9	2.2
	Z	6.6	3.6	3.5	4.4	2.0	0.8	1.1	0.9
C: Asymmetric with Thumb									
Targets		1	2	3	4	5	6	7	8
iPhone 4	X	5.1	12.8	12.0	5.5	5.8	1.1	6.0	0.7
	Y	5.6	18.3	18.0	6.1	7.0	1.4	8.9	0.9
	Z	2.6	4.9	4.7	2.4	2.1	0.6	2.1	0.2
iPhone 5	X	7.6	10.9	13.3	6.4	7.3	1.4	7.3	0.6
	Y	9.2	15.3	20.2	8.1	9.1	1.1	9.4	0.9
	Z	3.9	3.4	4.8	3.0	2.2	0.7	1.4	0.4
iPhone 6	X	10.2	16.7	17.4	10.9	9.7	2.1	10.9	1.8
	Y	14.1	32.9	34.1	13.4	18.4	2.8	17.4	2.4
	Z	8.3	10.9	10.1	9.1	4.8	1.2	3.9	0.7
iPhone 6+	X	9.1	12.9	10.7	5.4	7.7	1.7	8.6	1.3
	Y	9.9	19.6	19.8	5.4	10.6	1.7	12.4	2.1
	Z	7.9	6.7	5.6	4.9	2.9	0.8	2.6	0.6
D: Asymmetric with Finger									
Targets		1	2	3	4	5	6	7	8
iPhone 4	X	1.6	3.7	3.0	0.9	1.5	0.2	1.1	0.1
	Y	1.2	4.2	4.8	0.7	1.9	0.2	1.7	0.4
	Z	1.3	3.3	3.0	0.6	1.4	0.1	1.2	0.2
iPhone 5	X	0.9	2.6	2.1	1.1	1.8	0.2	1.2	0.6
	Y	1.1	2.5	2.4	1.1	1.8	0.5	1.6	0.5
	Z	0.9	1.8	1.2	0.7	1.1	0.5	0.9	0.5
iPhone 6	X	2.5	4.6	4.1	1.9	2.0	0.4	1.6	0.3
	Y	2.5	5.7	5.6	1.6	2.9	0.6	2.0	0.6
	Z	2.2	4.3	4.2	2.3	2.4	0.1	1.8	0.3
iPhone 6+	X	2.1	4.0	4.1	1.6	2.7	0.3	0.7	0.3
	Y	1.5	5.4	5.7	1.5	3.5	0.3	1.1	0.3
	Z	1.4	4.1	5.0	2.0	2.3	0.3	1.2	0.4

Table 4.7. Mean angle data for all targets and grips.

4.11.1 Security

The S Grip was significantly rated less secure than Grips B, AT and AF for iPhone 5, 6 and 6+. However, there were no other differences. In fact, if I look at Figure 4.12, I can see that the scores are very similar across a range of grip types and phone sizes, proving that participants felt secure when employing a two-handed grip.

4.11.2 Comfort

The S and AF grips were rated more comfortable than B and AT for the iPhone 4 and 5. However, this trend inverts for S, which is rated worse than AF, B and AT for the iPhone 6+. AF remains consistent and is the preferred grip out of the four for

Grips	Phone			
	4	5	6	6+
Secure				
S	5.13	4.44	3.31	2.06
B	5.50	5.50	5.56	5.56
AT	5.69	5.06	5.81	5.38
AF	6.00	5.25	5.75	5.81
Comfort				
S	5.81	4.94	4.25	2.31
B	4.31	4.44	4.44	4.75
AT	4.75	4.06	4.88	4.50
AF	5.81	5.31	5.75	5.75
Popular				
S	5.69	4.81	3.56	2.50
B	4.19	3.75	4.38	4.50
AT	4.25	3.69	4.13	4.19
AF	5.44	4.94	5.44	5.75

Table 4.8: Questionnaire Results: a) Security of the grip b) Comfort of the grip and c) Popularity of the grip for this task

the iPhone 6 and 6+. For Phone 6+ the grips B and AT are in second place. The questionnaire data for the S grip corresponds with participants’ comments during the task that the smaller iPhone 4 and 5 allowed them to grasp the phone and reach the target areas without much effort. However, as the phone size increased participants found great difficulty in completing the dual role of holding the phone and reaching the target areas. This resulted in larger shifts of grip with one participant complaining of hand strain.

4.11.3 Popular

The trends here are similar to those of the Comfort question. In fact, the same results were found as described above. As Napier **(Napier, 1993)** states, the selection of the grip depends on the task required and it is important to underline that these results are focused purely on the pointing task. Out of the four grips, AF grip is ranked best for three phones (iPhone 5,6 and 6+) and second best for the iPhone 4. Out of the four grips, the AF grip is the grip which provokes the smallest amount of movement (Figure 4.10) which partially validates my Hypothesis H6.

4.11.4 Summary of results

In this second study I looked at how the size of the mobile phone and the grip used affected how the phone was maneuvered. I validated all my hypotheses, except for H1 and H6. H1 was partially validated: I found that the two smaller phones had significantly less movements than the two larger ones. H6 was also partially validated: AF is the grip with the least movement, and this is preferred for three of the four phones with S being the preferred grip for the remaining phone.

4.12 Design insights

This study demonstrated that the hand adapts fluidly to device type and context of use, dealing with interactions such as menu selection or keyboard typing through a combination of grips and movements. As the hope is that this research can help benefit UI designers, I asked the questions at this point in the thesis: Can designers use this knowledge to create more compelling interactive experiences? In the last part of this chapter, I attempt to answer this question through three concepts that exploit insights gained from the above study to propose appropriate design responses focused on a touchscreen-based solution.

4.12.1 Concept design

Current touchscreen mobile phone operating systems, such as Apple’s iOS, is designed around a series of UI components **(Apple Developer, 2020)**. Using these components as a foundation, I generated three conceptual ideas around an adaptive UI method. That triggers UI changes by combining the task and its known tilt and rotational movement associations.

Concept 1: Adaptive keyboard

During the first qualitative study, participants were found to tilt the device from side-to-side along the Gamma axis to better access the keyboard target areas (Figure 3.13). Building on my hypothesis H3, I discovered that this tilting movement also occurred during the second quantitative study for Target Positions 5,6,7 and 8. Using the data shown in Figure 4.10 and Table 4.3, I see greater movement along the Gamma axis (in other words, a side-to-side motion). The adaptive keyboard concept in Figure 4.13 uses this side-to-side motion to shift the keyboard letters into a more reachable position. The concept is similar to the iGrasp technique **(Cheng et al. 2013)**. However, while iGrasp triggers the keyboard according to grip, the adaptive keyboard would be activated if a side-to-side tilt along the Gamma axis were initiated. The keyboard ‘slides’ as the phone tilts, placing the required letters in an easier-to-reach position for the thumb.

Figure 4.13: The adaptive keyboard concept

Concept 2: Adaptive scrolling

In the first qualitative study, I found that participants tilted the mobile phone along the vertical axis to select navigation options from the top bar (Figure 3.14 and 3.15). In the second study, participants made similar vertical tilts for Target Positions 1, 2, 3 and 4 along the Beta and Gamma axes, thus building on my Hypotheses H1, H3 and H5.

The concept of adaptive scrolling involves activating a feature when two conditions are met: a navigation bar is on the screen, and a tilt along the Beta axis is detected. Adaptive scrolling is then triggered, lowering the navigation bar items to place them within reach of the thumb (Figure 4.14).

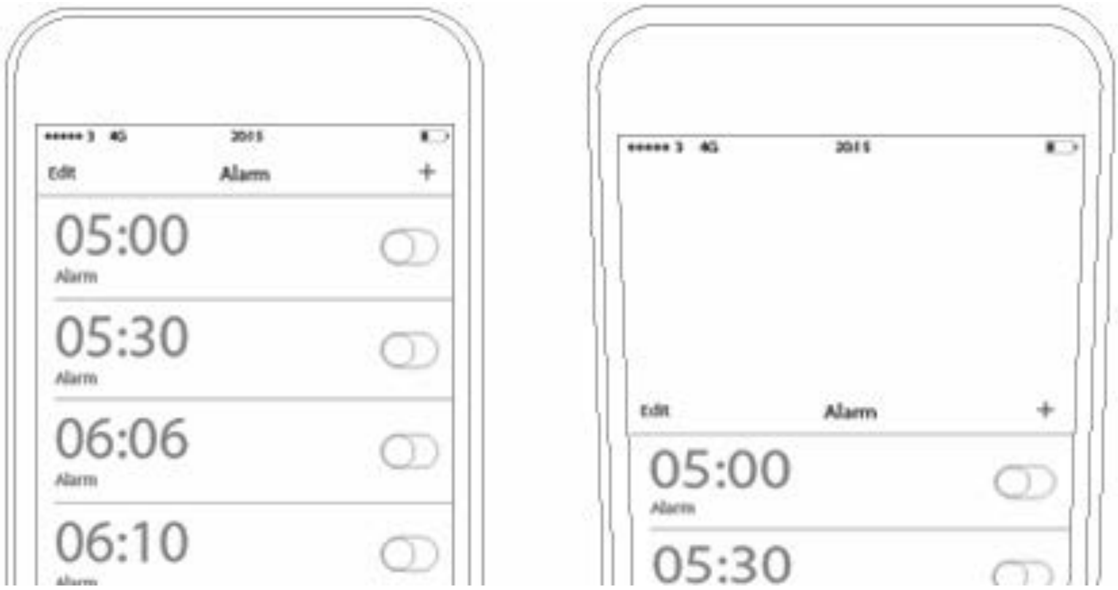


Figure 4.14: The adaptive scrolling concept

Concept 3: Adaptive homepage

In the first qualitative study, I found that when participants use the single-handed and asymmetric bimanual with a thumb grip to reach the top corner of the screen opposite the dominant hand’s thumb, the phone twisted along the Beta and Gamma axes (Figure 3.14 and 3.15). This area appeared to be difficult to reach and provoked the greatest tilt and rotation of the device. In testing hypotheses H1, H3 and H5, the second quantitative study also showed that participants made similar twists along the Beta and Gamma axes for Target Positions 1, 2, 3 and 4 (see Figures 4.10 and Table 4.3).

The adaptive homepage concept has similarities with “tilt slide” **(Chang et al., 2015)**. However, this concept homepage icons shift closer to the dominant hand when tilt is sensed along the Beta and Gamma axes (Figure 4.15). This reduces the amount of reach a participant needs to use to interact with the phone.

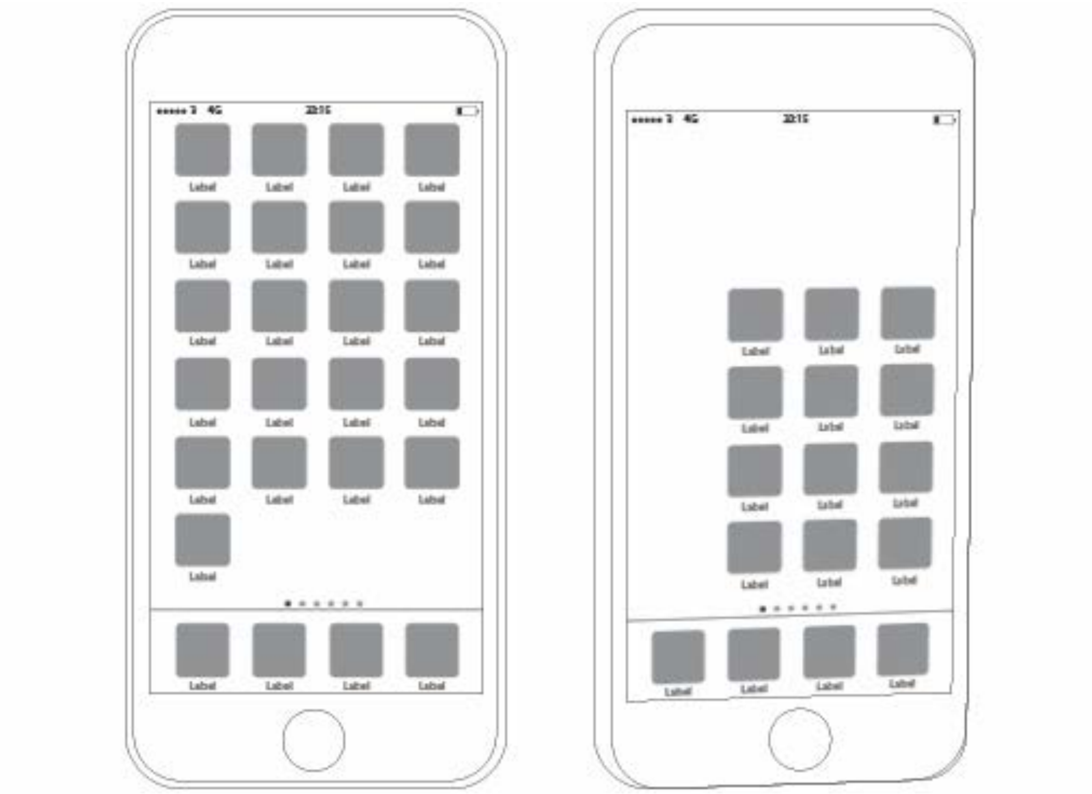


Figure 4.15.: The adaptive homepage concept

4.13 Conclusion

In this chapter, I conducted a study to investigate if the smartphone's size impacted the physical interaction method, as demonstrated in Chapter 3. I discovered that the size of the smartphone does have an impact on the motion (rotation and tilt) of the handheld device (Research question 3). The quantitative study showed a difference between the four grip's overall movement, AF having the least movement and S having the most. I found that the two smaller iPhones (4 and 5) had a statistical difference for the overall movement compared to that of the larger iPhones (6 and 6+); however, there were no statistical differences between the iPhone 4 and 5 or the iPhone 6 and 6+. Additionally, I discovered that the placement of targets on the touchscreen statistically affects the smartphone's overall movements. Those furthest away and not within the functional area of the thumb produced the most movement (Targets 2 and 3), and those closest and within the functional area of the thumb produced the least movement (Targets 6 and 8). As for the smartphone's overall mean value of movement, I discovered that Alpha produced the least movement, with Gamma producing the most movement for both grip type and size of the device.

I have proposed three smartphone interaction design concepts using the insights that I gathered from this quantitative research and Chapter 3's qualitative research. These allowed me to demonstrate how designers could benefit from understanding how hand and smartphone movements change according to the phone size and grip type. All three of the concepts' main interaction features are triggered by the smartphone's movement, shifting the screen-based content towards the interacting hand. Even though the concepts went beyond the current UI design guidelines **(Apple 2020a; 2020b and Google 2020)**, there were, in fact, already similar concepts created by other researchers **(Cheng et al., 2013 and Chang et al., 2015)**. As the ultimate intention for this research was to develop conceptual designs through design workshops (see Chapters 6 and 7), the three concepts presented in this chapter were not developed further. However, they were used to inspire those at the design workshops. In particular, concept 1: adaptive keyboard was presented during the workshop, as described in chapter 6.

In the next chapter of this PhD research (Chapter 5), I will take these findings further by investigating the impact on phone and grip movements of the body postures of participants (lying down, sitting at a table or standing). This will enable me to understand whether the hand or arm support might influence the smartphone movement.

Chapter 5: Investigating differences between ‘body postures’

Part of this chapter has been published at ACM CHI 2018.

This chapter continues the investigation into the hand interaction through the four user-defined grips presented in Chapter 3. However, these are explored within the context of three different body postures (Sitting at a table, Standing and Lying down).

The research question for this chapter:

Does the participant's body posture affect how the hand interacts with the handheld interactive device?

5.0 Introduction

In this chapter, I investigate how the individual's 'body posture' affects the smartphone's movement. I do this through a quantitative study that matches Chapter 4 and looks into how: (1) the body posture affects interaction design; (2) How the four user-defined grips (Chapter 3) affect the tilt rotation of the smartphone; (3) What the participants' perceptions are of different body postures during interaction.

I first speculate about the different physical body postures and question how they likely affect the hand smartphone interaction. Next, I created a number of hypotheses to study, as I did in Chapter 4. Then, as with Chapter 4, I run a quantitative study using the same procedure, smartphone application and questioners to understand how the movement affects an individual smartphone (iPhone 6). Ultimately, I identify a number of design insights that will inform the design activities in Chapters 6 and 7.

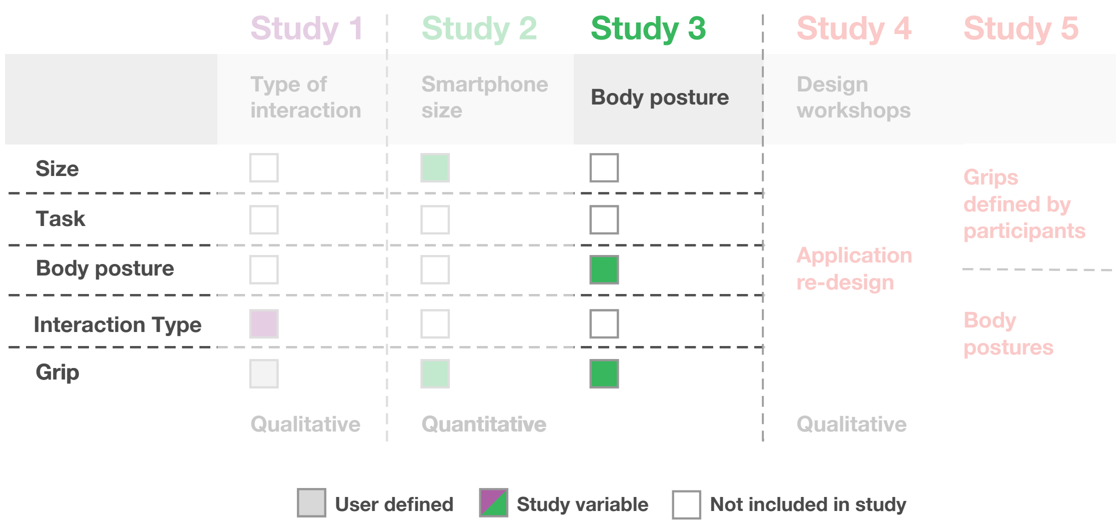


Table 5.1: Variables of study 3 design

The main results are: (1) the body posture with the most movement is Lying down, then Sitting at a table and Standing; (2) the orders of overall movement (the sum of movements made in the three rotational directions of the phone) for the grips are consistent throughout all body postures (Figure 5.1) corroborating (Chapter 4); (3) the rotation of the smartphone is dependent on body posture, with Lying down showing different rotational movement than Sitting at a table and Standing. Finally, I provide detailed descriptions of motions used in different body postures, using different grips, valuable for UX smartphone designers.

5.1 Experimental Design

This third study explores how the individual’s ‘body posture’ affects the participant-defined grips and the tilt/rotation of the smartphone observed in the initial ‘interaction type’ study (Chapter 3). To do so, I first listed common postures using personal experiences and observations and extrapolated other factors affecting hand usages: smartphone support, body support, and muscle usage.

5.1.1 Smartphone support

If I look at how the smartphone rests and inclines in the user's hands, I notice variations dependent on the user's body posture. For example, when standing, the smartphone rests on top of the users' fingers; however, when lying on the back, the smartphone needs to be held in place, without fingers or thumbs blocking the screen (Figure 5.1). Additionally, the grips used will affect the smartphone support for all body postures. The bi-manual grips, giving more contact area between the smartphone and the hands, are potentially perceived as more secure than the grip single-handed. I also expect the participants to compensate for the anxiety of dropping the smartphone, such as lying down on one's back (the smartphone falling towards the participant's face) and standing (dropping and damaging the smartphone).

Figure 5.1. Showing different angles of the smartphone within different body postures.

5.1.2 Body support

This work is inspired by **(Kim and Chae, 2012)**, who investigated how the biomechanical and muscle activity for different postures (sitting, standing and sitting at a table) affected smartphone usage. These researchers discovered that the body posture made a difference due to the mobility of the wrist and upper extremities. For example, when sitting at a table, arms will be anchored near the elbow, and biomechanical restrictions will be placed on the movement of the upper arm. The participant's perception of the smartphone support could thus be boosted, increasing smartphone movement. In addition, when lying down, the participants' arms will be lifted upwards to bring their hands together, enabling interaction via bimanual grips and allowing a clear view of the screen. Overall, I believe this will reduce the perception of stability and increase smartphone movement.

5.1.3 Muscles usage

When interacting with touchscreen devices (e.g., smartphone, tablet, tabletop, wall display), Bachynskyi et al. **(Bachynskyi et al., 2015)** showed that distinctive body postures use distinctive sets of muscles. This muscle usage relates to differing grips used for smartphone interaction: when sitting, a two-handed grip uses the lower back, upper back and shoulder muscles on the arm of the dominant hand. However, the single-handed grip uses just the dominant hand's upper back and back shoulder muscles. I believe that this distinctive muscle usage influenced the findings of Chapter 4, in which grips and location of targets altered the tilts and rotations of the smartphone. Based on these findings, I believe differing body postures will affect the smartphone's rotations again. In particular, variances should be seen when lying down, as distinctively different muscles will be utilised in supporting the smartphone.

After theorising about the other factors affecting hand usages when interacting with a smartphone, I selected three body postures (Sitting at a table, Standing and lying down) that were more affected by the three factors (smartphone support, body support and muscle usage). Additionally, I discarded non-symmetrical postures to ease the comparison of rotations between the postures (e.g., lying down on the left would skew the result to one side). Please see Figure 5.2. From this theoretical work, I created a number of hypotheses.

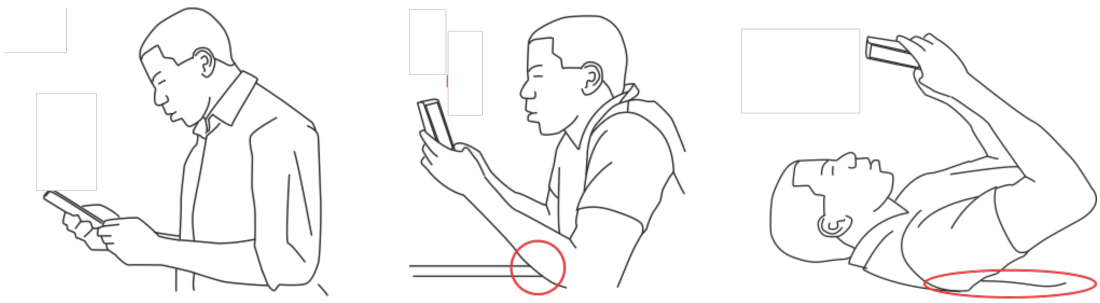


Figure 5.2. The three body postures selected - Standing, sitting at a table and lying down on back.

5.1.4 Hypotheses

From this, I again created a number of hypotheses regarding objective measurements regarding the variable of body posture (quantity of movement performed by the hand in the different axes) and subjective (users’ perception of security and comfort). I focused on three body postures (Sitting, Standing, lying down) to have a trackable set for a controlled experiment.

H1: The overall smartphone movement will be larger when lying down than other body postures due to the arm muscles being used to lift the smartphone upwards. I also think that the lack of support will render lying down the less “secure” posture.

H2: The overall amount of smartphone movement will be lower when standing than in other postures as participants will have full arm movement and flexibility. Additionally, the participants may be anxious concerning the breakage of the smartphone.

H3: The directional movement for lying down will be distinctive to the other body postures. I believe this is affected in the way the smartphone rests in the hand involving distinctive muscles (more beta and gamma movements when lying down). Effect should be stronger in S.

H4: Previous results on grips should be similar for Sitting at a table and Standing, i.e. S will have most movement, followed by AT, B and AF. This should differ for Lying down where AT and AF allow for a firmer grip and more stable hold and thus less movement.

H5: As before, the total movements of the smartphone will differ according to Target Position for all body postures (targets further away needing more movements and those in the functional area of the thumb, less).

H6: The lower the movement, the higher the rating for the conditions “secure” and “comfortable” (and those conditions will be preferred) e.g., S should be rated the worst when lying.

5.2 Study variables

As in Chapter 4, I answered these hypotheses through a controlled experiment using qualitative research methodology. To keep consistency within the studies, I decided to use the same tapping-interaction-based task as in Chapter 4.2 and the same two questionnaires, recording participant information and participant opinions about that study variables.

I continued to use the five variables as stated in the ‘smartphone size’ study chapter 4 and discovered during the ‘interaction type’ study in chapter 3 - for an overview, please see table 5.1. For this study on body posture, the variables I used were, firstly, a task (via a custom-built app as described in Chapter 4.4). Secondly, I retained the same interaction method (touchscreen smartphone). Thirdly, I retained the four grips discovered in the ‘interaction type’ study (Chapter 3). Finally, the fourth variable, ‘body posture’, had participants use the smartphone in three different body postures (Sitting at a table, standing and lying down).

5.2.1 Body posture

In order to reduce the independent variables, I used just one body posture for the ‘smartphone size’ and ‘interaction type’ study (Chapter 3 and 4), that of sitting at a table, hence ruling out interference from posture or whole-body movement. However, for the ‘body posture’ study, I added two further body postures: standing and lying down (Figure 5.2). I selected the additional two body postures as outlined in the discussion presented in Chapter 5.1: Experimental design.

5.2.2 Task

To control the position of the finger movement and analyze how these positions impact the phone's movement, I copied the 'smartphone size' study in chapter 4. This study uses a pointing task of two targets on a screen within eight different combinations, as shown in figure 5.3. For more information about the application design, please see chapter 4.5.

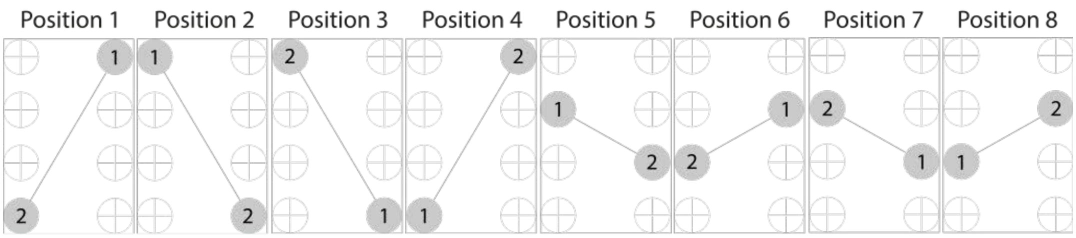


Figure 5.3. Possible target positions

5.2.3 Interaction type

To keep consistency with the 'smartphone size' study as presented in Chapter 4 I again used the touchscreen interaction smart phone technology.

5.2.4 Grips

I again, as stated in Chapter 4 (the 'smartphone size' study), used the four hand grips (Figure 5.4) as identified during the 'interaction type' study using this touchscreen smartphone in Chapter 3 (Asymmetric with a thumb, Symmetric bimanual, Single-handed and Asymmetric with a finger).

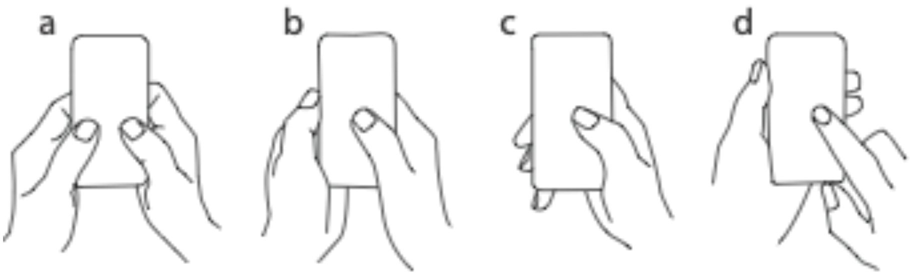


Figure 5.4. The four grips: a) Symmetric bimanual, b) Asymmetric with a thumb, c) Single-handed and d) Asymmetric with a finger.

5.3 Apparatus used

To keep consistency within this experiment, I used almost identical apparatus to Chapter 4 (the 'smartphone size' study). The matching apparatus included the cameras and software applications that recorded the sessions (4.3.4 cameras and recording software), the touchscreen tablet used to collect participants feedback and the online questionnaire used for recruitment

(4.3.1 Online recruitment questionnaire).

Changes to the apparatus were made by selecting just one of the smartphones (iPhone 6) and using more furniture to create comfortable positioning for the participants in the three-body postures. I additionally adjusted the participant feedback questionnaire to focus on the body posture and not the smartphone size.

5.3.1 Smartphones

Ask with the ‘smartphone size’ study (Chapter 4) I continue to use the same touchscreen interaction smartphone as the ‘interaction type’ study (Chapter 3). I selected the iPhone 6 as this showed the most movement variation during the ‘smartphone size’ study (Chapter 4). The smartphones used WiFi to connect to the internet during the study. The smartphones used were the iPhone 6 (Table 5.2).

	Height	Width	Depth
iPhone 6	138.1 mm	67.0 mm	6.9 mm

Table 5.2: Measurements of the smartphones used

5.3.2 Room furnishings

To complete the ‘body posture’ studies, four pieces of furniture were needed. First, a desk and chair were used for the body posture sitting at a table to keep consistency with the ‘interaction type’ study (Chapter 3) and the ‘smartphone size’ study (Chapter 4). Second, I additionally used a chair to accommodate the sitting body posture and provided a single air bed for the participants to comfortably rest during the lying down body posture.

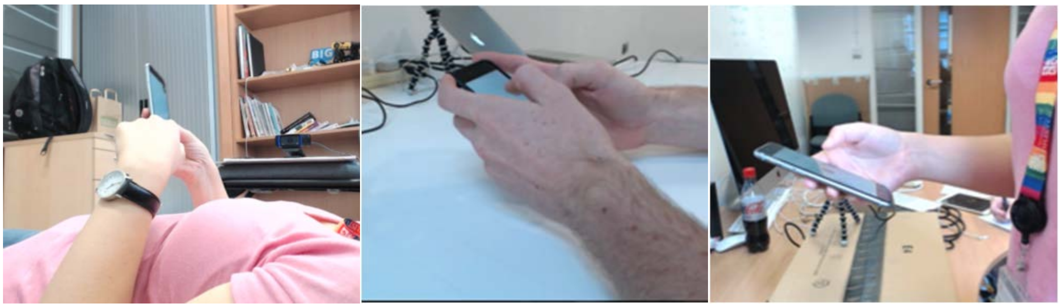


Figure 5.5: Images of the smartphone during the three body postures.

5.3.3 Participants feedback questionnaire

As with the ‘smartphone size’ study (Chapter 4), I asked the participants to fill in a feedback questionnaire. The only difference between this questionnaire and that of the ‘smartphone size’ study was that I focused on the three-body postures (Sitting at a table, Standing and lying down) rather than the four smartphone sizes.

The participant feedback questionnaire had two parts as with the ‘smartphone size’ study. An admin section where the grips and the body posture was inputted. In the second section, where participants were asked to rate the studies variables for the questions asked for an example, see Appendices B.2 and B.3.

As with the ‘smartphone size’ study, the ratings were completed using a Likert scale to rate the grips and body posture **(Likert, 1932)**.

5.4 Custom application

For the ‘body posture’ study, I repurposed the custom-built application used for the ‘smartphone size’ study (Chapter 4.4 Custom application). In addition, a small modification was made to the application design, removing the different sizes of smartphones (iPhone 4, iPhone 5, iPhone 6 and iPhone 6 plus) and replacing this configuration option with a list of the body postures to be studied (sitting at a table, standing and lying down). Please see figure 4.5

for more details.

5.5 Participant sessions

For the ‘body posture’ study, I kept the same participant session structure as the ‘smartphone size’ study (Chapter 4.5 participant sessions). breaking down the session into seven parts. (1) Explain the experiment to the participants and sign a consent form. (2) Discuss unclear information from the recruitment questionnaire. (3) Take participants’ hand measurements. (4) Adopting the body posture assigned (5) Hand preset smartphones to the participant to complete the task. (6) Participants complete a questionnaire based on their experience with those activities (7) Repeat parts 4, 5 and 6 until the study was completed (All three body postures).

5.6 Participants

For the body posture study, 20 righthanded participants with no known disabilities (10 males and 10 females) aged between 18 years to 41 years took part. All participants either studied at or worked for a University and had owned the phone for between one month to three years.

All participants had previous experience with touchscreen smartphones. 19 participants owned touchscreen smartphones, 10 used an iOS device, 9 used an Android device, and one used a Nokia device. In addition, 10 of the participants had added an external casing to their smartphone.

The participants’ smartphone sizes ranged from W:58.6mm, H:120.3mm, D: 6.8mm to W:75.8mm, D:9.2mm, H:154.4mm. The smallest smartphones were the HTC One and the iPhone 5s, while the largest was the Samsung S6 and the Samsung Galaxy S6 Edge Plus.

The top applications used were social media (Instagram, Facebook and Snapchat). Messaging (text, WhatsApp) and Calls. The top locations used were public transport (bus, train), Work/University (during breaks, lectures), and home.

The participants' hands ranged in size: Overall hand length: 165-205mm, Palm length: 81-117mm, Palm width: 76-100mm, Thumb length: 52-69mm and Finger length: 75-92mm.

5.7 Data gathering

To keep consistency with the 'smartphone size' study chapter 4, I gathered the data following the same steps. These steps were, (1) video recording with two synchronized cameras; (2) feedback questionnaire as described in chapter 4.3, (3) taking participants hand measurements as described in chapter 4.6 and (4) collecting the data from the custom application as described in chapter 4.5.

For the 'body posture' study, no participants made identifiable errors observed during the 'smartphone size' study in chapter 4.7.3 Data from a custom application.

5.8 Analysis of the data

A Shapiro-Wilk test confirmed that the assumption of normality was met for the data ($p<0.001$). I first provide an analysis of the overall movement (the sum of movements made in all three directions as shown in Figure 2) before detailing the directional movements gathered via the device's inbuilt sensors. I also analyse the post questionnaire using the Analysis of Covariance on the sum of the absolute values of the accelerometer movements on each axis. ANCOVA extends the analysis of variance by including additional variables (covariates) that influence the dependent variables – here, the size of participants’ hands. To generate a unique covariate using the four hand measurements (palm width & palm length, thumb length and middle finger length), I used a Principal Component Analysis to reduce the number of dimensions, similarly to in Chapter 4. This created a hand size score metric, which is a good indicator of the general hand size. The variances were also not significantly different from each other, thus showing that the assumption of homogeneity of covariance holds. In the rest of the analysis, I used a p-value below 0.05.

5.9 Overall movements

I found a main effect for Body posture ($F_{2,1728}$ =119.251), Grip ($F_{3,1728}$ =3.901) and for Body posture x Grip ($F_{6,1728}$ =2.038). I performed Post-Hoc comparisons using Least Significant Difference (LSD). Figure 5.6 shows the estimated means, i.e., the hypothetical means unbiased by the hand size scores after correction by the ANCOVA. I found that the statistical test showed that there was a significant effect for postures, that lying down (LD) produced most movements, followed by Sitting and Standing. I also found significant differences between grips, Single-handed (S) having more movements than Asymmetric bimanual Thumb (AT) and Asymmetric bimanual Finger (AF). Differences were found between Symmetric bimanual (B) and Asymmetric bimanual thumb (AT). The differences between grasps were due to the interaction with Lying body posture for which these results were significant compared to other body postures. There was no effect for target positions.

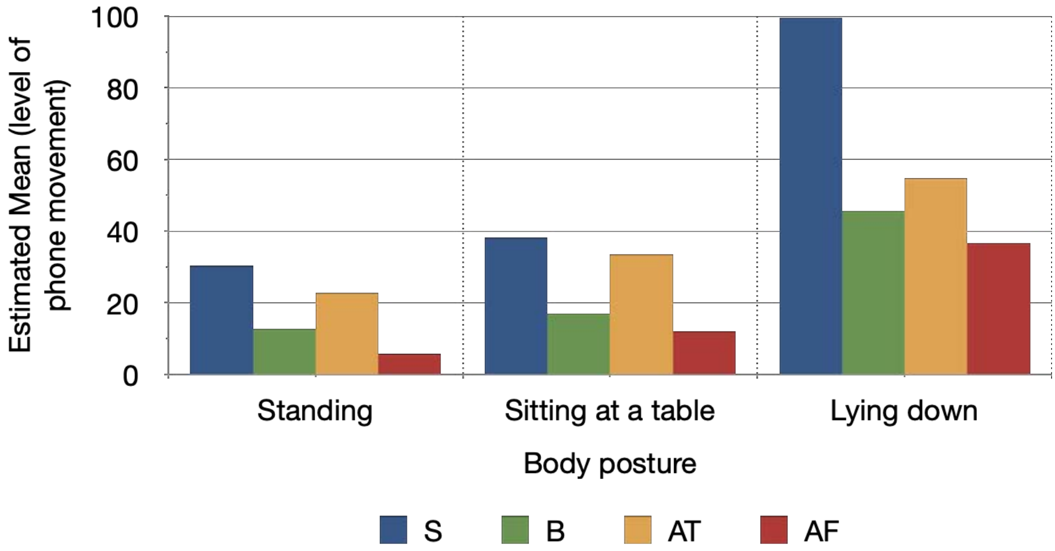


Figure 5.6: Estimated level of phone movement for the interaction between the different factors

Grips	Body posture		
	Stand	Sitting table	Lying
S	30.3	38.2	99.5
B	12.6	17.0	45.5
AT	22.8	33.6	54.7
AF	5.8	12.1	36.6

Table 5.3: Estimated level of phone movement for the interaction between the different factors

5.10 Directional movements

In preparing data for the ANCOVA in this next phase I followed an identical process to that used to assess overall movements. I focused this time on the movements around each axis of the mobile phone: Alpha (z-axis), Beta (x-axis) and Gamma (y-axis) (Figure 5.7).

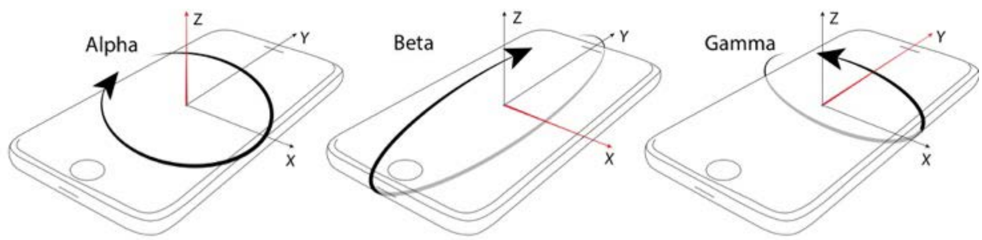


Figure 5.7: Movements around each Axis (Alpha, Beta and Gamma).

For Alpha I found a main effect for Grip ($F_{3,1728}$=3.025), Body posture x Grip ($F_{6,1728}$=3.552), Body posture x Target position $F_{14,1728}$=2.535), Grip x Target position ($F_{21,1728}$=3.146) and Body posture x Grip x Target position ($F_{42,1728}$=2.566). For Beta I found a main effect for Target position ($F_{7,1728}$=249.835), Body posture x Target ($F_{14,1728}$=5.345), Grip x Target position ($F_{21,1728}$=20.468) and Body posture x Grip x Target position ($F_{42,1728}$=1.395). For Gamma I found a main effect for Grip ($F_{3,1728}$=3.131), Target position ($F_{7,1728}$=26.897), Body posture x Grip ($F_{6,1728}$=3.914), Body posture x Target $F_{14,1728}$=2.359), Grip x Target position ($F_{21,1728}$=8.205), Body posture x Grip x Target position ($F_{42,1728}$=2.956).

As before I used least Significant Difference (LSD) for performing Post-Hoc comparisons **(Williams, 2010)**. For Alpha, I found that statistically S had the greatest movement, followed by AT, B and AF. I also found that there was a significant difference between S and all other grips. For Beta no significant statistical findings were found. For Gamma, I found that statistically S had the greatest movement, followed by AT, B and AF showing the least movement. I also found that there were significant differences between grips S and the grips B and AT.

5.11 Post questionnaire

Using the same analysis tool but for overall movements, I found a main effect for Q1 (Secure) on Body posture ($F_{2,1728}$ =161.290) and Grip ($F_{3,1728}$ =390.936) and Grip x Body posture ($F_{6,1728}$ =42.431); Q2 (comfort) on Body posture ($F_{2,1728}$ =60.092) and Grip ($F_{3,1728}$ =195.284) and Grip x Body posture ($F_{6,1728}$ =37.685); Q3 (popularity) on Body posture ($F_{2,1728}$ =51.668) and grip ($F_{3,1728}$ =205.344) and Grip x Body posture ($F_{6,1728}$ =33.980);

A: Single-handed									
Targets		1	2	3	4	5	6	7	8
Stand	X	18.4	15.5	15.9	15.9	8.4	2.6	9.4	2.9
	Y	9.6	25.9	28.6	9.6	15.1	4.1	14.7	3.8
	Z	6.8	7.6	6.8	7.2	5.6	1.5	4.7	1.7
Sitting at table	X	17.7	18.5	16.7	15.2	8.8	2.9	9.6	3.0
	Y	17.3	35.6	42.4	16.7	21.0	4.2	19.5	5.7
	Z	9.3	10.4	9.9	7.8	5.1	1.8	4.2	2.3
Lying down	X	17.2	24.3	32.4	15.0	16.6	2.3	19.1	2.9
	Y	46.9	46.3	63.4	44.9	44.3	20.7	48.6	13.0
	Z	46.1	45.8	71.0	50.4	40.8	19.5	50.7	13.0
B: Symmetric Bimanual									
Targets		1	2	3	4	5	6	7	8
Stand	X	8.8	5.8	6.2	7.6	1.6	2.7	1.2	2.2
	Y	11.1	7.9	7.4	10.1	2.4	3.8	2.4	3.5
	Z	2.9	3.0	4.4	2.3	0.8	0.9	0.7	1.2
Sitting at table	X	11.1	7.7	6.2	11.1	2.1	2.9	2.7	2.8
	Y	12.1	10.8	11.2	12.3	3.4	4.4	2.4	3.1
	Z	4.3	5.2	8.4	6.6	1.2	1.1	1.6	1.4
Lying down	X	12.7	13.7	12.3	14.1	2.9	3.9	2.8	2.3
	Y	16.6	31.4	24.8	27.4	10.1	14.4	14.2	14.0
	Z	18.7	30.5	26.7	25.2	8.7	13.2	12.6	13.0
C: Asymmetric with Thumb									
Targets		1	2	3	4	5	6	7	8
Stand	X	8.3	13.3	11.9	7.7	6.7	1.1	6.8	1.1
	Y	7.4	26.3	26.0	8.1	14.1	2.7	14.2	2.2
	Z	5.0	6.4	5.8	4.9	2.6	1.0	2.6	0.6
Sitting at table	X	12.9	19.1	19.6	10.4	8.3	1.2	9.4	1.3
	Y	17.2	33.8	32.0	13.8	17.1	1.7	16.6	2.2
	Z	11.7	13.8	11.6	8.0	4.4	1.6	4.3	0.7
Lying down	X	14.4	21.2	23.0	13.4	9.6	2.4	9.8	2.1
	Y	18.9	35.2	42.6	27.7	23.5	13.7	18.4	4.9
	Z	20.5	37.3	27.3	29.3	15.3	11.2	12.3	3.9
D: Asymmetric with Finger									
Targets		1	2	3	4	5	6	7	8
Stand	X	1.4	3.4	3.1	1.6	1.2	0.5	1.2	0.3
	Y	1.2	5.2	4.4	1.3	3	0.7	2.7	0.8
	Z	1.6	4.4	3.2	1.6	1.6	0.4	1.9	0.2
Sitting at table	X	2.6	6.1	5.0	2.2	3.1	0.7	2.7	0.5
	Y	3.7	11.4	11.7	3.2	6.9	1.0	5.3	0.7
	Z	3.2	8.2	8.4	2.6	3.6	0.8	2.6	0.4
Lying down	X	2.9	6.4	7.9	2.4	3.7	1.5	4.8	0.3
	Y	9.8	25.3	28.2	10.3	12.6	12.2	25.3	3.2
	Z	11.4	26.7	31.5	11.8	11.4	12.2	27.1	3.7

Table 5.4: Mean angle data for all targets and grips

5.11.1 Security

For body postures, participants found that lying is significantly different from standing and sitting and viewed it as the least secure, followed by Sitting, with Standing being the most secure. For the grips, I found that in a significant manner S was considered least secure, followed by AT, B and AF. The exception here is the body posture standing in which AF and B were switched. No significance was found for target positions. (Figure 5.8i).

5.11.2 Comfort

For body postures, the participants found that lying is significantly different from standing and sitting and is the least comfortable posture, followed by Sitting and Standing. For the grips, I found that in a significant manner S was considered least comfortable, followed by AT, B and AF (Figure 5.8ii).

5.11.3 Popular

For body postures, participants found that lying is significantly different from standing and sitting and being the least popular, followed by Sitting and Standing. For the grips, I found that in a significant way S was considered least popular, followed by AT, B and AF. The exception is for Sitting where the grips AT and B are rated the same in popularity (Figure 5.8iii).

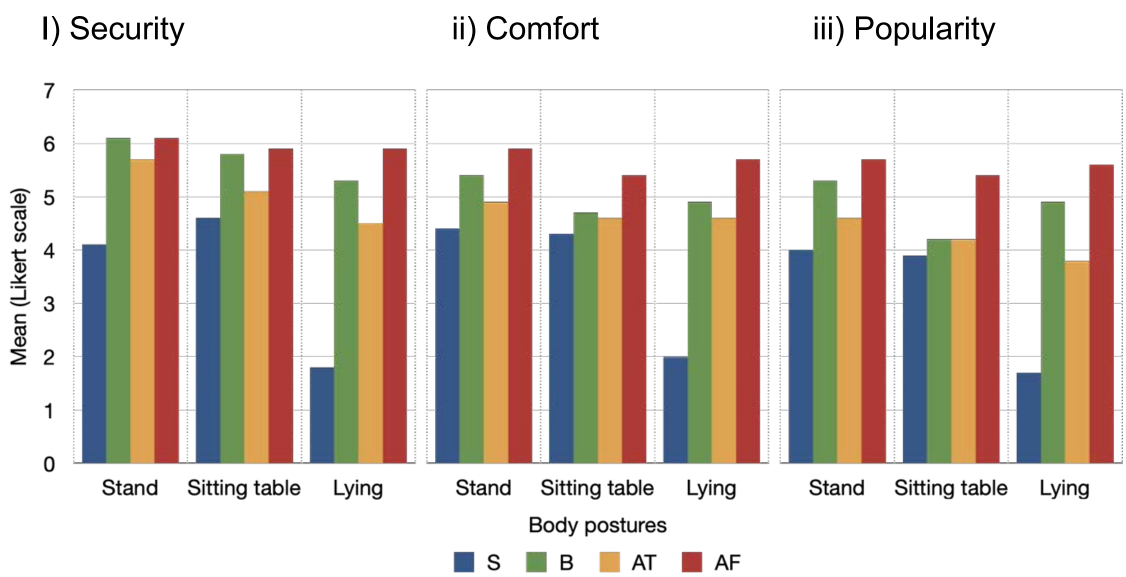


Figure 5.8: Questionnaire Results: i) Security ii) Comfort and iii) Popularity

Grips	Body postures		
	Standing	Sitting at a table	Lying down
Secure			
S	4.1	4.6	1.8
B	6.1	5.8	5.3
AT	5.7	5.1	4.5
AF	6.1	5.9	5.9
Comfort			
S	4.4	4.3	2.0
B	5.4	4.7	4.9
AT	4.9	4.6	4.6
AF	5.9	5.4	5.7
Popular			
S	4.0	3.9	1.7
B	5.3	4.2	4.9
AT	4.6	4.2	3.8
AF	5.7	5.4	5.6

Table 5.5: Questionnaire Results: i) Security ii) Comfort and iii) Popularity

5.12 Design insights

I now revisit the hypothesis in light of the results. In this study, I looked at handgrip and smartphone interaction, questioning how body posture affects the tilt and rotation of the smartphone. I found the body posture with the largest movement to be Lying, which is true for all grip types, partially validating H1. Additionally, Lying down was considered the least secure body posture, partly validating H1. However, I only predicted that participants would use their arms to raise the smartphone. I did not expect participants to rest their arms on their upper torso. This finding needs further investigation to understand how it may impact smartphone interaction.

For the smartphone’s movement, I found that the body posture Lying had different directional movements to that of Sitting and Standing, thus partially validating H3, with Lying showing the most movement for Beta, Alpha and finally Gamma (Figure 5.7). This may be compared to Sitting and Standing, which had the most movement for Alpha, Beta and then Gamma. Lying had the greatest movement for Alpha and Beta, but the least Gamma movement.

This is different from the prediction, as I believed there would be more Beta and Gamma movement. I found that the movement of the overall grip matched the findings of (Chapter 4) for all body postures. The body posture with the most overall movement was Lying, then Sitting and finally Standing. This partially validates H4. The only difference I found for Lying was an increase in the movement for all grips. All body postures mapped the same movements as Chapter 4. The non-functional targets of the larger distance have the most movement, and the functional targets with the least distance have the lowest movement (Figure 5.2), thus validating H5. AF - the grip with the lowest movement for all body postures - was considered the most secure, popular and comfortable grip. An exception to this is for Standing when B was considered the most secure grip, partially validating H6. S was rated lowest for all conditions and body postures, validating this part of H6.

I also provide the raw data of the mean angles for each body posture and grip used for the eight target positions (Figure 5.8). This table extends the data provided in (Chapter 4) and, I think, will benefit designers. For more than half a century, empirical data have underpinned design and architecture, for example, Henry Dreyfuss’ humanscale metrics **(Dreyfuss, 1967)**. The goal is similar. For example, I can see from the table that the Y and Z angles for Lying down are greater than other body postures (Sitting and Standing). This data can be used to update physical interaction with the smartphone by changing the screen lighting for low light conditions when detecting movement patterns typically associated with a user lying down. I can also see that the mean angles are directional by further looking at the targets (Figure 6). Here I see that depending on the grips, Targets 1 and 4 have similar angles, as do 2 and 3. From this mean angle data, designers can start to predict the grip used and the locations the users need to reach. I hope that this will lead to the moving of graphical elements to better positions depending on postures or grips, allowing users to interact with minimal hand movements.

5.13 Conclusion

In this study, I asked if the body posture affects the hand smartphone interaction as measured by the movement of the physical smartphone using the four hand grips as demonstrated in Chapter 3. I have discovered that the body posture and hand grips influence participants' perception of the grip and physical movement (Research question 4). This quantitative study showed a difference between the three-body posture, with the lying down producing the most movement and the body posture standing producing the least movement. As with the smartphone size study presented in Chapter 4, the grip with the least movement is that of AF, and the grip with the most movement is the S grip.

To progress this research now adds to the two other datasets that I have gathered during this PhD, the first (Chapter 3) qualitative and the second and third (Chapters 4 and 5) quantitative. My next step will be to see how these findings can inform designers and understand how these learnings can help develop conceptual user experience in smartphone interaction design.

Chapter 6: Investigating the re-design of applications

Part of this chapter has been run as a workshop at UX Bristol 2017 and findings described in this chapter were published in the proceedings of ACM DIS 2018

In this chapter I investigate how the observational research and empirical data gathered from the previous chapters could be used in the design of smartphone interactions.

Research question for this chapter:
How can we design interactive, handheld objects better for the user's hand interaction?

6.0 Introduction

With this study, I aim to question and validate the insights gained from the data acquired in Chapter 3 ‘type of interaction’ and Chapter 5 ‘body posture’, in order to understand how UX designers can use the research findings to concept new smartphone screen-based interactions for specific hand grips (Asymmetric with a thumb, Symmetric bimanual, Single-handed and Asymmetric with a finger) and body postures (Sitting at a table, standing and lying down).

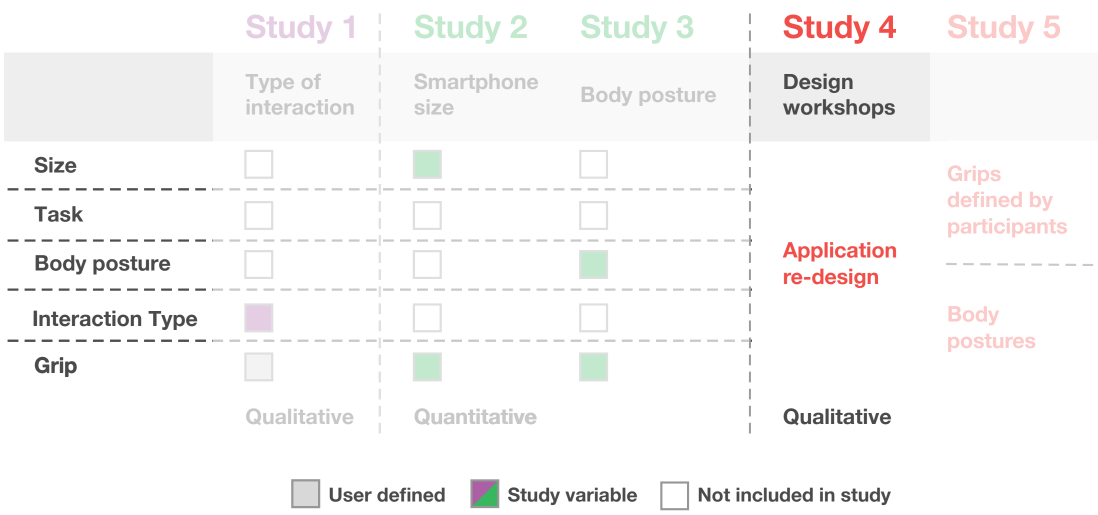


Table 6.1: Variables of study 4 design

To facilitate the involvement of design professionals in this study, I submitted and had a workshop proposal accepted for a UX conference **(UX Bristol, 2017)**. Doing this gave me access to professional UX designers and their years of industrial experience. During the workshop I focused on re-designing two specific types of applications. In particular, I focused on (1) The smartphone’s security and how the motion of the smartphone can enable fraudsters to predict PIN entry **(Mehrnezhad *et al.*, 2018)** and (2) the scenario discussed in Chapter 3 - how participants use the smartphone to enter and send text messages.

In this chapter I will first present the method which I used to translate the data gathered from the ‘type of interaction’ and ‘body posture’ studies into materials suitable for the workshop. I will then discuss the decisions made during the process of selecting the two applications that I ask the workshop participants to design. I will then go on to discuss the workshop including the materials created, the process undertaken and ultimately provide an analysis of the produced design concepts.

6.1 Experimental Design

Once I had systematically analyzed and defined the movement patterns of smartphones in a number of different cases (type of interaction, smart phone size and body posture). I next wanted to see how I could validate the value of previously gathered empirical data by using that information to enable UX designers to create more compelling experiences. To this end, I designed and ran a design workshop that focused on specific application design, motivated by the grip and body posture data collected as shown in chapter 5, with the hope that workshop participants would find this real-world data compelling.

This workshop focused on the re-design of two applications focused on the themes of “messaging” and “security”. The hope here is that the participants would use the gathered data presented to them to re-design the applications in a manner that takes these concerns into account. This application-focused design session took 55 mins and generated 22 design concepts. Analysis showed that the workshop had succeeded in generating a number of thought-provoking concepts using the empirical data. However, when I reviewed the concept designs, I had no ability to compare the body postures or grips in order to identify if there were any overarching interaction themes that were grip or body posture specific.

6.2 Presenting the data

I wanted to understand how UI designers might use the data that I gathered during the studies presented in Chapters 3 and 5 to create more compelling interactive experiences. Focusing on the data of Chapter 5 ‘body posture’, I created 12 cards explaining the Alpha, Beta and Gamma rotational movements of the smartphone corresponding to the three body postures (Sitting at a table, standing and lying down) and four handgrips (Asymmetric with a thumb, Symmetric bimanual, Single-handed and Asymmetric with a finger).

The 12 data cards presented: (1) color coding and labelling of the specified body postures (Figure 6.1a); (2) image of the specified grip (Figure 6.1b); (3) four visual examples of the movements made by the hand when interacting with the smartphone (Body posture colour is the first position of movement with the dark grey colour being the last position of movement) (Figure 6.1c); (4) data for the Alpha, Beta and Gamma corresponding to the eight tapping tasks (Figure 6.1f).

An example drawn from these card sets is presented in Figure 6.2. This shows an informational card showing grip information relating to the standing body posture, including specific data for the single handed, symmetric bimanual, asymmetric bimanual with the thumb and a symmetric bimanual with a finger. For a full set of these cards see Appendix D.1.

6.3 Re-designing an application

As part of this research I applied and received acceptance for a workshop at UX Bristol 2017 **(UX Bristol, 2017)**, a yearly one-day paid-to-attend conference for professional UX designers. This workshop focused on the re-design of two applications (messaging and security) for multiple handgrips and body postures. The session was entitled ‘Rock ’n’ roll your phone’ and ran on 14th of July 2017.

The “Messaging” application

The messaging application is the traditional interface used in all smartphones to write text messages. I found it particularly interesting as previous research shows that users use a large variety of grips for texting (Chapter 3 & 4). I was thus curious to understand how physical interaction could, through design changes, affect screen-based interaction.

The “Security” application

The security application is the traditional interface to enter a pin code. Mehrnezhad et al **(Mehrnezhad *et al.*, 2018)** highlight through their research that a PIN code could be exposed with a tracking application running in the background recording the movements of a smartphone. I thus wonder how this could be re-designed so that the movement of the phone is less likely to reveal the pin input data.

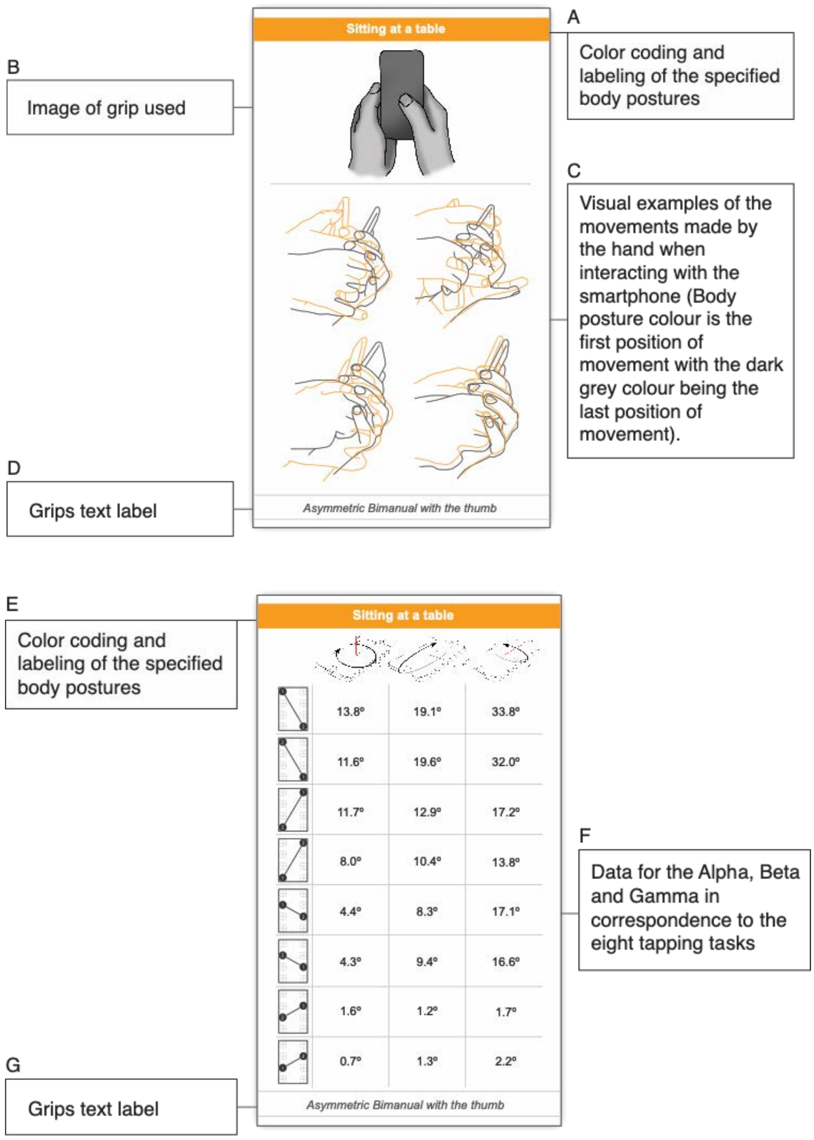


Figure 6.1: Example of the front and back of the data card

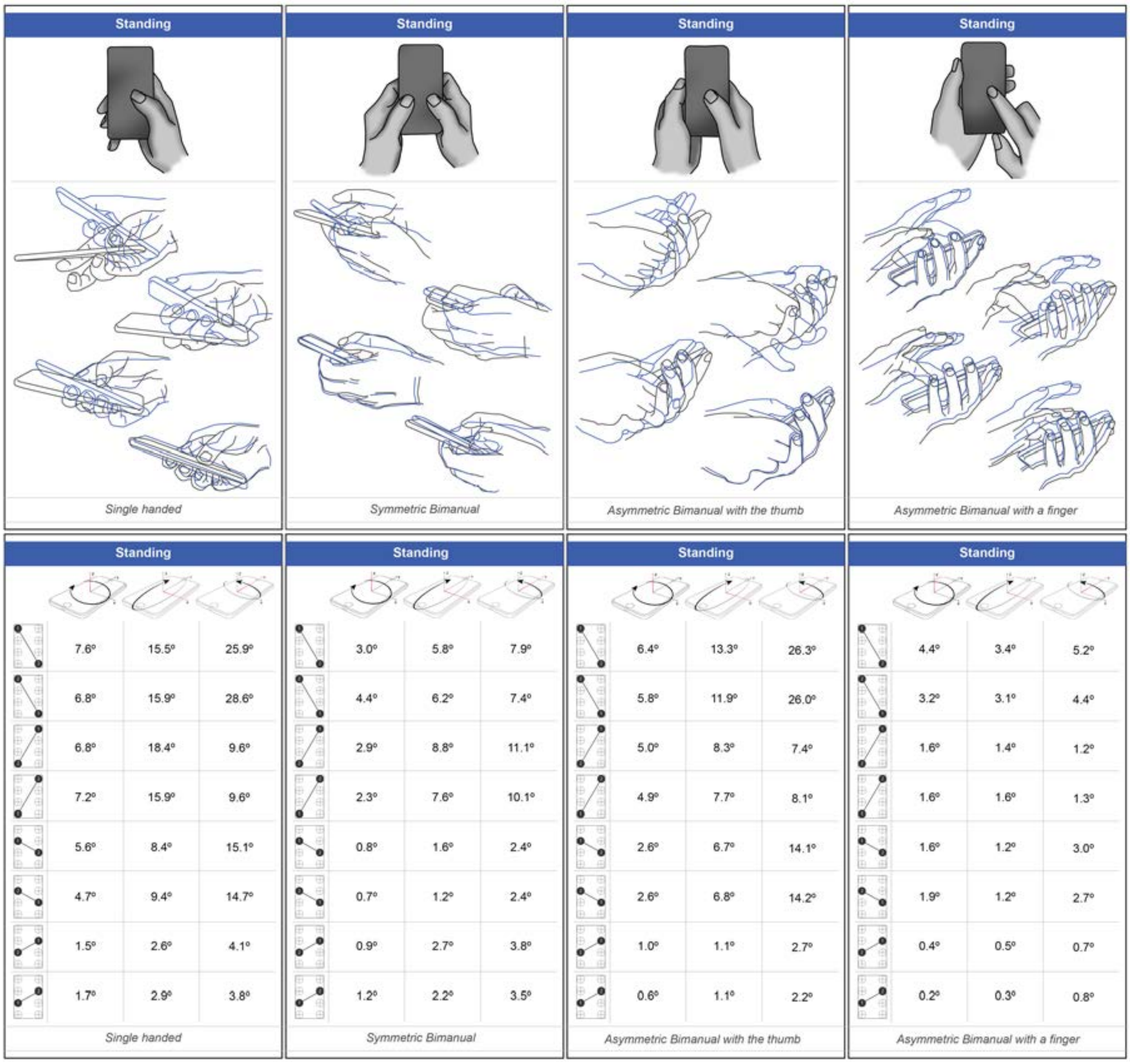


Figure 6.2: Detailed view of the data cards for the standing body posture

6.3.2 Methodology

My goal for this design session was to see how UX designers would create or re-design two standard smartphone applications (Messaging and Security). To do this I ran a 55-minute design session with professional UX designers. As joining the workshop was voluntary, I was unaware how many would attend until the workshop started. This required the materials to be created in such a way that they could be adapted to support any number of participants.

Material pack

I prefilled eight envelopes containing the application to be redesigned (messaging or security), the body posture to use (sitting at the table, standing or lying down), and cards with the data gathered about the defined body posture (Figure 6.1) (taken from chapter 5). As I was unsure of participant numbers, I used a die to randomize the grip selection (Single-handed, Symmetric bimanual, Asymmetric bimanual-finger or Asymmetric bimanual-thumb) to remove any unconscious bias in my selection (Figure 6.3).

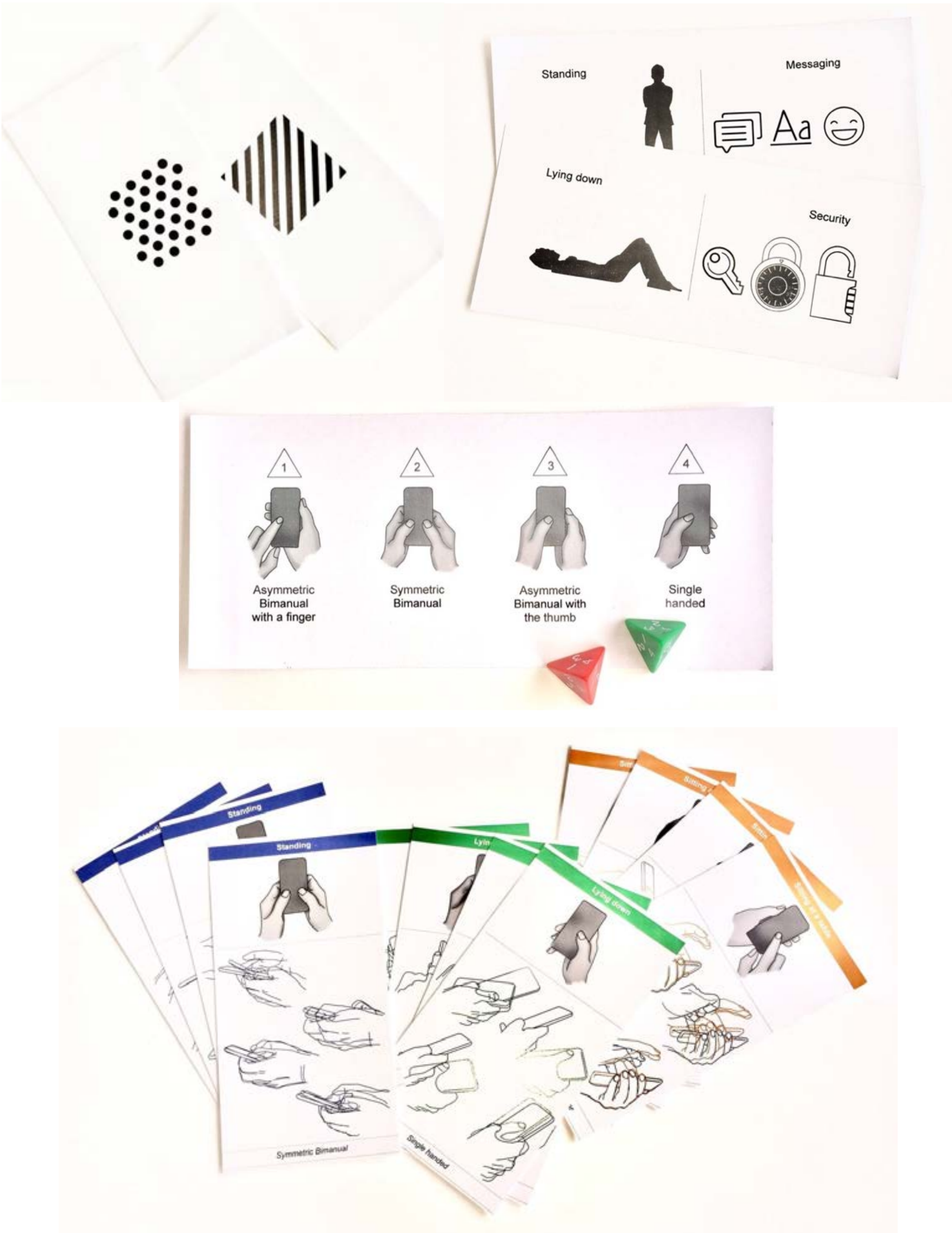


Figure 6.3: Items given to the workshop teams

Envelopes

So that I understood which application was in which envelope I assigned a pattern. The envelopes with stripes contained the messaging application, while the envelopes with dots contained the security application. Each table had one of each type of envelope and the two teams randomly selected one (Figure 6.3).

Body posture and application cards

To help focus the workshop participants, I created cards that informed the participants of a) which body posture they would be designing for, as defined in Chapter 5, and b) which of the two applications they would be re-designing (messaging or security). The eight cards were broken down so that two applications were placed on four cards each. The body postures were randomly selected to have two cards for sitting at a table and three cards each for standing and lying down (see Table 6.2).

	Sitting at a table	Standing	Lying down
Messaging	1	2	1
Security	1	1	2

Table 6.2: Variables of the workshops for body postures and application design.

Grip selection

For the participants to be able to randomly select the grip that they would be designing for, I created a card that showed the four grips and a number from one to four above those grips (Single-handed, Symmetric bimanual, Asymmetric bimanual-finger or Asymmetric bimanual-thumb). using a four-sided die which matched the number of grips available. I asked the teams to roll the die and design for the resulting grip (Figure 6.3).

Data cards

I handed out the data cards to the participants of the workshop (Figure 6.2) that matched the body posture presented to them within their envelope.

6.3.3 Design session structure

The design session lasted 55 minutes and had five stages; (1Explain to the participants that this workshop is part of a PhD project , provide a participant information sheet and opportunity to ask any questions, and then ask them to consent to ethics if they choose to continue; (2) Highlight previous research to the participants through practical tasks and presentation; (3) Set tasks by creating teams and set the team focus (Application, Body posture and Grip to be used); (4) Provide materials to allow the teams to sketch ideas and ultimately present those sketched ideas to the other workshop members.

Step 1: ethical consenting (5 min)

Once the conference attendees sat down in the workshop room to begin the session, the conference attendees were informed that this workshop was part of a PhD research project. An overview of what the study intended to accomplish was presented and they were given the option to sign the ethics form. All conference attendees completed the ethics form and joined the workshop as participants.

Step 2: previous research and design concepts (10 mins)

Once the workshop began, the participants were asked to perform a practical task with their smartphone, by simply going through the motion of typing a text message. The participants were then asked to stop and look at the grip they used. This initiated a discussion about the different types of grips used when interacting with the smartphone as defined by the ‘interaction type’ study (Chapter 3). I then presented a high-level overview of the quantitative data discovered in the ‘smartphone size’ and ‘body posture’ studies (Chapter 4 & 5). To finish, I visually presented the overall smartphone movement data of lowest to highest for the four grips, body posture, rotational angle, smartphone sizes, the functional area available to the thumb **(Bergstrom-Lehtovirta and Oulasvirta, 2014)** and how the placement of items change the smartphone’s movement (Figure 6.4).

Figure 6.4: Visual images presented of research in Chapter 2, 3 & 4 during the UX Bristol 2017 workshop to give an overview of the collected data

Next, I introduced the participants to four tangible application design concepts that used the movement of the smartphone in four different ways (reachability, movability, predictability and individuality).

A: Reachability

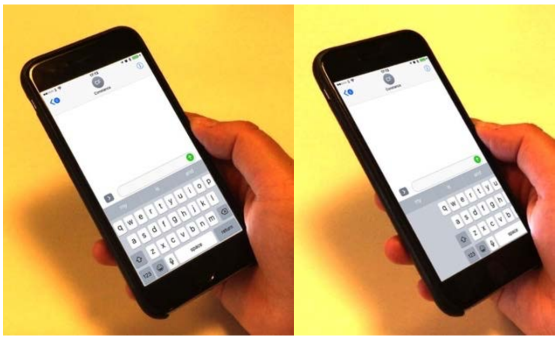


Figure 6.5: Using the subconscious motion of the smartphone to move action items to locations easily reached by the hand (Chapter 3 & 4).

B: Movability

Figure 6.6: Using the conscious motion of the smartphones to control an item on the screen (Yeo *et al.*, 2017)

C: Predictability

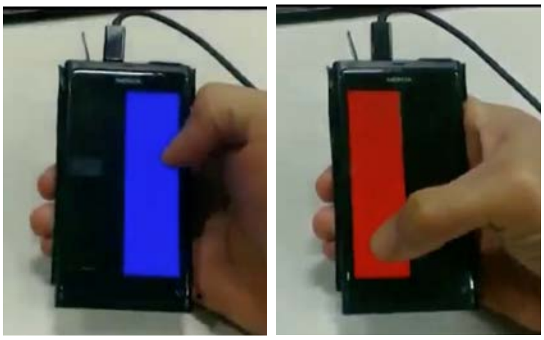


Figure 6.7: Using the subconscious motion of the smartphone to predict which action items the user is trying to select (for single-handed grip only) (Noor *et al.*, 2014)

D: Individuality

Figure 6.8: Using the subconscious motion of the smartphone to update items on the smartphone so the context of use is also broadcast (Buschek, De Luca and Alt, 2015)

Step 3: assigning factors and giving material pack (10 min)

Once I had completed the presentation of previous academic research and relevant design concepts, I grouped the 20 participants into four tables and a total of eight teams (two per table). Each table had two of the prefilled eight envelopes, one striped and one dotted. The two teams selected one at random (Figure 6.3). I then explained the contents of the envelopes and the participants were introduced to how to use the materials to start their exercise.

Step 4: design and present new screen interactions (35 min)

Each team was provided with A3 paper and pens and asked to sketch their ideas. The design stage ultimately concluded with each team presenting their ideas to the other workshop participants (see figure 6.9 for an example of these sketches).

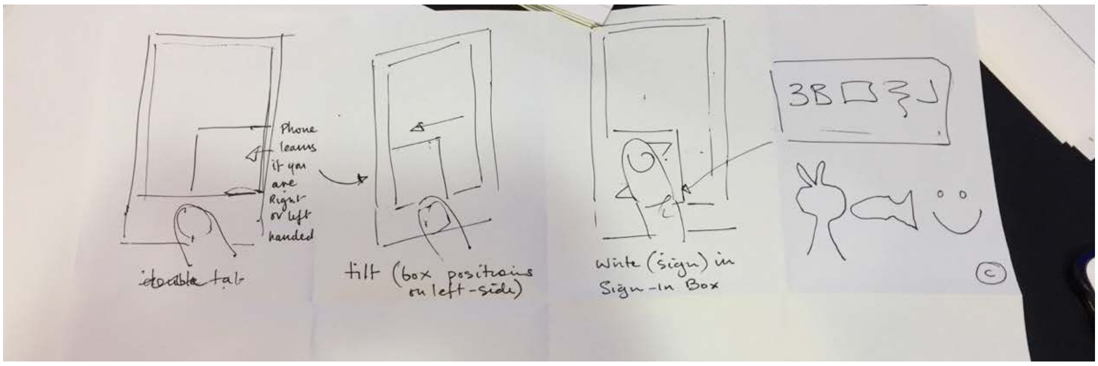


Figure 6.9: Example of outcomes from a team for the re-design application design session.

6.3.4. Participants

20 participants (11 Male and 8 Female) attending the UX conference chose to join the workshop. All participants were professional UX or UI designers with an interest in smartphone interaction (figure 6.10).

Figure 6.10: Participants at the UX Bristol 2017 workshop

6.4 Findings

The workshop resulted in a total of 21 concept sketches. This included 12 sketches for the messaging scenario that resulted in six concepts and nine sketches for the security scenario that resulted in six concepts. I used affinity diagramming to categorization the sketches into seven different themes (three for “messages” and four for “security”).

6.4.1 Messaging

The three themes created from the concepts for the messaging scenario included; (1) Movement as a form of action (with two concepts); (2) Updating the UI to reduce movement (with two concepts) and (3) Accessibility (with two concepts).

1: Movement as a form of action

Two concepts used the smartphone’s movement in order to control items on the screen. The first looked at creating images to send via messaging and used the idea of moving a paint brush with the tilt of the device to permit the user to draw single-handed (figure 6.11).

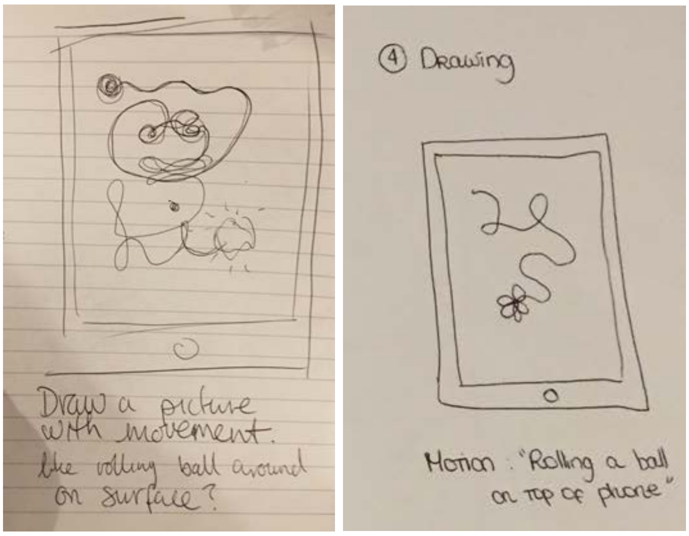


Figure 6.11: Two sketches of drawing an image single-handed with the movement of the smartphone

For the second concept, the workshop participants use the tilt of the smartphone to change the application mode or make additions to the message. e.g. tilting the smartphone to the left or right in order to change the keyboard content (figure 6.12).

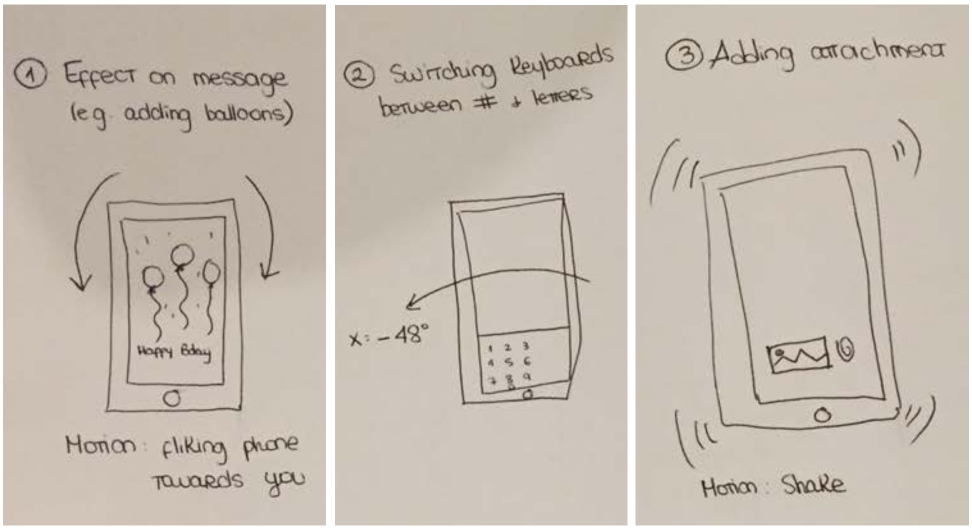


Figure 6.12: Three sketches that update the application using the tilt of the smartphone

2: Updating the UI to reduce movement

Two concepts updated the location of interactive action items to reduce the distance that the hand is required to reach. The first concept moved UI action items on the screen so that they were within easy reach of the hand, therefore reducing movement (figure 6.13).

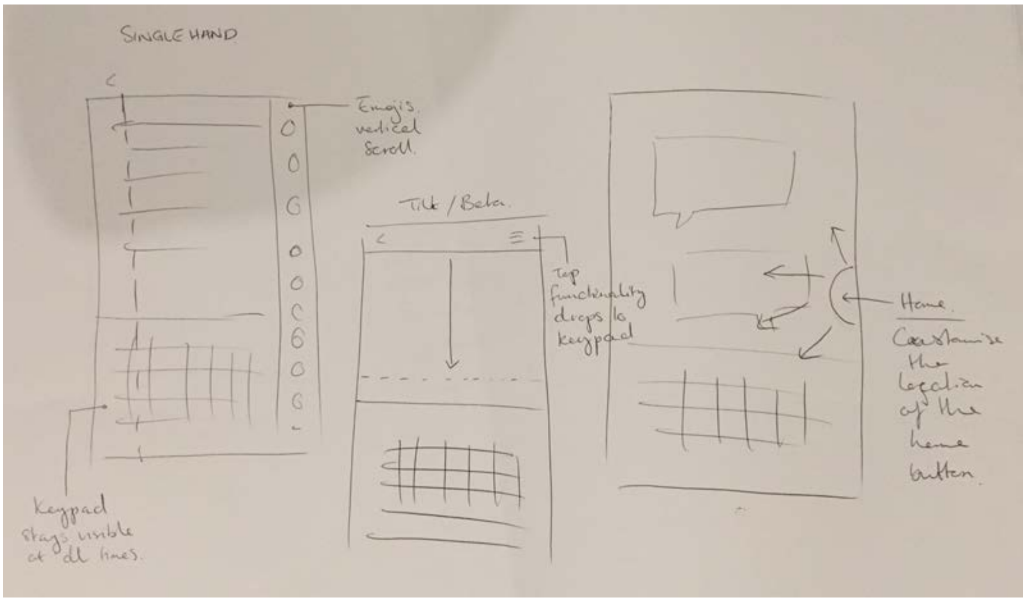


Figure 6.13: Three sketches on how the UI could be updated to reduce movement

The second concept for updating the UI added a dynamic twist, in which interactive elements would revealed due to the movement of the smartphone, sliding within reach of the hand and thumb, in a manner dependent on the action item’s frequency of use (figure 6.14).

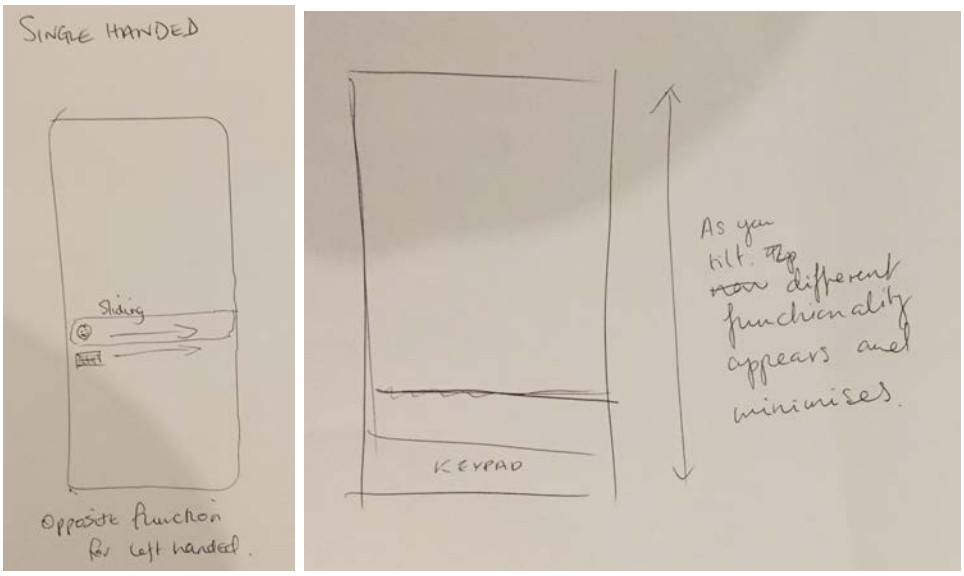


Figure 6.14: Two sketches showing a dynamic element to how the UI could be updated depending on the hands reach

3: Accessibility

One workshop team believed that the motion of the phone could help individuals who have accessibility issues. They created two concepts. The first concept used the tilt of the smartphones to control audio playback of the messages received (e.g., Tilt smartphone towards user to play the next message) (figure 6.15).

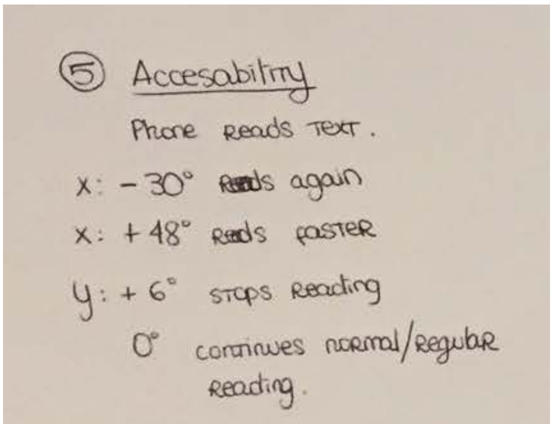


Figure 6.15: Concept of tilting the smartphone so that the user can control the audio playback

The second concept looked at how the movement of the smartphone could enhance UI elements, here enlarging an element on the screen so that the text is more visible (figure 6.16).

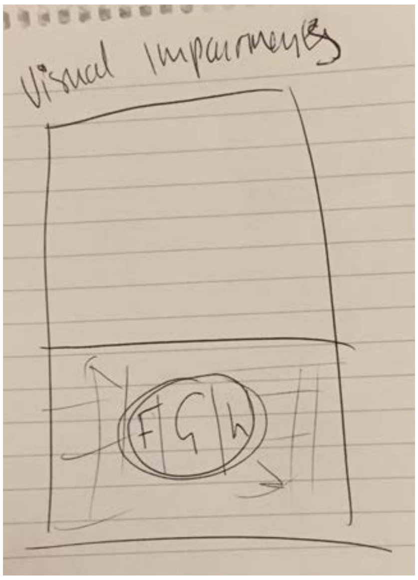


Figure 6.16: A lens that enlarges the elements on the screen with its position controlled by the movement of the smartphone

6.4.2 Security

The three themes created from the concepts for messaging included; (1) Randomization (with 2 concepts); (2) Functional area of the thumb (with 2 concepts) and (3) Mechanical (with 2 concepts).

1: Randomisation

Two concepts randomized the number positions, in order to confuse the PIN tracking software. The first kept to the same button layout as is customarily used today. However, the numbers were randomized (Figure 6.17a). The second concept again randomizes the numbers. However, these are presented in a circular format (Figure 6.17b). Both of these concepts would slow the user down when entering the PIN. However, it would be impossible to guess the PIN code through the smartphone's movement.

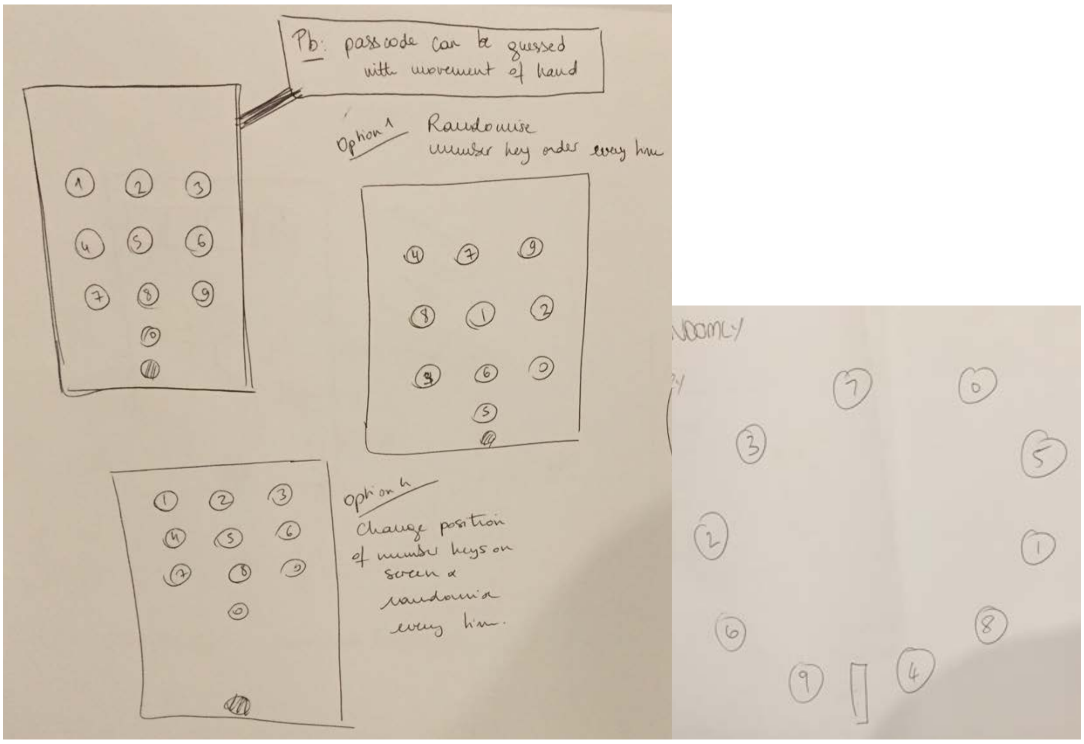


Figure 6.17: Randomizing the numbers so that you cannot predict the PIN code being entered

2: Functional area of the thumb

For the functional area of the thumb **(Bergstrom-Lehtovirta and Oulasvirta, 2014)** the participants came up with two concepts. The first placed the number keypad in a random order, but within the functional area of the thumb **(Bergstrom-Lehtovirta and Oulasvirta, 2014)**. This concept would, due to the button placement, reduce the movement of the smartphone. Because of the randomization of the numbers, it would also make it impossible to guess the PIN code from the motion of the device (Figure 6.18).

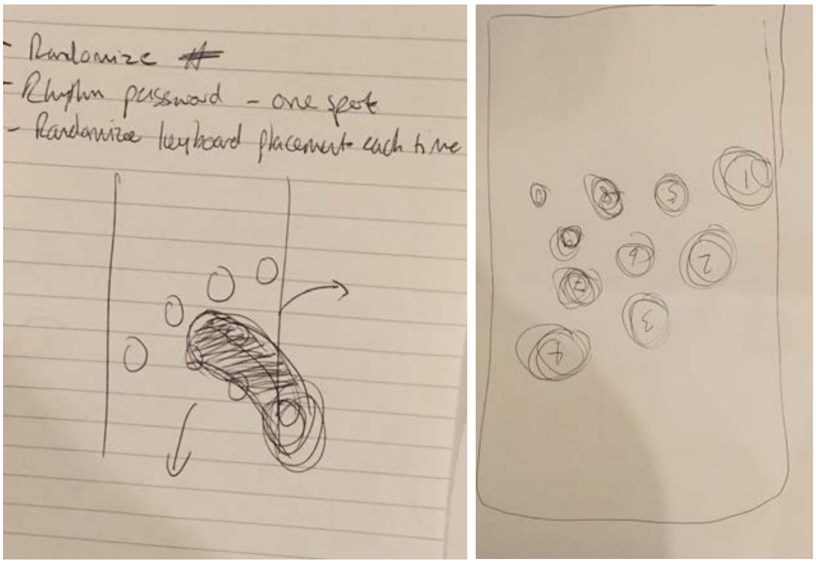


Figure 6.18: Concept where the numbers are randomized and placed within the functional area of the thumb

The second concept had the security code transformed from numbers to symbols, using gestures to input their security code. Again, the input areas are within the functional area of the dominant hand's thumb **(Bergstrom-Lehtovirta and Oulasvirta, 2014)**, reducing the movement of the smartphone (Figure 6.19).

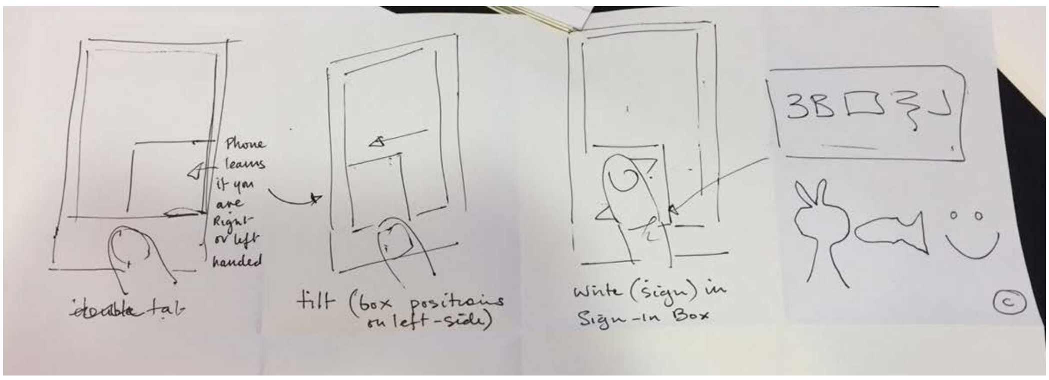


Figure 6.19: Concept where the numbers are randomized and placed within the functional area of the thumb

3: Mechanical

Two slightly different concepts were developed based on analogy to a mechanical lock. The first allowed you to select a number by swiping left or right and then tapping to confirm that number (Figure 6.20a). The second concept allowed you to rotate the numbers as if it were a bike lock (Figure 6.20b).

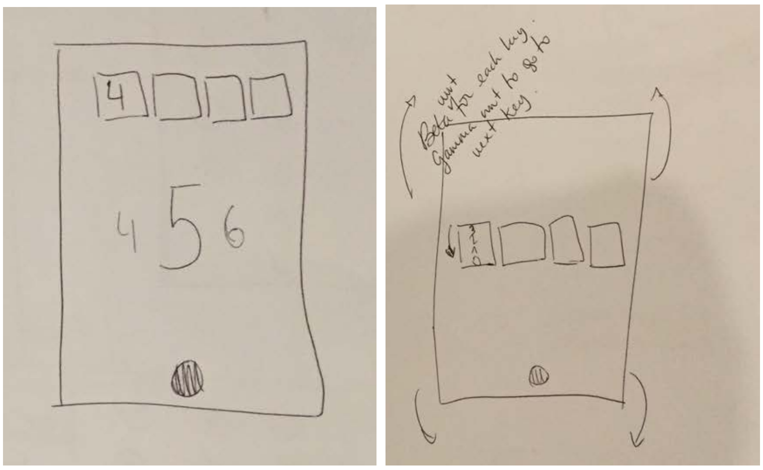


Figure 6.20: Concept showing how you can enter a pin code as if you are interacting with a physical dial padlock

6.5 Conclusion

In this chapter I questioned how the research gathered in Chapters 3, 4 and 5 can enable UI designers to create user interactions, based on an understanding of the movement that occurs during smartphone interaction. To do this I created a number of data cards (Figure 6.1 and 6.2) and presented further additional qualitative data to UI designers in a visual manner (Figure 6.4). I specifically narrowed the designs around two applications to understand what types of concepts the UI designers would develop and to ease analysis.

6.5.1 Messaging application

Looking at the concepts developed for the messaging application, the workshop participant designs went beyond the idea of using a keyboard to enter information. Firstly, a design proposed using the deliberate tilt of the smartphone to manipulate a paint brush creating custom images to send as a message (Figure 6.11), an interaction concept similar to **(Yeo *et al.*, 2017)**. Secondly, a more aggressive form of using the smartphone tilt was conceptually used to add characteristics to the messages, alter the keyboard mode and add attachments (Figure 6.12). Thirdly, the functional area of the thumb **(Bergstrom-Lehtovirta and Oulasvirta, 2014)** and the hand's reachability (Chapter 3 and 4) were used to re-design the placement of interactive elements on the smartphone screen (Figure 6.13 and 6.14). This permitted moving these interactive elements on the screen so that they were closer to the thumb's range on the dominant hand. The placement of these interaction areas was proposed to be defined statistically or dynamically based on the tilt of the smartphone or the predictability as shown by **(Noor *et al.*, 2014)**. The final concepts considered accessibility, enabling those with limited vision to play back audio messages with a directional tilt (Figure 6.14) and using the screen and a deliberate tilting gesture to enlarge an interactive element both visually and in terms of the active area (figure 6.16).

6.5.2 Security application

Inspired by the research of **(Mehrnezhad *et al.*, 2018)** who identified the security issues that simply entering a PIN code can have with the unconscious movement of the smartphone, I asked the workshop participants to create concepts that could reduce this identified security risk. The workshop participants did this, firstly, by randomizing the numbers (Figure 6.17) so that the movement of the smartphone could not be linked to a specific number, a concept that would cause a great deal of cognitive load on the user. The randomization concept additionally considered randomizing the area on the screen in which the buttons appeared, changing the movement of the smartphone each time. Secondly, as with messaging, the functional area of the thumb played a large part in the design concepts **(Bergstrom-Lehtovirta and Oulasvirta, 2014)**, with concept Figure 6.18 not just using randomization for the number order but also placing these numbers within the reach of the thumb. The concept Figure 6.19 again used the same location, however, the team proposed that gestures would be used, rather than randomizing the number keyboard. The final concept (Figure 6.19) used the metaphor of a pad lock to hide the PIN code input, using either gesture or movement of the smartphone to select the required number.

6.5.3 Body posture and grip use

During the workshop, the participants were asked to note, alongside the concepts they were developing, the grips (shown in Figure 6.13 and Figure 6.14) and body posture that they expected would be used. However, this was not communicated as a necessity and the groups did not do this activity. I discovered this limitation issue during the analysis phase when I questioned how the concepts related to the grips and body posture. Consequently, two sections for both 6.4.1 Messaging (Accessibility and Movement as a form of action) and 6.4.2 Security (Mechanical and Randomization) could not be fully analyzed.

From visual analysis, I have interpreted that the workshop participants designed these concepts (Figure 6.13, Figure 6.14, Figure 6.18, Figure 6.16) for the single-handed grip. What these concepts have in common are that the UI elements are maneuvered or placed to be within the functional area of the thumb **(Bergstrom-Lehtovirta and Oulasvirta, 2014).**

6.5.4 Next steps

Although the workshop was a success in creating a number of conceptual interaction designs when considering the smartphone as a physical entity, there were a number of methodological issues that caused substantial problems in the analysis of the data in terms of grip or body posture used. The first, noticed during analysis, was the lack of a participant annotation stating the grip or body posture envisaged to be used, and secondly, noted during discussion after the workshop, the use of the four sided die to randomize the grips, with participants unsure of their use and instead picking their preferred grip. Alongside these notable issues, I believe that further investigation, is needed to understand if there was any overarching consistency in how the workshop participants created these concepts. This inspired a second round of workshops that focused specifically on the grip or body posture, allowing the workshop participants to select their own application and ways of interacting. This workshop is presented in (Chapter 7). To counteract the first workshop's methodological issues, I firstly created work sheets for this workshop that had the grip and body posture at the top to be circled (Figure 7.2) and structured the workshop so that the participants were presented with a grip or body posture and then systematically taken through each of the corresponding body postures or grips during the workshop.

Chapter 7: Understanding the design possibilities

Findings described in this chapter were published in the proceedings of DIS 2018.

In this chapter, I present the final study of this PhD research. The second round of design workshops follows on from the Chapter 6 workshop. This workshop focuses on specific grips or body posture allowing the participants to select the application to design.

The research question for this chapter:
How can we design interactive, handheld objects for the user's hand interaction?

7.0 Introduction

This final study questions UI design considerations specific to the individual grips and body postures that a user might adopt when using a device. Unlike the workshop in Chapter 6 that looked at how the research from Chapters 3, 4 and 5 could be used to re-design specific smartphone applications, the two workshops in this chapter investigate if any design considerations emerge from the choice of grip or body posture used by the individual. The first workshop is focused on one of four grips (single-handed, symmetric bimanual, asymmetric bimanual with the thumb and asymmetric bimanual with a finger) as defined in Chapter 3 when used in three different body postures. The second workshop is focused on one of three body postures (Sitting at a table, standing and lying down) as defined in Chapter 5 when holding the smartphone in four different grips.

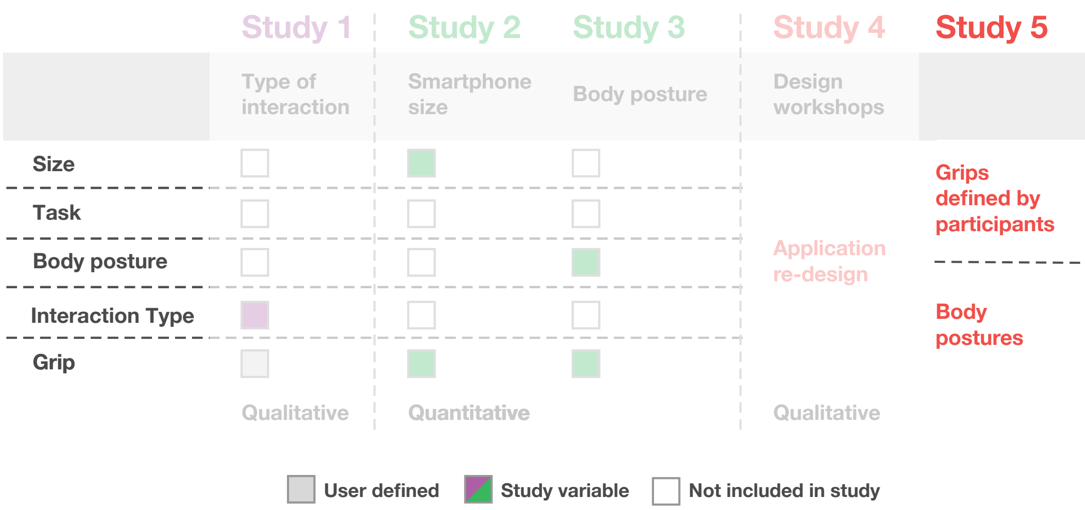


Table 7.1: Variables of study 4 design

By conducting these two workshops, I question if using a specific grip or body posture raises individual design requirements that can help inform professional UX designers. I approached this question by combining the sketches completed from both workshops (a total of 60 sketches). For example, as shown in Table 7.2, the two workshops produced a total of four sketches for the single-handed grip and the standing body posture combination. Through this combination of the sketches drawn from the two prior workshops, I created five themes showcasing different UI smartphone interactions. These have been defined from the research in Chapters 3, 4 and 5.

7.1 Experimental Design

After completing the workshop in Chapter 6, I understood that using the research findings from Chapters 3, 4 and 5 enabled the UI designers to think differently about smartphone application design. However, what the workshop in Chapter 6 did not provide is an understanding of how the grip types and body postures may individually influence smartphone UI design requirements. Therefore, I continued the research with two new workshops. In these, I asked participants firstly, in a ‘fixed grip’ workshop, to specifically focus on a handgrip and secondly, in a ‘fixed body posture’ workshop with the participants, to design specifically for one body posture.

These workshops focused on the grip and body posture data (Table 5.3) and left open the output of the design sessions to the participants. The two separate design workshops, firstly, focus specifically on the four different grips (“Fixed Grip”), and the second focused on the three different body postures (“Fixed Posture”). The “Fixed Grip” design session asked 13 participants to focus on one assigned hand grip (within the four shown in Figure 7.1), designing for three different body postures (Figure 7.1). In the second design session, “Fixed Posture”, nine participants focused on one of the body postures, designing for the four different hand grips. The body postures and grips were chosen based on previously gathered empirical data, on which participants of both design sessions (Fixed Grip & Fixed Posture) were thoroughly briefed (Chapter 5).

7.2 Methodology

The goal of the two 60-minute design workshops was to validate the value of previously gathered empirical data by asking designers to use this data and develop new screen-based interaction design concepts. I asked participants to focus on one assigned hand grip and design for three different body postures (Figure 7.1a). In the second workshop, participants focused on one assigned body postures, designing for the four different hand grips (Figure 7.1b). The postures and grips were chosen based on my previously gathered empirical data, on which participants of both workshops were thoroughly briefed (Chapter 3 and 5). I split the workshops into two, avoiding presenting too many conditions to the participants and reducing the overall workshop duration. Ethics for these workshops were applied for and granted through the university ethics board.

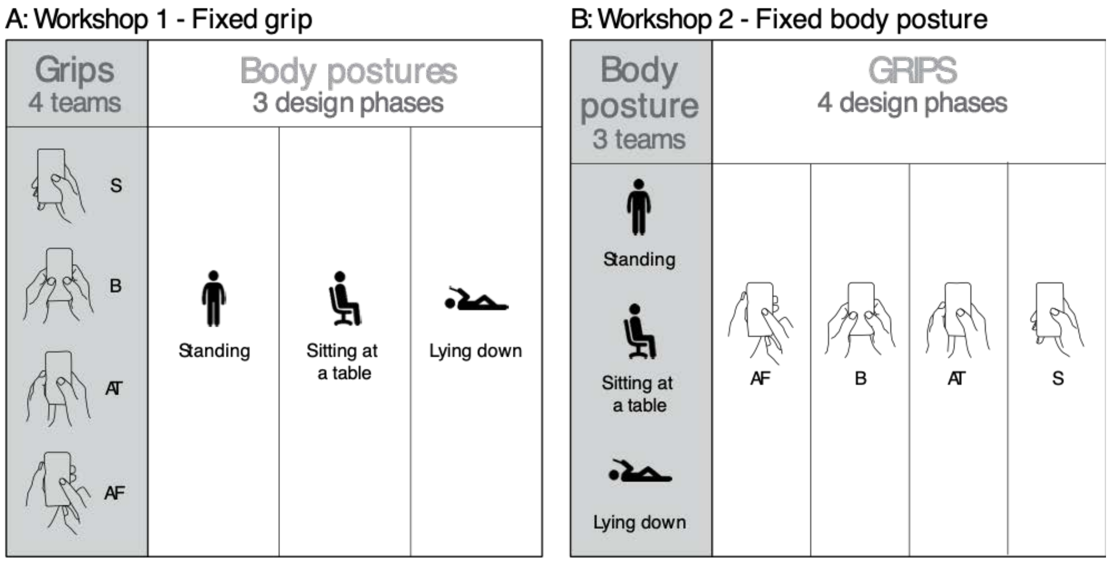


Figure 7.1: A) Showing the four individual handgrips assigned to one of four teams (From chapter 3) and the body postures they designed for. B) Showing the three individual body postures assigned to one of three teams (drawn from chapter 5) and the hand grips they designed for.

7.2.1 Material pack

Each team of participants were given a material pack described below.

Prototype material

To enable the participants to consistently communicate their interaction concepts, I supplied them with (1) A physical model of the iPhone 6 (Height 138.1mm x Width 67mm x Depth 6.9mm) constructed out of foam board with the target locations used previously printed on a transparent cover; (2) Printed A4 sheets with four smartphone templates for sketching screen concepts, annotating the concepts and indicating body posture and grip that the participants were designing for; (3) number cards used for team splitting (described further); (4) a pen (Figure 7.2);

Data cards

Using the data gathered from Chapters 3, 4 and 5, I created two types of data cards. The first showed the rotational movement and have been previously presented in Figure 6.2 and explained in 6.2. Presenting the data (to view a full set of these cards, please see Appendix C.1). The second totalled seven cards (four handgrips and three-body postures) presenting the overall movement data for a specific body posture or handgrip (figure 7.3).

Overall movement

The overall movement showed statistical data comparing the body postures/handgrips (Figure 7.3 and Appendix D.1). Quantitatively, this highlighted which of the “body postures” or “hand grips” had the most movement. This also identified the direction of the movement in terms of Alpha, Beta and Gamma and the qualitative data showing the feeling of grip security, the comfort of grip and the preferred body posture or handgrip.

Figure 7.2: Prototyping material given to each team.

In summary, I gave each team a total of four or five cards depending on the workshop type: three body posture cards plus the overall data cards in the “fixed grip”; four hands grip cards plus the overall data card in the “fixed posture” workshop.

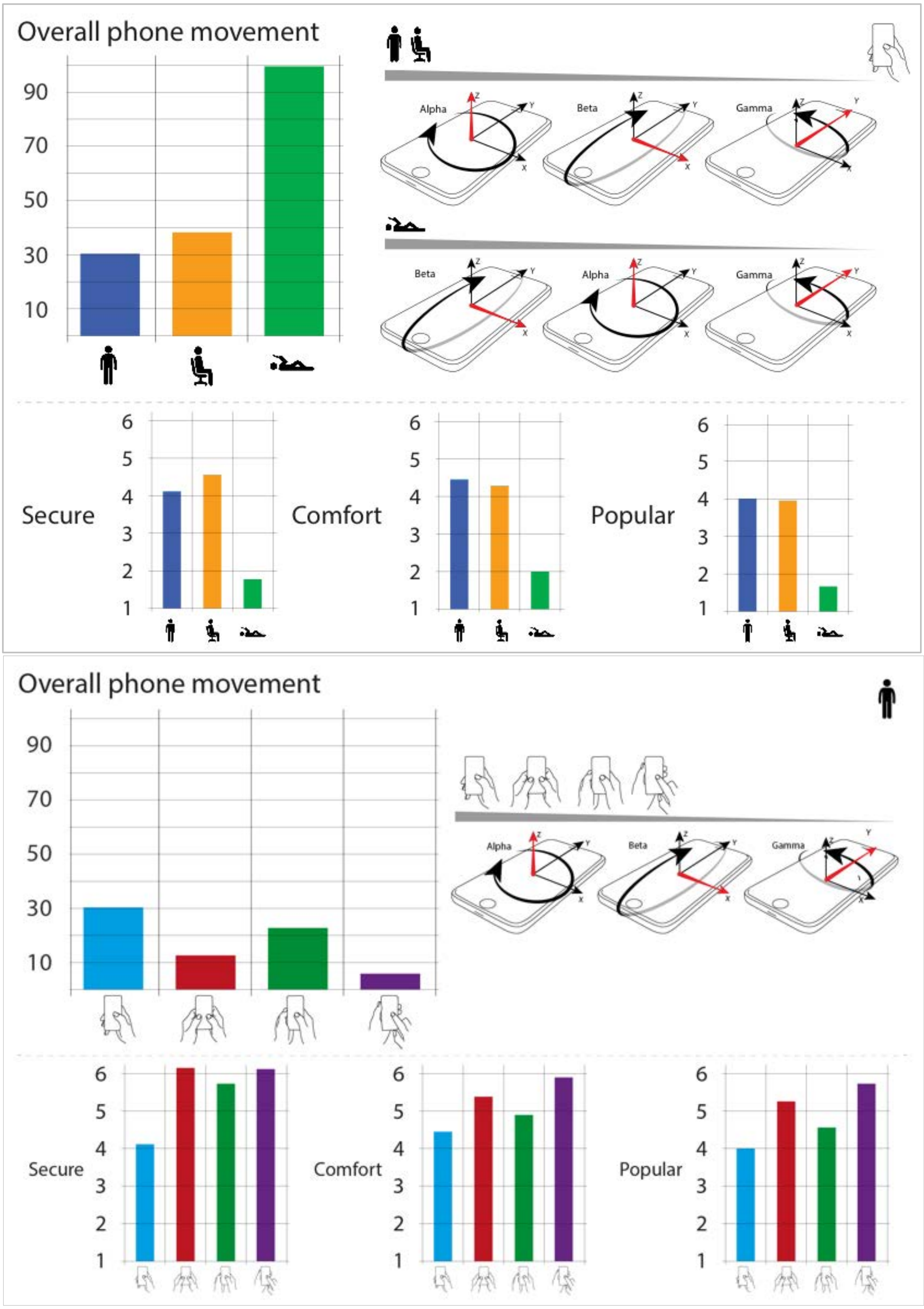


Figure 7.3: Example of the overall movement for teams assigned "Single-handed" grip and "Standing" body posture.

7.2.2 Participants

22 participants studying product design at the same university with mixed levels of education attended one of two, 60 min, design workshops.

Fixed Grip workshop: 13 participants (12 male and one female) including five masters' students, four third year and four second year product design students.

Fixed Posture workshop: Nine participants (six male and three female) including four master's students, three third year and two second year product design students.

Fig 7.4: Participants attending the workshop discussing designs ideas within their teams.

7.2.3 Workshops structure

Each workshop lasted for 60 minutes and was broken up into five steps:

Step 1: organizing the participants (5 min)

Participants were organized into teams. This was done by asking the participants of each academic year to randomly pick a card with a number between one and four printed on it for the "fixed grip" and one and three for the "fixed posture" workshop (Figure 7.2). The numbers corresponded to each participant's team, ensuring that each team contained a mixture of academic levels.

Step 2: informing participants of previous research (15 min)

Participants were asked about their average daily smartphone usage and the types of applications used on an average day. The discussion then transitioned to locations where the smartphones were used, culminating in conversations centred on the body postures participants adopted for various applications or contexts. Additionally, I asked participants to list the top three applications they used on a standard day, with the discussion serving the additional purpose of bonding and relaxing the group. Next, I asked each participant to imagine writing a text message on their phone. They were then asked what type of grips they used. This exercise was conducted to facilitate a discussion with all participants about different grip types (Figure 7.1B). At this point, the teams were informed about the researchers' previously gathered metrics on smartphone body postures and grip types and told that they would be given this data to work from in the form of a 'material pack'.

Step 3: assigning factors and giving a material pack (10 min)

Each team was handed a material pack that defined the grip/body posture that they would design for. The 'fixed grip' workshop participants had three body posture variables to design for: Standing, Sitting at a table and Lying down. The 'fixed posture' workshop participants had four grip variables to design for: Single-handed, Asymmetric bimanual with a finger, Asymmetric bimanual with a thumb, Symmetric bimanual.

Step 4: designing new UIs (45 min)

Each team was asked to design an existing application chosen from the top three applications listed in Stage 2. Next, they were asked to create new screen interaction concepts for the application they selected using the material pack's data. Finally, they were asked to sketch the interaction design and circle the body posture and grip they were designing for at the top of their sheet (See top of Figure 7.5). Participants were encouraged to assume the body posture and, if possible, use the selected application on their smartphone to inform their design process.

Step 5: presenting new UIs (15 min)

When the team finished their designs, they presented their interaction design concepts to the rest of the design workshop participants.

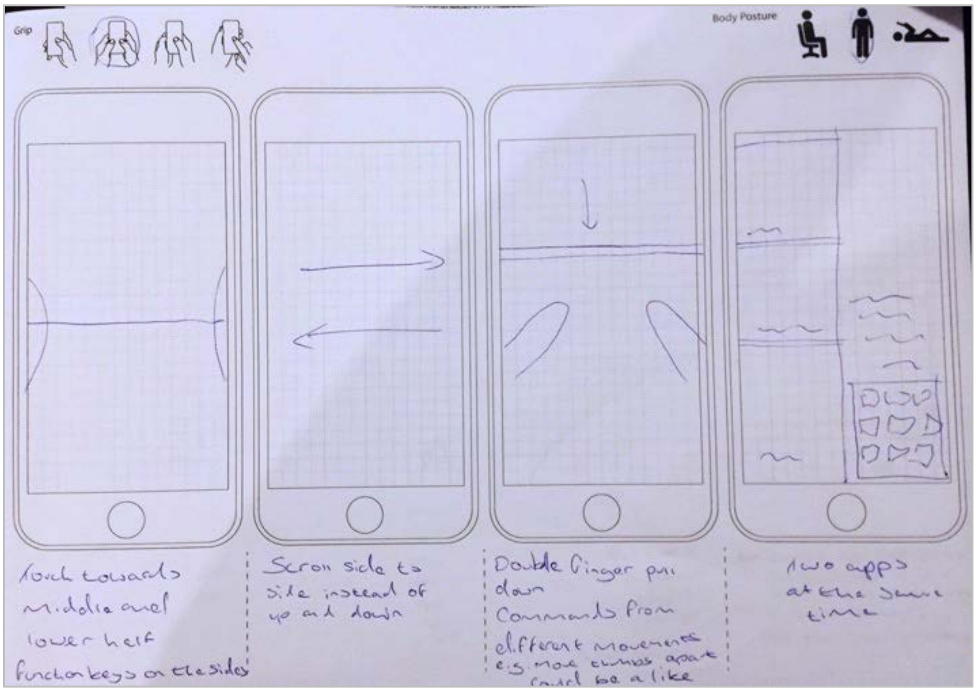


Fig 7.5: Example of outcomes from a team for the Grip “Symmetric bimanual” and the Body posture “Standing”.

7.3 Findings

I describe and analyze the results of the two workshops, but first, I explained how I analyzed the sketches made by the participants. I then analyze the results by theme, body posture and hand grips.

7.3.1 Analysis of sketches

Of the 63 individual sketches produced, three were discarded as being out of scope: Two sketches were discarded as they presented the scrolling of a smartphone in landscape mode. As argued in Chapter 3 (3.3.2 Reach movements), this was out of scope for this research. In addition, one sketch used eye-tracking to select action items, which was also considered out of scope for this research as I focused on the findings of Chapter 3, the tilt and rotation of the smartphone.

As shown in Table 7.2, the 60 sketches produced by the participants provided a mean of five sketches per grip/body posture (Appendix D.2 and D.3). With grip AT and body posture sitting at a table having the least (two sketches) and grip S and body posture lying down having the most (eight sketches). Next, the 60 individual sketches were coded on interaction methods and then categorized into groups following the affinity diagraming method **(Huang., 2015)**, resulting in five themes that ranged from placement of action items to using the phone’s movement to change the current app. During the categorization process, I also looked at how variation in grips or postures affected the designs and any trends and then solidified the concepts and created visuals for them.

	Standing	Sitting at table	Lying down
Single handed	4	5	8
Asymmetric bimanual with thumb	4	2	5
Asymmetric bimanual with finger	6	5	5
Symmetric bimanual	6	6	4

Table 7.2: Overall sketches broken down into grips and body postures.

7.3.2 Results by themes

Six of the seven teams selected the Facebook newsfeed application, and one chose Instagram. Five themes emerged: (1) the placement of buttons on the screens; (2) using the passive movement of the smartphone; (3) using the deliberate movement of the smartphone; (4) layout of information on the screen and (5) areas of the screen having specific types of integration. I now explain these in more detail.

Theme 1: Placement of buttons on the screen

Of 18 initial sketches, three key concepts were formed around the action items being repositioned on the screen to improve reachability. For example, in Figure 7.6, I can see that all of the main action items have been removed from the top bar of the screen and have been placed to fit within the functional area of the thumb **(Bergstrom-Lehtovirta and Oulasvirta, 2014)**. These concepts differed only in the location of the action items (Bottom right/left area of the screen, down the side of the screen and central area of the screen).

By analysing the grips and body postures in which the participants created the sketches for this theme (Table 7.3), I noticed that there was a higher percentage of sketches for Standing (10 sketches) than Lying down (seven sketches) and finally Sitting at a table (three sketches). For the grips, I found that AF and AT had the most (seven Sketches) with B next (three sketches) and finally S (two sketches).

It is worth noting that grip B only had sketches for the UI concept with action items on the side of the screen (Figure 7.6b & 7.6c) and only for body postures Standing and Lying down. Grip S only had sketches for the UI concept with the action items at the bottom (Figure 7.6a) and body postures Sitting at a table and Lying down. For Grip AF, five out of the seven sketches occurred for the body posture Standing, with one each for Sitting at a table and lying down. Most sketches occurred for UI concepts that included moving action items to the bottom right of the screen (Figure 7.6a).

	Standing	Sitting at table	Lying down
Single handed	4	5	8
Asymmetric bimanual with thumb	4	2	5
Asymmetric bimanual with finger	6	5	5
Symmetric bimanual	6	6	4

Table 7.3: Showing how the 19 sketches for Theme 1 mapped between grips and body postures.

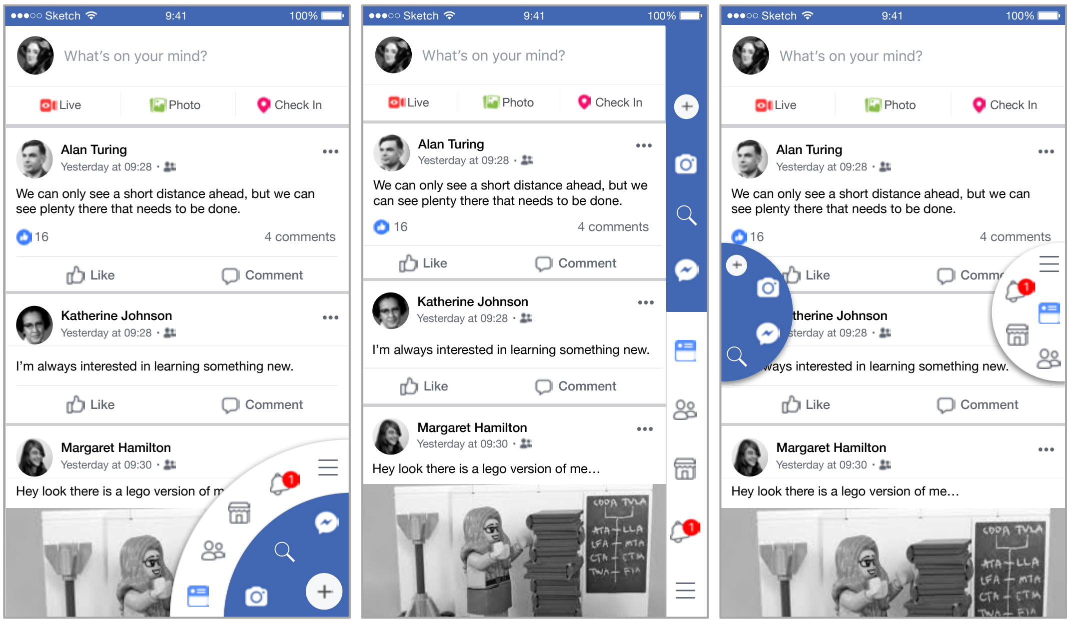


Figure 7.6: Changing the placement of buttons on the screen to improve accessibility for right-handed users (a) Bottom right (b) Right side and (c) Middle.

Theme 2: Passive movement of the smartphone

Eight sketches centred on two key concepts formed around the passive movement of the phone, similarly to TiltSlide by Chang et al. **(Chang 2005)**. The first group had the action items moving around the screen to relocate to a more reachable area, while the second enlarged the action items, so they were easier to tap.

	Standing	Sitting at table	Lying down
Single handed		2	
Asymmetric bimanual with thumb	1	1	
Asymmetric bimanual with finger		3	1
Symmetric bimanual	1		

Table 7.4: Showing how the nine sketches for Theme 2 mapped between grips and body postures

For example, in Figure 7.7a, as the user tilts the phone up in order for their thumb or finger to reach the top action items, the action items will transition to the bottom of the screen for easier reach. For Figure 7.7b, the same tilting action occurs. However, in this case, the action item's visual representation and touch area expand, making it easier for the user to complete their intended task.

Looking at the grips and body postures of the sketches (Table 7.4), I found that the body posture Sitting at a table was the most popular (six sketches), followed by Standing (two sketches) and finally Lying down (one sketch). AF was the most popular grip (four sketches). Grip S only accounted for one moving action item concept for the body posture, sitting at a table while sketches for grips AF and B showed UI concepts involving expanding action items with a mixture of body postures.

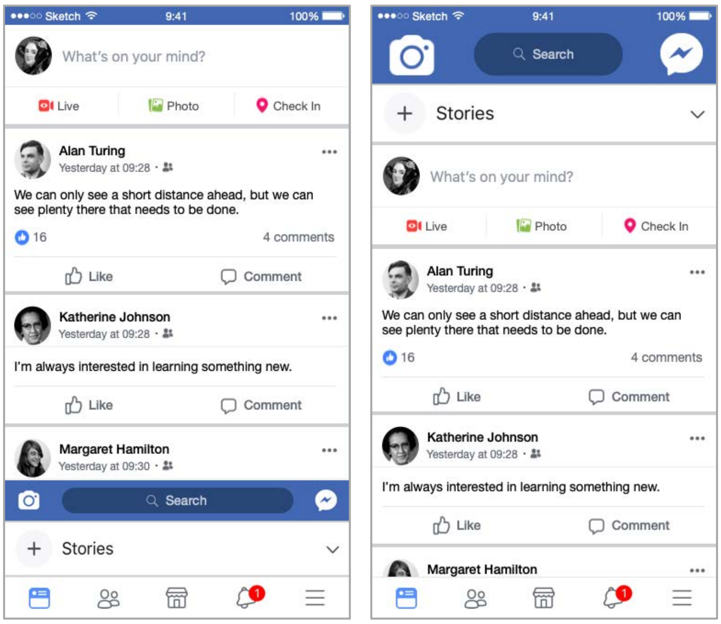


Figure 7.7: Concepts for passive movement updating the UI

Theme 3: Deliberate movement of the smartphone

13 sketches focused on three key concepts enabled via the smartphone's inbuilt sensors. The first aspired to use the physical casing to identify the user's grip or position of the hand and update the screen layout accordingly,

which is a similar concept to that presented by Wimmer et al. **(Wimmer and Boring, 2009)**. The second conceived of a screen-based sensor that traced the thumb's location and located the action items next to it, similar to previous research undertaken by Hinckley et al. **(Hinckley et al., 2016)**. Finally, the third set of concepts used the smartphone as a physical gesture device so that deliberate manipulation of the phone would update the functionalities of an application or switch the application itself.

Figure 7.8a illustrates a concept whereby when a user picks up the smartphone, and the action items appear automatically within reach of their hand, no matter how or where they are gripping the phone. The concept in Figure 7.8b moves action items close to the thumb's contact point based on its proximity to the screen. Finally, in Figure 7.8c, I see a concept with the user flicking the smartphone to reveal the action items via a pop-up box.

Body posture Lying down accounted for most sketches (6), with Sitting next (4) and Standing (2). Next, all grips were included, with B and S having the most sketches (4), followed by AF (three sketches) and finally AT (two sketches).

	Standing	Sitting at table	Lying down
Single handed	2	1	1
Asymmetric bimanual with thumb			2
Asymmetric bimanual with finger		1	2
Symmetric bimanual		3	1

Table 7.5: Showing how the 13 sketches for Theme 3 mapped between grips and body postures.

Grip B only had the concept types shown in Figure 7.8b and for body postures Sitting at a table and Lying down. Grip AT concepts focused on the concept types shown in Figure 7.8a and the body posture Lying down. Grip AF concepts were split, with one sketch of the Figure 7.8a type (body posture Lying down) and two sketches of the Figure 7.8c type (body postures Sitting at a table and Lying down).

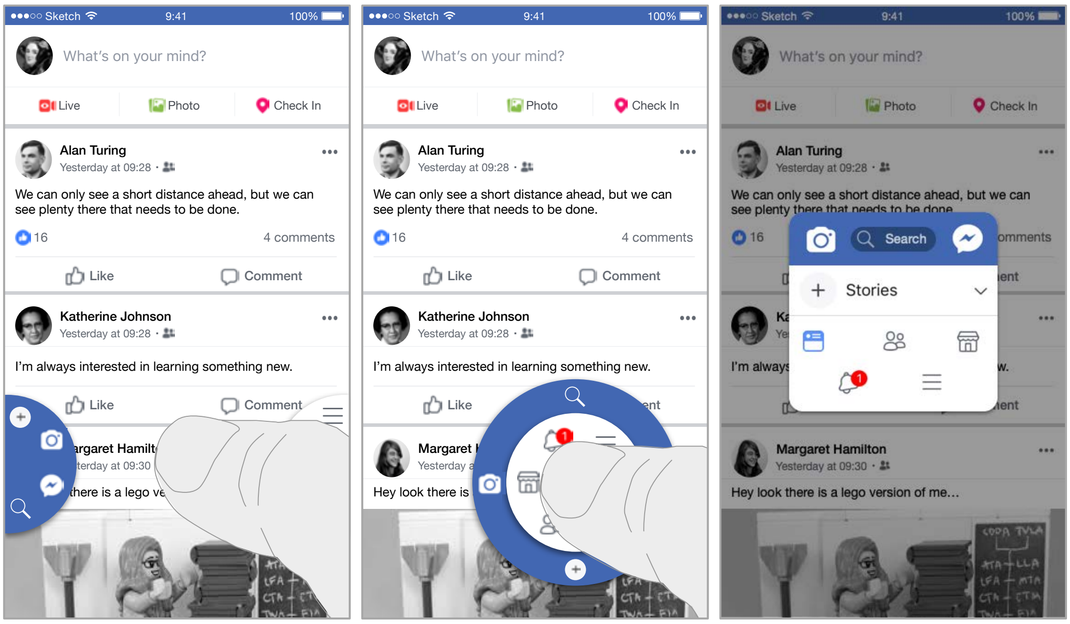


Figure 7.8: Concepts for physical sensors (a) Action items move position depending on the grip (b) Action items position dependent on the location of the thumb (c) Deliberately tilting the smartphone brings the action items on the screen

Theme 4: Layout of information on the screen

Based on the screen layout, the eight concepts produced in Theme 4 can be grouped into three key concepts. The first uses the phone's internal sensors to tilt screen content according to the angle at which it is being held. The second uses the motions of the phone to present content in the form of a 3D scroll. Finally, in the third concept group, the user taps to trigger a 3D horizontal tilt to scroll interaction.

Figure 7.9a illustrates a UI screen designed for users viewing Facebook via a smartphone while lying down. Instead of the phone transitioning directly from portrait to landscape as currently occurs, this UI has the screen tilt to match the angle at which the user is gripping the smartphone. In Figure 7.9b, a 3D transition occurs when the user tilts the smartphone horizontally, left or right, to change the applications mode or move on to the next application. The third design matched the work done by Oakley and O'Modhrain **(Oakley and O'Modhrain 2005)**, presenting a rotary card layout that was interacted through tilting the smartphone to scroll content on the screen. However, this tilt to scroll interaction had interaction issues with centrally placed cards and the production of extra movement that occurs when the user reaches to interact with content on the screen **(Oakley and O'Modhrain 2005)**.

	Standing	Sitting at table	Lying down
Single handed	1		3
Asymmetric bimanual with thumb			
Asymmetric bimanual with finger	1		1
Symmetric bimanual	1		1

Table 7.6: Showing how the 8 sketches for Theme 4 mapped between grips and body postures.

By analysing the grips and body postures, I see that only Lying down (five sketches) and Standing (three sketches) provoked concepts. The grip that triggered the most ideas was S (four sketches), followed by AF and B (two sketches). Neither the AT grip nor the Sitting at a table body posture provoked any concepts.

The UI concept shown in Figure 7.9a utilises only the S grip and incorporates the body postures Standing and Lying down. Figure 7.9c illustrates the only concept that integrated the AF grip sketches, highlighting scrolling by tilting the smartphone.

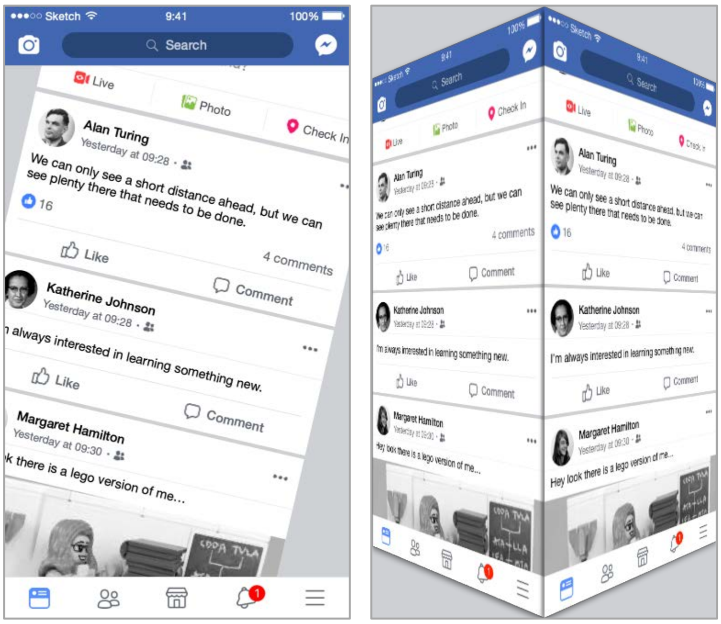


Figure 7.9: Concepts for physical sensors (a) Tilting the content of the screen to its in line with the user's physical position (b) Using the physical gestures to via a 3D effect switch to another application.

Theme 5: Areas of screen with specific types of integration

The 11 sketches in Theme 5 can be categorized as two UI approach types. The first uses a given screen area either as a trackpad (Figure 7.10a) or as a more sensitive display area, allowing the user to scroll quicker (Figure 7.10b). The second splits the screen in half, allowing the separate content for each half of the screen to be scrolled independently (Figure 7.10c).

	Standing	Sitting at table	Lying down
Single handed	1		3
Asymmetric bimanual with thumb			
Asymmetric bimanual with finger	1		1
Symmetric bimanual	1		1

Table 7.7: Showing how the 11 sketches for Theme 5 mapped between grips and body postures.

In Figure 7.10a, I see the user utilising the bottom part of the screen as a touchpad to control a pointer (red circle) to select the required action items. This concept is similar to the ForceRay project by Corsten et al. **(Corsten et al. 2019)**. Figure 7.10b illustrates a concept where the part of the screen within the functional area of the thumb for a right-hand user is made more sensitive. Scrolling in this area speeds up the standard scroll to view the Facebook feed or photos quicker. The third UI concept splits the screen into two halves allowing the user to scroll each independently of the other (Figure 7.10c).

The body postures Sitting at a table and Lying down produced the most concepts (4) while Standing accounted for three concept sketches. Only grip S (5 sketches) and B (6 sketches) provoked concepts.

The concepts displayed in Figures 7.10a and 7.10b worked for grip S and all body postures. The concept illustrated in Figure 7.10c is intended predominantly for grip B, although one concept used grip S and the Lying down body posture.

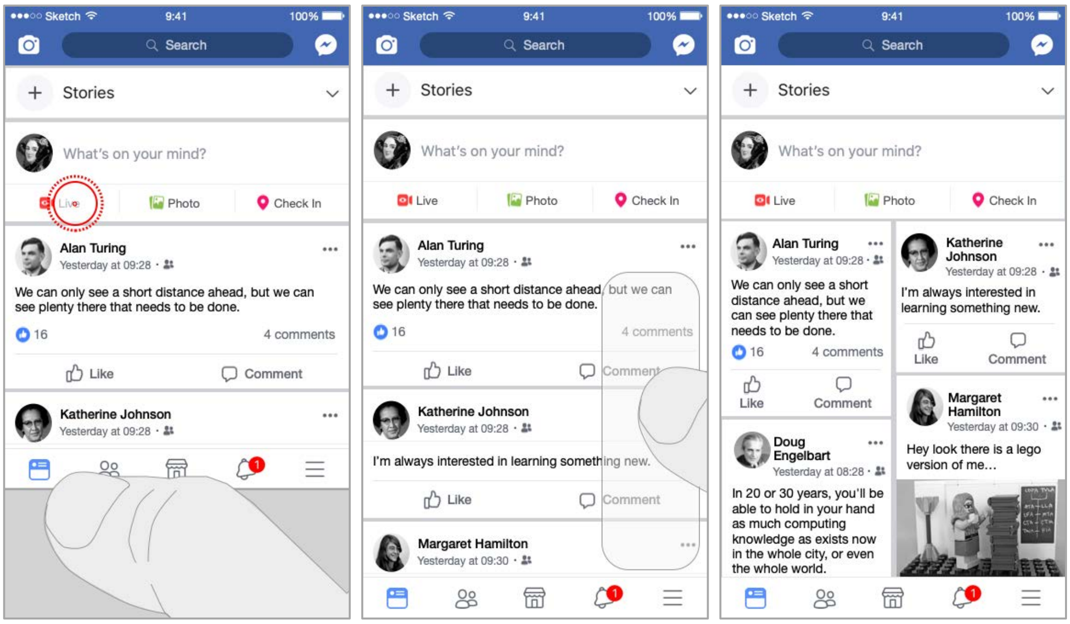


Figure 7.10: Concepts for physical sensors (a) A trackpad-controlled icon shows the selection location (b) Area on the screen shows a more sensitive area for scrolling (c) Split screen content allows for each side of the screen to scroll.

7.3.3 Results by grips and body postures

I analysed the workshop results to identify any key characteristics for individual grips and body postures and made a series of findings:

Grips

Symmetric bimanual

The concepts focused around grip B incorporate four themes. Examples can be seen illustrated in Figures 7.6b, 7.6c, 7.7b, 7.8b and 7.10c. Two key characteristics are true for most of these concepts:

- Action items down both sides of the screen can be used with the corresponding thumb (Figures 7.6c and 7.10c).
- Generic interaction methods allow either thumb to activate the action items (Figures 7.7b and 7.8b).

The odd concept out is Figure 7.6b which has the action items down the side of the screen so it can be accessed via the user's dominant hand rather than both hands at the same time.

Single handed

The concepts related to grip S are Figures 7.6a, 7.7a, 7.9a, 7.10a and 7.10b, which incorporate four themes. These figures show three key sets of characteristics:

- Action items sit within range of the functional thumb and are either placed at or controlled from the bottom of the screen (Figures 7.6a, 7.7a, 7.10a).
- Action items are placed on the dominant hand side of the screen and within the functional arc of the thumb (Figure 7.10b).
- They were designed for single-handed use, utilising the smartphone's in-built sensors to adjust how information is viewed (Figure 7.9a).

Asymmetric bimanual with thumb

The concept sketches associated with grip AT focused on three themes, and are illustrated in Figures 7.6a, 7.6c, 7.7a, 7.7b and 7.8a. These concepts have two key characteristics:

- Action items are placed or are designed to appear near the lower end of the screen within the functional area of the thumb for the dominant hand (Figure 7.6a, 7.6c, 7.7a and 7.8a).
- Action items interactively enlarge to improve reachability (Figure 7.7b).

Asymmetric bimanual with finger

Grip AF concepts cover four themes seen in Figures 7.6a, 7.7b, 7.8a, 7.8c and 7.9c. There are two key characteristics:

- Action items are revealed or maneuvered depending on the activities or physical placement of the non-dominant hand (Figures 7.7b, 7.8a, 7.8c and 7.9c).
- Action items appear in the bottom corner of the screen (Figure 7.6a).

Body posture

Standing

The Standing body posture is included in all 5 themes and concepts can be seen in Figures 7.6a, 7.6c, 7.7a, 7.8b, 7.9c, 7.10b, 7.10c. These figures have three key characteristics:

- Action items that are positioned in or which transition to be within the functional area of the thumb (Figures 7.6a, 7.7a, 7.8b and 7.10b).
- Action items that are positioned on either or both side(s) of the screen (Figures 7.6c and 7.10c).
- The ability to interact with the smartphone’s scrolling functions using its in-built sensors (Figure 7.9c).

Sitting at a table

Sitting at a table is included in four themes with illustrations which can be found in Figures 7.6a, 7.6b, 7.7a, 7.7b, 7.8c, 7.10a and 7.10c. There are 4 key characteristics:

- Action items are positioned or actively transition to be within the functional area of the thumb (Figures 7.6a, 7.7a and 7.10a).
- The movement of the smartphone is used to update the content of the screen either passively or through deliberate user input (Figures 7.7b and 7.8c).
- Action items are positioned on the dominant hand side of the screen (Figure 7.6b).
- Content is split vertically down the middle of the screen, allowing either side to be separately activated (Figure 7.10c).

Lying down

The Lying down body posture is included in all 5 themes and concepts can be seen in Figures 7.6a, 7.6c, 7.7b, 7.8a, 7.9a, 7.9c, 7.10a, 7.10b and 7.10c. There are three key characteristics:

- Action items are within the range of the functional thumb and are either placed, transitioned or controlled from the bottom of the screen (Figures 7.6a, 7.10a and 7.10b).
- The phone's in-built sensors are used to update the controls so they either reachable, within the functional area of the thumb or can control the viewing of information (Figures 7.7b, 7.8a, 7.9a and 7.9c).
- Action items that are positioned on either side of the screen or both (Figures 7.6c and 7.10c).

7.4 Conclusion

As with Chapter 6, these two design workshops used the findings from Chapter 3 and Chapter 5 to investigate how UI designers could design for smartphone interaction with a focus on the physicality of the hand smartphone interaction. However, unlike Chapter 6, where the participants focused on a predefined application, these participants were given either a predefined grip or body posture. The structure of the design workshop allowed for the results of the workshops to be combined so that analysis can be completed to question what differences there might be which are dependent on body posture or hand grip.

We discovered through the sketches created that the participants believed that placing the interactive elements within the functional area of the thumb **(Bergstrom-Lehtovirta and Oulasvirta, 2014)** is key to reducing the movement of the smartphone. The participants used this in the design of the concepts for Theme 1 (Figure 7.6) and Theme 5 (Figure 7.10). The use of the functional area of the thumb can also be seen in Theme 3 (Figure 7.8), however with the added functionality similar to the work by Wimmer et al. **(Wimmer and Boring, 2009)** and Hinckley et al. **(Hinckley et al., 2016)** of the smartphone predicting the participant's grip.

In the next chapter (Chapter 8: Discussion and conclusion), I examined further how these themes, in relation to the grips and body postures, have defined design possibilities of smartphone interactions. Finally, I show in Figures 8.1 and 8.2 areas where UI action items should be placed when designing smartphone interaction for different grips and body postures.

Chapter 8: Discussion and conclusion

In this concluding chapter, I will draw together the overarching work that has formed this PhD research. Which began with understanding the 'Type of interaction' those participants use (Chapter 3) by identifying the grips and movements used to interact with smartphones and how the 'size of the smartphone' (Chapter 4) alters the movement for each grip and participants perception of their interaction. I then investigated how the participant's body posture (Chapter 5) again affects the movements for each grip and the participants' perception of security and comfort. Finally, using these findings, I ran design workshops; that first focused on redesigning an application (Chapter 6), and second looked specifically at the data collected for grips and body postures (Chapter 7).

8.0 Introduction

In this PhD research, I have presented a systematic investigation into how the hand interacts with handheld technology such as the smartphone. Chapters 3 to 5 present three studies. The first questioned how the hand interacts with three different interaction types (touchscreen, stylus and button base). Secondly, I investigated Napier's **(Napier 1993)** claims about hand interaction and device size by studying the effects on the movement of four differently sized smartphones (iPhone 4, 5, 6 and 6 +). Thirdly, I looked at how three different body postures inspired by Bachynskyi **(Bachynskyi et al. 2015)** might act as external factors in the interaction between the hand and the smartphone.

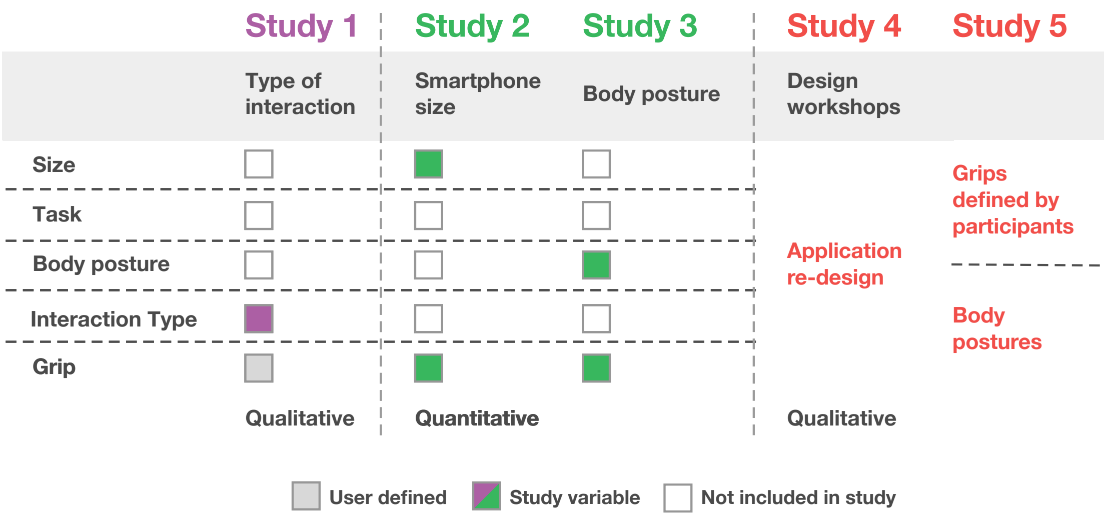


Table 8.1. Layout of approach

I discovered whilst researching Chapters 3 to 5 that the 'type of interaction' (Chapter 3) affects how the hand interacts with the smartphone. With the hand using four different grips to interact with the iPhone 4, I discovered that the 'size of the smartphone' (Chapter 4) affects the hand smartphone interaction, with the larger smartphones requiring the hand to manipulate the devices further so that UI activity items are within reach. For 'body posture' (Chapter 5) not only affects the motion of the smartphone but also the confidence participants report in gripping and interacting with the smartphone.

In Chapters 6 to 7, I used the findings to run two types of design workshops. The first focused on the ‘re-design of the application’ (Chapter 6), and the second focused on the data allowing the workshop participants to decide what they would do with it (Chapter 7).

8.1 Reviewing the research questions

I now look to the initial research questions posed in the research introduction (Chapter 1). In doing so, I can discuss the responses that I have gained during this body of research.

1) **How does the design of handheld interactive devices affect hand interaction?**

As discovered in Chapters 3 and 4, the physical smartphone's design does influence the way the hand interacts. For example, chapter 3 identified that different grips were used for the three smartphone interaction types. In Chapter 4, I discovered that the physical size of the smartphone affects the amount of reach that the participant needs and therefore affects the smartphone's movement.

2) **Do the interaction methods change the way participants use their hands to interact?**

In Chapter 3, I compared three different interaction types (touchscreen, button-based and stylus) when completing a task (sending a text message). The interaction method did affect the handgrip used by the participants. For the touchscreen, four grips were used (S, AF, AT and B); for the button-based device, three grips were used (S, AF and B), and the stylus-based had just one grip used (AS).

3) **Does the size of the handheld interactive object change the way the hand interacts?**

Chapter 4 looked at the movement of four different sized smartphones (iPhone 4, 5, 6, and 6 +) with four different grips (Chapter 3). The size of the smartphone does affect hand interaction. The smaller smartphones (iPhone

4 and 5) require that the hand reach a shorter distance and produce less movement. The larger smartphones (iPhone 6 and 6 +) require a large reach to interact with UI elements at the top corners of the touchscreen.

4) Does the participant's body posture affect the way the hand interacts with the handheld interactive device?

Chapter 5 investigated how a smartphone was interacted with using four grips (Chapter 3) in three body postures (sitting at a table, lying down and standing). The body posture did affect the smartphone's movement, with the body posture lying down being the least preferred and having the most movement for all four grips. In contrast, the body posture standing had the least movement.

5) How can we design interactive, handheld objects better for the user's hand interaction?

In Chapters 6 and 7, I ran design workshops that first asked the participants to re-design an application and, secondly, design concepts focused on the grips (Chapter 3) and body posture (Chapter 5). These workshops produced concepts that changed the location of action items or used a flick or tilt of the smartphone to change UI elements and modes.

8.2 Reviewing the contribution

8.2.1 Type of interaction

The first study (Chapter 3) was inspired by Napier **(Napier 1993)** and his understanding of how the hand dynamically adapts to objects depending on the context of use. I investigated the hand interacted of three different interaction styles (Touch screen, Stylus and Button based) and found five different hand grips used to interact with all three smartphones (figure 3.10). The stylus interaction used one grip, with the non-dominant hand grasping the smartphone and the dominant hand using the stylus (figure 3.13). The button-based interaction used three grips, B, AT and S (figure 3.12), and the smartphone interaction used four grips, B, At, S and AF (figure 3.11).

Using video analysis (please see Chapter 3.2), I identified five types of grips (B shown in Figure 3.14, AT shown in figure 3.15, S shown in figure 3.16, AF shown in figure 3.17, and asymmetrical with a stylus shown in Figure 3.18) for the three types of interaction methods. Additionally, I identified the hand moving the smartphone to reach the action items. It is this movement of the smartphone that I investigated further in Chapters 4 and 5.

Chapter 3 demonstrated that the hand adapts fluidly to the device type and its context of use, such as menu selection or typing on the keyboard through a combination of grips and movements. The next stage of this research was to gather empirical evidence through the device's inbuilt sensors.

8.2.2 Smartphone size

As shown in Chapter 4, I progressed the research findings from Chapter 3, type of interaction, to investigate how size altered the smartphone's movement with the four defined grips (AF, AT, S and B). Focusing on the touchscreen smartphone as this had the greatest number of grips. I selected four smartphones from the same manufacture (iPhone 4, 5, 6 and 6 +) and created an application that defined targets and captured the smartphone's movement during this interaction (Chapter 4.4).

I discovered that the grip with the most movement was S and the least AF. Statistically, the two smaller smartphones (iPhone 4 and 5) had less movement than the larger ones (iPhone 6 and 6+). For the targets within the functional area of the thumb and with smaller distances, 6 and 8 had the least movement, with the non-functional area and largest movement having the most movement. The participants perceived both the AF and S grips as the most comfortable for the iPhone 4 and 5. However, the S grip had mixed feedback, being considered less secure for the iPhone 5, 6 and 6 + and less comfortable for the iPhone 6 +. I belied this was due to the fact that the smaller phones allowed the participant to reach targets using the grip S comfortably. To understand how designers could use these results, I created a number of concepts using insights from the data Chapter 4.12 Design insights.

8.2.3 Body posture

Chapter 5 furthered the research from Chapters 3 and 4, type of interaction and smartphone size, by investigating the four grips and three body postures. Inspired by the research of Bachynskyi **(Bachynskyi et al. 2015)**, I understood that body postures affected muscle usage and could affect hand smartphone interaction. I questioned how smartphone movement with the four grips (AF, AT, S and B) defined in Chapter 3 could change due to the three symmetrical body postures (Standing, Sitting at a table and Lying down). The first body posture matched the data gathering in Chapters 3 and 4, sitting at a table. The second and third were selected due to body support and muscle usage; they are lying down on the back and standing.

I found that the body posture and grip with the most movement were S and lying down, matched the participants' ratings as S and lying down were defined as the least secure, comfortable and popular grip/body combination. The body posture and grip with the least movement was AF and standing, and this grip/body combination was rated as the most comfortable and popular. However, the participants rated the most secure grip/body combination as B and standing. As with the findings for chapter 4, the targets within the non-functional area of the thumb **(Bergstrom-Lehtovirta and Oulasvirta 2014)** produced the most movement (Figure 5.3).

From this data, I created a number of design aids in figure 6.2 (Appendix D.1), figure 6.4 and figure 7.3 (Appendix D.1) that visually highlighted the grip, body posture, participant preferences, and smartphone movement. The next stage of this research was to use these design aids to run several design workshops, as shown in chapter 6 and 7.

8.2.4 Design workshops

To understand how I could use the research findings from Chapters 3, 4, and 5, I conducted two types of design workshops that investigated how designers could first re-design an application and, secondly, design from the data gathered about smartphone interaction. Both workshop types used the findings from the grips in Chapter 3 and the body posture study in Chapter 5.

The re-design of applications

The participants focused on two research areas for the concepts created during the application re-design (Chapter 6). The first is using the identified smartphone movements, and the second is placing the UI components closer to the functional area of the thumb to reduce the smartphone movement.

Three of the themes (2x messaging and 1x security) used the smartphone's movement as a way to interact. Figures 6.11 and 6.16 use the deliberate act of tilt and rotation to move objects around the screen, whereas Figures 6.12 and 6.15 use short sharp gestural movements to act as a mode selector. The security concept (Figure 6.16) uses the smartphone's deliberate movement to alter the UI so that the data collected cannot be tracked. Two themes (1x messaging and 1x security) moved UI elements close to the functional area of the thumb so that the smartphone's motion was reduced, as with these research findings in Chapters 4 and 5. In addition, the concepts Figures 6.13, 6.14, 6.18 and 6.19 moved the navigational and menu items within the thumbs range.

Due to the limitation of the concepts from this workshop, I could not compare the body postures or grips to identify if there were any overreaching interaction themes. Therefore, I decided to run a second round of workshops (Chapter 7) that focused on the data collected in Chapters 3, 4, and 5.

Understanding the design possibilities

When reviewing smartphone UI designs from the workshops in Chapter 7, it needs to be understood that smartphone UI designers have to create designs for many technology platforms (e.g., Apple iOS and Google Android). Whilst part of the design process gives UI designers freedom to create, the relevant platforms' design guidelines somewhat limit them. For example, looking at the Apple iOS design guidelines **(Apple 2020a; 2020b)** and Google Android's material design notes **(Google 2020)**, I find that they have very distinct recommendations for the location of action items, i.e., the top and bottom of the screen. Apple call this top screen area "Navigation/Search bars" while Google refers to it as "App bar/Primary toolbar". Meanwhile, the bottom screen area is named "tab bars/Toolbars" by Apple and 'Bottom bar' by Google. Our participants focused on non-commercial consumer requirements given an open brief to investigate how they might design for the smartphone's movement in terms of grips and body postures.

This work brings a new perspective on smartphone UI design, focusing not just on the screen but also on the devices' physicality. I was aware that this study has limitations as I only focused on certain applications defined by the workshop participants and specific postures, as shown in Chapter 5. Additionally, I need to make sure that I do not ignore the cognitive price that may occur for an ever-changing interface with these new smartphone UI concepts. Automatic changes could be confusing, and further investigation is needed

Insights by themes

ILooking at the five themes in Chapter 7.4.2, we can see that four out of the five categories of concepts adjust the location of action items from the top of the screen area to the sides, bottom or in a dynamic position governed by the thumb's location. Additionally, three out of five themes are designs exploiting extra functionality via the smartphone's internal sensors, which is not currently prominent within the design guidelines.

Insights by grips and body postures

For the grips and potential locations of items, the participants' sketches showed that each grip has a preferred location for items (Figure 8.1). We can see that this means having items down either side or at the bottom of the screen for the B grip. For the AT grip, action items should appear down the dominant hand's side and on the lower part of the screen. The S grip is similar but with a smaller action area at the bottom of the screen. In contrast, the preferred area with the AF grip is the lower corner of the dominant hand's side of the screen.

When it came to body postures, both Sitting at a table and Lying down positioned action items down the sides and bottom of the screen. However, the action items differed for Standing (Figure 8.2), with the preferred action items location being down the side of the dominant hand and on the lower part of the screen.

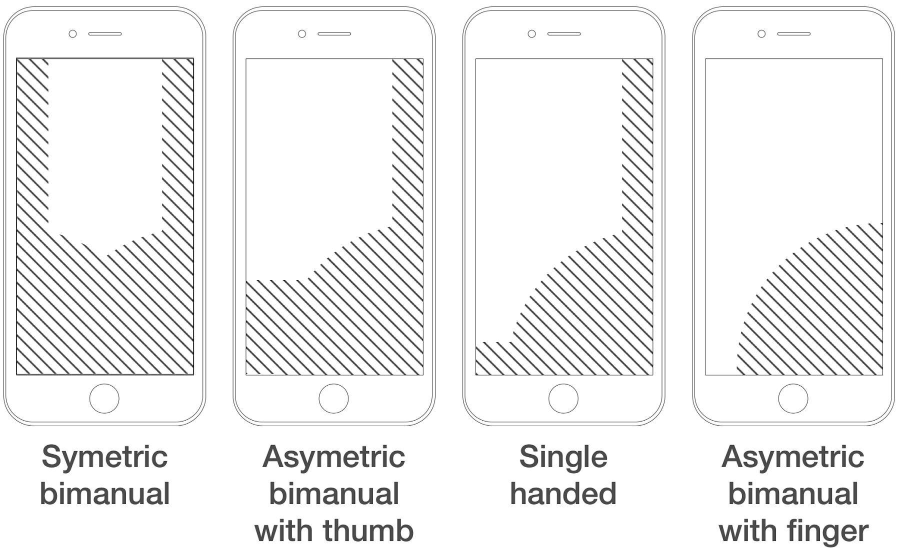


Figure 8.1: Main areas of action item placement from participants' sketches for each grip shown in grey

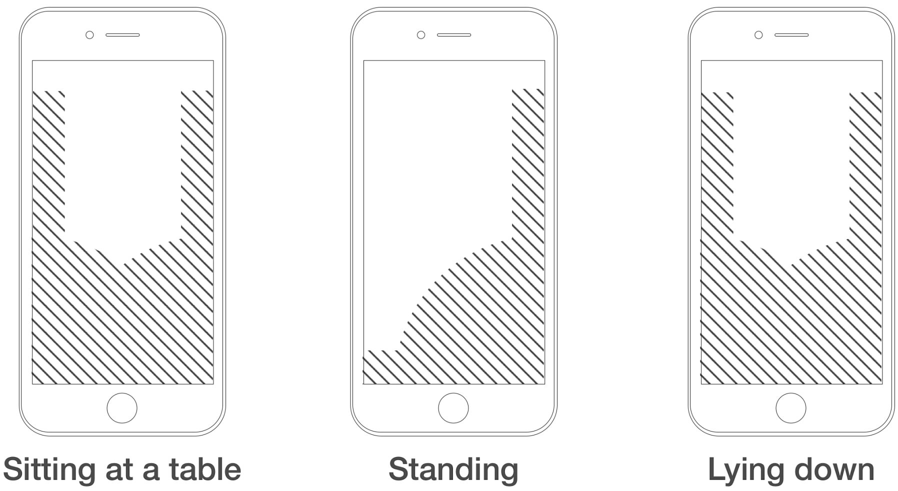


Figure 8.2: Main areas of action item placement from participant's sketches for each body posture shown in grey

8.2.5 Research contributions

During this body of research, I gained seven research insights that have expanded my knowledge of hand smartphone interaction.

1) Expanding on Napier's **(Napier 1993)** research on gripping different objects, I revealed in Chapter 3 that different interaction types use different grips. Four grips for touchscreen interaction (Asymmetric with a finger, Asymmetric with a thumb, Single-handed and Symmetric bimanual), three for button interaction (Asymmetric with a thumb, Single-handed and Symmetric bimanual) and one for stylus interaction (Asymmetric with a stylus).

2) I observed that the participants moved all three different interaction type smartphones during the Chapter 3 study. This movement angled the smartphone for better hand interaction (e.g., moving the smartphone close to the thumb).

3) Looking specifically at the touchscreen interaction smartphone, I have identified during the studies in Chapters 4 and 5 that the grip that moved the most was S, AT less movement, then B, and the grip with the lowest movement was AF.

4) As discovered in Chapter 4 for the smartphone's size, the iPhone 6 and 6 + displayed a statistically larger movement than the iPhone 4 and 5.

5) Again, in Chapters 4 and 5, the location of action items impacted the smartphone's movement. Again, those within the functional area of the thumb **(Bergstrom-Lehtovirta and Oulasvirta 2014)** had the least amount of movement.

6) I have discovered that, as presented in Chapter 5, body posture affects the smartphone's movement. For example, the body posture standing had the least movement, followed by sitting down and finally lying down, which has the most movement.

7) In Chapters 3, 4 and 5, a number of design workshops were run that highlighted the above findings. Additionally, during these workshops, design features were developed (e.g., action item placement, smartphone movement, information layout and interactive concepts).

8.3 Conclusion

During this PhD, I have looked at how the human hand and the smartphone interact, using a systematic approach to investigate the type of interaction and grips used for smartphone interaction. I have also investigated, in a quantitative manner, the extent of movement on the smartphone for different device sizes and body postures. To this end, I have created a number of concepts demonstrating how user interaction can encompass how the human hand interacts with a smartphone better. This includes placing items on the screen and how the smartphone moves during an interaction.

I have also presented the results and analysis of workshops to prove how existing empirical data relating to smartphone hand grip and posture can provide valuable material for new UI concepts. I believe this work will be helpful for designers, not only by providing new ideas for design approaches but also by bringing relevant insights on how design can change through the accommodation of body posture and handgrip. Additionally, I hope this research demonstrates the importance of gathering empirical data and how such datasets can be a critical research source for designing more adapted user interfaces.

Overall, with this PhD, I have firstly provided insights from the literature by Napier **(Napier 1993)** and Wilson **(Wilson 1999)** to close the loop between the perception of the hand and smartphone UI design. I have secondly used the research findings (Chapters 3, 4 and 5) and worked with UI designers to understand how this research could be implemented as a fully developed design solution. Finally, I have created a general framework that has allowed other researchers to build upon and develop their research **(Corsten et al., 2019** and **Ikematsu et al., 2020)**.

8.4 Limitations

During this PhD study, many limitations have been defined to help progress the research by reducing the study variables. These limitations include the participants for data gathering, concept design creation, smartphone selection, and smartphone interaction.

The participants who aided data collection were limited to university students and staff. However, further investigation should include different age ranges, for example, participants under 18 years with smaller hand sizes and older adults who may be retired and not necessarily technologically aware. Other compelling research would be to understand how participants with disabilities (physical or cognitive) use their hands to interact (Igual et al., 2013). Finally, although we had the opportunity to recruit UI designers with industrial experience for the workshop in Chapter 6, the second round of workshops (Chapter 7) participants were university students, which may have limited the created concepts.

For the smartphone hardware, the investigation was limited to a pointing task with an application that is basic enough to generalize the results to interaction styles (e.g., selection of keys, items) as it is arguably the most standard smartphone input. Secondly, for the qualitative data gathering (Chapters 4 and 5), touchscreen interaction as it provided access to the greater number of grips (Chapter 3) and thirdly, holding the smartphone in a portrait orientation as this reduces the variables for data collection in Chapters 4, 5 and 7. Finally, gesture interaction and holding the smartphone in landscape orientation are valid interaction methods and deserve investigation. The data analysis used in Chapters 3 and 4 showed how the hand influenced the smartphone's movement. However, if researchers wish to use this data to develop machine learning algorithms, I believe there is a need for a more robust data-gathering technique.

8.5 Future work

Future work for this PhD would include validating several design concepts, investigating new and developing handheld device technology and interpreting the findings into a format that is easy for UI designers to understand.

In Chapters 5 and 6, I collaborated with UI designers during the workshops. These concepts need to be validated by constructing clickable prototypes using applications such as ProtoPie **(ProtoPie 2020)** or HTML. I would then use such prototyping software to evaluate the position of the action items and movement of the UI concepts shown in Chapters 6 and 7 and select current applications such as text messaging via usability testing. These usability tests will include people who have a range of ages, genders and technology awareness. This usability testing highlights the best design approaches concerning the placement of action items and the cognitive load that the transitions may place on the individual.

During the time it has taken to complete this PhD, many technological developments have occurred that need consideration. For example, Shape-changing technology is an expanding field of research within the HCI community **(Goguey et al., 2019, Qamar et al., 2018)** and in commercial smartphones such as the Galaxy Z Fold 2 **(Samsung 2020)** and LG Wing **(LG 2020)**. In addition, vision technology has been developed to track how hands grasp objects **(Taheri et al. 2020, Le et al. 2018)** and sensors placed within the smartphone's hardware **(Hinckley et al. 2019, Le et al. 2019)**.

Finally, any knowledge gained through this research that can support commercial UI designers needs to be shared through the design of online education material or integration into the iOS and Android design patterns. Future directions are to explore interactive tools to inform UI designers as they develop these UI screens through plugins for professional mobile screen design tools such as Sketch **(Sketch 2020)**.

References

Adams, W. C. (2015) CONDUCTING SEMI-STRUCTURED INTERVIEWS.

Apple (2020a) App bars: top - Material Design. Available at: https://material.io/components/app-bars-top (Accessed: 10 January 2021).

Apple (2020b) Search Bars - Bars - iOS - Human Interface Guidelines - Apple Developer. Available at: https://developer.apple.com/design/human-interface-guidelines/ios/bars/search-bars/ (Accessed: 10 January 2021).

Apple Developer (2020) iOS - Human Interface Guidelines. Available at: https://developer.apple.com/design/human-interface-guidelines/ios/overview/themes/ (Accessed: 10 January 2021).

Azenkot, S. and Zhai, S. (2012) 'Touch behavior with different postures on soft smartphone keyboards', MobileHCI'12 - Proceedings of the 14th International Conference on Human Computer Interaction with Mobile Devices and Services, pp. 251–260. doi: 10.1145/2371574.2371612.

Bachynskyi, M. et al. (2015) 'Performance and Ergonomics of Touch Surfaces: A Comparative Study Using Biomechanical Simulation'. doi: 10.1145/2702123.2702607.

Barde, C R and Purkar, K. T. (2008) A dynamic touch screen interface like Tactus for mobile and automotive devices, Certified Journal.

Barnes, S. B. (1997) 'Douglas Carl Engelbart: Developing the underlying concepts for contemporary computing', IEEE Annals of the History of Computing, 19(3), pp. 16–26. doi: 10.1109/85.601730.

Bergin, T. (2018) 'An Introduction to Data Analysis97', in. SAGE Publications Inc.

Bergstrom-Lehtovirta, J. and Oulasvirta, A. (2014) 'Modeling the functional area of the thumb on mobile touchscreen surfaces', in Proceedings of the

32nd annual ACM conference on Human factors in computing systems - CHI ’14. doi: 10.1145/2556288.2557354.

Burdea, G. et al. (1991) ‘Direct-Drive Force Feedback Control for the Dataglove’, in Engineering Systems with Intelligence. Springer Netherlands, pp. 453–460. doi: 10.1007/978-94-011-2560-4_52.

Buschek, D., De Luca, A. and Alt, F. (2015) ‘There is more to Typing than Speed: Expressive Mobile Touch Keyboards via Dynamic Font Personalisation’, in Boring, S. et al. (eds). ACM. doi: 10.1145/2785830.

Buxton, W. and Myers, B. A. (1986) A STUDY IN TWO-HANDED INPUT.

Card, S. K., Moran, T. P. and Newell, A. (1983) The Psychology of Human-Computer Interaction. Lawrence Eribaum Associates, Inc.

Chang, Y. et al. (2015) ‘Understanding Users’ Touch Behavior on Large Mobile Touch-Screens and Assisted Targeting by Tilting Gesture’, in Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI ’15. doi: 10.1145/2702123.2702425.

Charness, G., Gneezy, U. and Kuhn, M. A. (2012) ‘Experimental methods: Between-subject and within-subject design’, Journal of Economic Behavior and Organization. North-Holland, 81(1), pp. 1–8. doi: 10.1016/j.jebo.2011.08.009.

Cheng, L.-P. et al. (2012) iRotate: Automatic Screen Rotation based on Face Orientation.

Corsten, C., Lahaye, M., Borchers, J. and Voelker, S., (2019), May. ForceRay: Extending Thumb Reach via Force Input Stabilizes Device Grip for Mobile Touch Input. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-12).

Creswell, J. W. and Plano Clark, V. L. (2011) Designing and Conducting Mixed Methods Research. 2nd edn. Sage Publications, Inc. Available at:

Deininger, R. L. (1960) ‘Human Factors Engineering Studies of the Design and Use of Pushbutton Telephone Sets’, Bell System Technical Journal. John Wiley & Sons, Ltd, 39(4), pp. 995–1012. doi: 10.1002/j.1538-7305.1960.tb04447.x.

Dix, A. (2002) driving as a cyborg experience. Available at: http://www.hcibook.com/alan/papers/cyborg-driver-2002/ (Accessed: 29 December 2020).

Dourish, P. (2004) Where the Action is: The Foundations of Embodied Interaction. MIT.

Drake, R., Vogl, A. W. and Mitchell, A. (2010) Gray’s Anatomy for Students . 3rd edn. Churchill Livingstone an imprint of Elsevier Inc. Available at:

Dreyfuss, H. (1955) Designing for People. Simon and Schuster,. Available at:

Dreyfuss, H. (1960) The measure of man;: Human factors in design. Whitney Library of Design.

Dreyfuss, H. (1967) The measure of man;: Human factors in design.

Eardley, R. et al. (2016) ‘Investigating how the hand interacts with different mobile phones’, in Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct - MobileHCI ’16. doi: 10.1145/2957265.2961840.

Eardley, R. et al. (2017) ‘Understanding Grip Shifts: How Form Factors Impact Hand Movements on Mobile Phones’, Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI ’17. doi: 10.1145/3025453.3025835.

Eardley, R. et al. (2018a) ‘Designing for Multiple Hand Grips and Body Postures within the UX of a moving Smartphone’, in Proceedings of the 2018 on Designing Interactive Systems Conference 2018 - DIS ’18. doi: 10.1145/3196709.3196711.

Eardley, R. et al. (2018b) ‘Investigating How Smartphone Movement is Affected by Body Posture’, in Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI ’18. doi: 10.1145/3173574.3173776.

Eardley, R., Gill, S. and Thompson, S. (2012) Investigating the biomechanical hand and its role in designing interactions.

Engelbart, D. (1968) Doug Engelbart 1968 Demo. Available at: https://web.stanford.edu/dept/SUL/library/extra4/sloan/mousesite/1968Demo.html (Accessed: 11 January 2021).

English, W. K., Engelbart, D. C. and Berman, M. L. (1967) ‘Display-Selection Techniques for Text Manipulation’, in IEEE Transactions on Human Factors in Electronics, March 1967, Vol. HFE-8, No. 1, pp. 5-15. Available at:).

Fitzmaurice, G. W., Ishii, H. and Buxton, W. (1995) Bricks: Laying the Foundations for Graspable User Interfaces.

Goel, M., Findlater, L. and Wobbrock, J. O. (2012) WalkType: Using Accelerometer Data to Accommodate Situational Impairments in Mobile Touch Screen Text Entry. Available at: http://www.cs.waikato.ac.nz/ml/weka (Accessed: 12 January 2021).

Goguey, A., Steer, C., Lucero, A., Nigay, L., Sahoo, D. R., Coutrix, C., ... & Jones, M. (2019). PickCells: A physically reconfigurable cell-composed touchscreen. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-14).

Gold, J. E. et al. (2012) ‘Postures, typing strategies, and gender differences in mobile device usage: An observational study’, Applied Ergonomics. Elsevier Ltd, 43(2), pp. 408–412. doi: 10.1016/j.apergo.2011.06.015.

Goldin-Meadow, S. (2003) Hearing Gesture, How our hands help us think. Belknap Press of Harvard University Press.

Google (2020) Navigation Bars - Bars - iOS - Human Interface Guidelines - Apple Developer. Available at: https://developer.apple.com/design/human-interface-guidelines/ios/bars/navigation-bars/ (Accessed: 10 January 2021).

Grant, D. A. (1948) 'The latin square principle in the design and analysis of psychological experiments', Psychological Bulletin, 45(5), pp. 427–442. doi: 10.1037/h0053912.

Guiard, Y. (1987) Asymmetric Division of Labor in Human Skilled Bimanual Action: The Kinematic Chain as a Model, Journal of Motor Behavior. Available at: http://cogprints.org/625/0/jmb_87.html (Accessed: 10 January 2021).

Guiard, Y. and Ferrand, T. (1996) 'Asymmetries in Bimanual Skills', in Elliott, D. and Roy, E. A. (eds) Manual Asymmetries in Motor Performance.

Harboe, G. and Huang, E. M. (2015) 'Real-world affinity diagramming practices: Bridging the paper-digital gap', Conference on Human Factors in Computing Systems - Proceedings, 2015-April, pp. 95–104. doi: 10.1145/2702123.2702561.

Harrison, C. and Hudson, S. E. (2009) Providing Dynamically Changeable Physical Buttons on a Visual Display.

Hatwell, Y., Streri, A. and Gentaz, E. (2003) 'Touching for knowing: Cognitive psychology of haptic manual perception', Advances in consciousness research. Edited by Y. Hatwell, A. Streri, and E. Gentaz. Amsterdam: John Benjamins Publishing Company (Advances in Consciousness Research), 53. doi: 10.1075/aicr.53.

Hemmert, F. et al. (2010) Take me by the Hand: Haptic Compasses in Mobile Devices through Shape Change and Weight Shift.

Hiltzik, M. (1999) Dealers of Lightning: Xerox PARC and the Dawn of the Computer Age. HarperCollins.

Hinckley, K. et al. (2010) ‘Pen + touch = New tools’, UIST 2010 - 23rd ACM Symposium on User Interface Software and Technology, pp. 27–36. doi: 10.1145/1866029.1866036.

Hinckley, K. et al. (2016) ‘Pre-touch sensing for mobile interaction’, Conference on Human Factors in Computing Systems - Proceedings, pp. 2869–2881. doi: 10.1145/2858036.2858095.

Hoggan, E., Brewster, S. A. and Johnston, J. (2008) ‘Investigating the effectiveness of tactile feedback for mobile touchscreens’, Conference on Human Factors in Computing Systems - Proceedings, pp. 1573–1582. doi: 10.1145/1357054.1357300.

Holz, C. and Baudisch, P. (2010) The Generalized Perceived Input Point Model and How to Double Touch Accuracy by Extracting Fingerprints.

Hornecker, E. (2011) ‘The Role of Physicality in Tangible and Embodied Interactions’, (ACM Interaction magazine vol 18 issue 2).

Hornecker, E. and Buur, J. (2006) Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction.

Huang., G. H. and E. M. (2015) ‘Real-World Affinity Diagramming Practices: Bridging the Paper-Digital Gap.’ Available at: https://dl.acm.org/doi/abs/10.1145/2702123.2702561.

Igual, R., Plaza, I., Martín, L., Corbalan, M., & Medrano, C. (2013). Guidelines to design smartphone applications for people with intellectual disability: A practical experience. In Ambient Intelligence-Software and Applications (pp. 65-69). Springer, Heidelberg.

Ikematsu, K., Oshima, H., Eardley, R., & Siio, I. (2020). Investigating How Smartphone Movement is Affected by Lying Down Body Posture. Proceedings of the ACM on Human-Computer Interaction, 4(ISS), 1-17.

Ingold, T. (2000) ‘Evolving Skills’, in Rose, H. and Rose, S. (eds) Alas Poor Darwin: Arguments Against Evolutionary Psychology. Vintage.

Ishii, H. and Ullmer, B. (1997) Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms.

Iwata, H. (2008) ‘History of haptic interface’, in Human Haptic Perception: Basics and Applications. Birkhauser Verlag AG, pp. 355–361. doi: 10.1007/978-3-7643-7612-3_29.

Jensen, M. V., Buur, J. and Djajadiningrat, T. (2005) ‘Designing the user actions in tangible interaction’, in Critical Computing - Between Sense and Sensibility - Proceedings of the 4th Decennial Aarhus Conference. New York, New York, USA: ACM Press, pp. 9–18. doi: 10.1145/1094562.1094565.

Keisi L.L.C. (2020) HeadsUp - Webcam Viewer. Available at: https://apps.apple.com/gb/app/headsup-webcam-viewer/id583912513?mt=12 (Accessed: 10 January 2021).

Kim, D.-S. and Chae, W.-S. (2012) ‘Biomechanical Analysis of a Smartphone Task with Different Postures’, Korean Journal of Sport Biomechanics. Online, 22(2), pp. 2093–9752. doi: 10.5103/KJSB.2012.22.2.253.

Kim, K.-E. et al. (2006) Hand Grip Pattern Recognition for Mobile User Interfaces. Available at: www.essd.com (Accessed: 9 January 2021).

Klatzky, R. L., Lederman, S. J., & Metzger, V. A. (1985). Identifying objects by touch: An “expert system”. Perception & psychophysics, 37(4), 299-302.

Klatzky, R. L., Lederman, S. J., & Reed, C. (1987). There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. Journal of experimental psychology: general, 116(4), 356.

Le, H. V., Mayer, S., Bader, P., & Henze, N. (2018). Fingers' Range and Comfortable Area for One-Handed Smartphone Interaction Beyond the Touchscreen. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (pp. 1-12).

Le, H. V., Mayer, S., & Henze, N. (2019). Investigating the feasibility of finger identification on capacitive touchscreens using deep learning. In Proceedings of the 24th International Conference on Intelligent User Interfaces (pp. 637-649).

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. Cognitive psychology, 19(3), 342-368.

Lederman, S. J., & Klatzky, R. L. (1990). Haptic classification of common objects: Knowledge-driven exploration. Cognitive psychology, 22(4), 421-459.

LG (2020) LG WING, Official Site, LMF100N, 2020. Available at: https://www.lg.com/global/lgwing (Accessed: 10 January 2021).

Licklider, J. C. R. (1960) 'Man-Computer Symbiosis', IRE Transactions on Human Factors in Electronics, HFE-1(1), pp. 4–11. doi: 10.1109/THFE2.1960.4503259.

Likert, R. (1932) 'A technique for the measurement of attitudes', in Archives of Psychology, 22 140, 55. Available at: https://psycnet.apa.org/record/1933-01885-001 (Accessed: 10 January 2021).

Lin, Y.-C. (2013) 'The Relationship between Touchscreen Sizes of Smartphones and Hand Dimensions', in LNCS. Springer, Berlin, Heidelberg, pp. 643–650. doi: 10.1007/978-3-642-39194-1_74.

MacKenzie, I. S. (2012) Human-Computer Interaction: An Empirical Research Perspective. Elsevier Science.

Mcmanus, I. C. (2009) The history and geography of human handedness.

Mehrnezhad, M. et al. (2018) 'Stealing PINs via mobile sensors: actual risk versus user perception', International Journal of Information Security. Springer Verlag, 17(3), pp. 291–313. doi: 10.1007/s10207-017-0369-x.

Mistry, P. and Maes, P. (2009) Emerging Technologies | Invited Work 85 SixthSense: a Wearable Gestural interface.

Morris, M. R., Wobbrock, J. O. and Wilson, A. D. (2010) Understanding Users' Preferences for Surface Gestures.

Napier, J. (1993) Hands. Edited by R. Tuttle. Princeton: Princeton University Press.

Napier, J. R. (1956) 'The prehensile movements of the human hand.', The Journal of bone and joint surgery. British volume. The British Editorial Society of Bone and Joint Surgery, 38 B(4), pp. 902–913. doi: 10.1302/0301-620x.38b4.902.

Negulescu, M. and McGrenere, J. (2015) 'Grip Change as an Information Side Channel for Mobile Touch Interaction', Proceedings of the ACM CHI'15 Conference on Human Factors in Computing Systems. doi: 10.1145/2702123.2702185.

Ng, A., Brewster, S. and Williamson, J. (2014) 'Investigating the effects of encumbrance on one- and two- handed interactions with mobile devices', in Conference on Human Factors in Computing Systems - Proceedings. New York, NY, USA: Association for Computing Machinery, pp. 1981–1990. doi: 10.1145/2556288.2557312.

Nintendo (2020) Nintendo Switch | Nintendo Switch Family | Nintendo. Available at: https://www.nintendo.co.uk/Nintendo-Switch-Family/Nintendo-Switch/Nintendo-Switch-1148779.html (Accessed: 12 January 2021).

Noor, M. F. M. et al. (2014) '28 Frames Later : Predicting Screen Touches From Back-of-Device Grip Changes', Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. doi: 10.1145/2556288.2557148.

Oakley, I. and O'Modhrain, S., (2005), Tilt to scroll: Evaluating a motion based vibrotactile mobile interface. In First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference (pp. 40-49). IEEE.

Paterson, M. (2007) The Senses of Touch: Haptics, Affects and Technologies. Edited by 1st. Routledge.

Perry, K. B. and Hourcade, J. P. (2008) Evaluating One Handed Thumb Tapping on Mobile Touchscreen Devices.

ProtoPie (2020) ProtoPie | The interactive digital prototyping tool, 2020. Available at: https://www.protopie.io/ (Accessed: 10 January 2021).

Qamar, I. P., Groh, R., Holman, D., & Roudaut, A. (2018). HCI meets material science: A literature review of morphing materials for the design of shape-changing interfaces. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (pp. 1-23).

Quintanilha, M. (2007) Marble Answering Machine | Interaction Design Thesis. Available at: https://interactionthesis.wordpress.com/2007/02/01/marble-answering-machine/ (Accessed: 3 January 2021).

Roudaut, A., Karnik, A., Löchtefeld, M., & Subramanian, S. (2013). Morphees: toward high" shape resolution" in self-actuated flexible mobile devices. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 593-602).

Rutherford, A. (2001) Introducing Anova and Ancova: A GLM Approach. SAGA Publications Ltd.

Samsung (2020) Samsung Galaxy Z Fold 2 5G | Smartphones | Samsung UK, 2020. Available at: https://www.samsung.com/uk/smartphones/galaxy-z-fold2/ (Accessed: 10 January 2021).

Seipp, K. and Devlin, K. (2014) ‘BackPat: One-Handed Off-Screen Patting Gestures’. doi: 10.1145/2628363.2628396.

Shapiro, S. S. and Wilk, M. B. (1965) ‘An analysis of variance test for normality (complete samples)’, in Biometrika , Dec., 1965, Vol. 52, No. 3/4 (Dec., 1965), pp. 591-611.

Shirazi, A. S. et al. (2013) Upright or Sideways? Analysis of Smartphone Postures in the Wild.

Silverback (2015) Silverback - Software Testing Tools Guide. Available at: http://www.testingtoolsguide.net/tools/silverback/ (Accessed: 10 January 2021).

Sketch (2020) Sketch — The digital design toolkit, 2020. Available at: https://www.sketch.com/ (Accessed: 10 January 2021).

Stakelon, J. (2015) Frameless - a full-screen web browser. Available at: https://apps.apple.com/gb/app/frameless-a-full-screen-web-browser/id933580264 (Accessed: 10 January 2021).

Stammers, R. B. and Shepherd, A. (1991) 'Task analysis', in Wilson, J. R. and Corlett, E. N. (eds) Evaluation of Human Work. 2nd edn.

Taheri, O., Ghorbani, N., Black, M. J., & Tzionas, D. (2020). GRAB: A dataset of whole-body human grasping of objects. In European Conference on Computer Vision (pp. 581-600). Springer, Cham.

Taylor, A. S. et al. (2006) Augmenting Refrigerator Magnets: Why Less is Sometimes More.

Tilley, A. R. (2002) The Measure of Man and Woman: Human Factors in Design. Wiley. Available at:

Tubiana, R., Thomine, J.-M. and Mackin, E. (1996) Examination of the Hand and Wrist . WB Saunders Company.

UX Bristol (2017) UXBristol 2017 - A conference. About UX. In Bristol. In 2017. UXBristol 2017. Available at: http://2017.uxbristol.org.uk/ (Accessed: 10 January 2021).

Viet Le, H. et al. (2016) 'Finger Placement and Hand Grasp during Smartphone Interaction'. doi: 10.1145/2851581.2892462.

Villar, N. et al. (2018) 'Project Zanzibar: A Portable and Flexible Tangible Interaction Platform'. doi: 10.1145/3173574.3174089.

Wachs, J. P. et al. (2011) ‘Body posture and finger pointing are a natural modality for human-machine interaction, but first the system must know what it’s seeing’. doi: 10.1145/1897816.1897838.

Waldrop, M. M. (2002) The Dream Machine: J.C.R. Licklider and the Revolution That Made Computing Personal.

Weiser, M. (1991) ‘The Computer for the 21 st Century’, Scientific American, Vol. 265,(No. 3, SPECIAL ISSUE: Communications, Computers and Networks: How to Work, Play and Thrive in Cyberspace), pp. 94–105. doi: 10.2307/24938718.

Wellner, P., Mackay, W. and Gold, R. (1993) Back to the real world. doi: 10.1145/159544.159555.

Williams, L. J. (2010) Fisher’s Least Signiflcant Difierence (LSD) Test. Available at: https://www.researchgate.net/publication/242181775 (Accessed: 12 January 2021).

Wilson, F. R. (1999) The Hand: How Its Use Shapes the Brain, Language, and Human Culture. NY: Vintage Books. Available at: https://www.amazon.co.uk/Hand-Frank-R-Wilson/dp/0679740473 (Accessed: 9 January 2021).

Wimmer, R. and Boring, S. (2009) ‘HandSense - Discriminating different ways of grasping and holding a tangible user interface’, Proceedings of the 3rd International Conference on Tangible and Embedded Interaction, TEI’09, pp. 359–362. doi: 10.1145/1517664.1517736.

Wobbrock, J. O., Myers, B. A. and Aung, H. H. (2008) ‘The performance of hand postures in front- and back-of-device interaction for mobile computing’, International Journal of Human Computer Studies. Academic Press, 66(12), pp. 857–875. doi: 10.1016/j.ijhcs.2008.03.004.

Wood Jones, F. (1920) The Principles of Anatomy as Seen in the Hand.

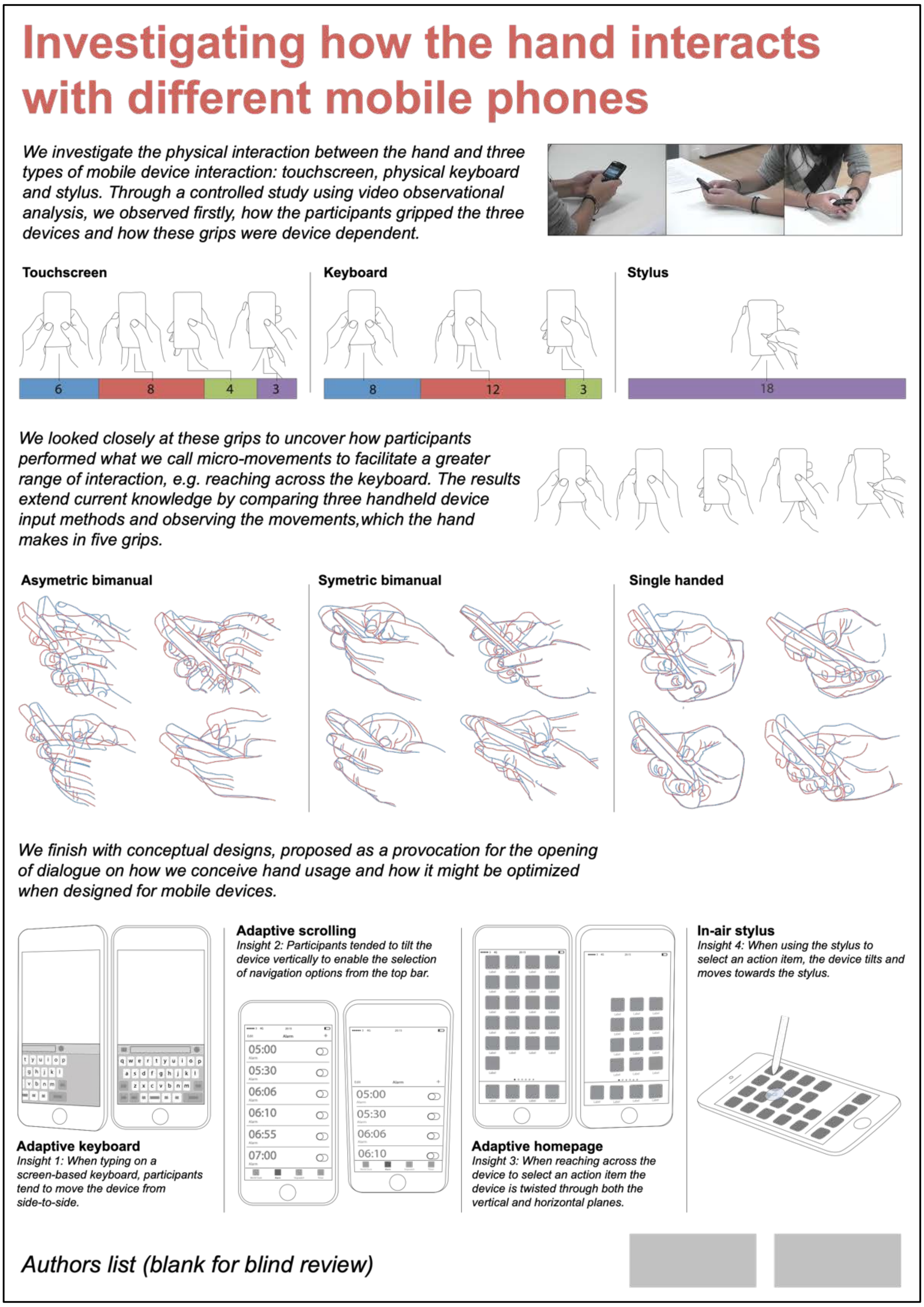
Wu, M. and Balakrishnan, R. (2003) Multi-Finger and Whole Hand Gestural Interaction Techniques for Multi-User Tabletop Displays. Available at: www.smarttech.com (Accessed: 12 January 2021).

Yeo, H. S. et al. (2017) 'Investigating tilt-based gesture keyboard entry for single handed text entry on large devices', in Conference on Human Factors in Computing Systems - Proceedings. New York, NY, USA: Association for Computing Machinery, pp. 4194–4202. doi: 10.1145/3025453.3025520.

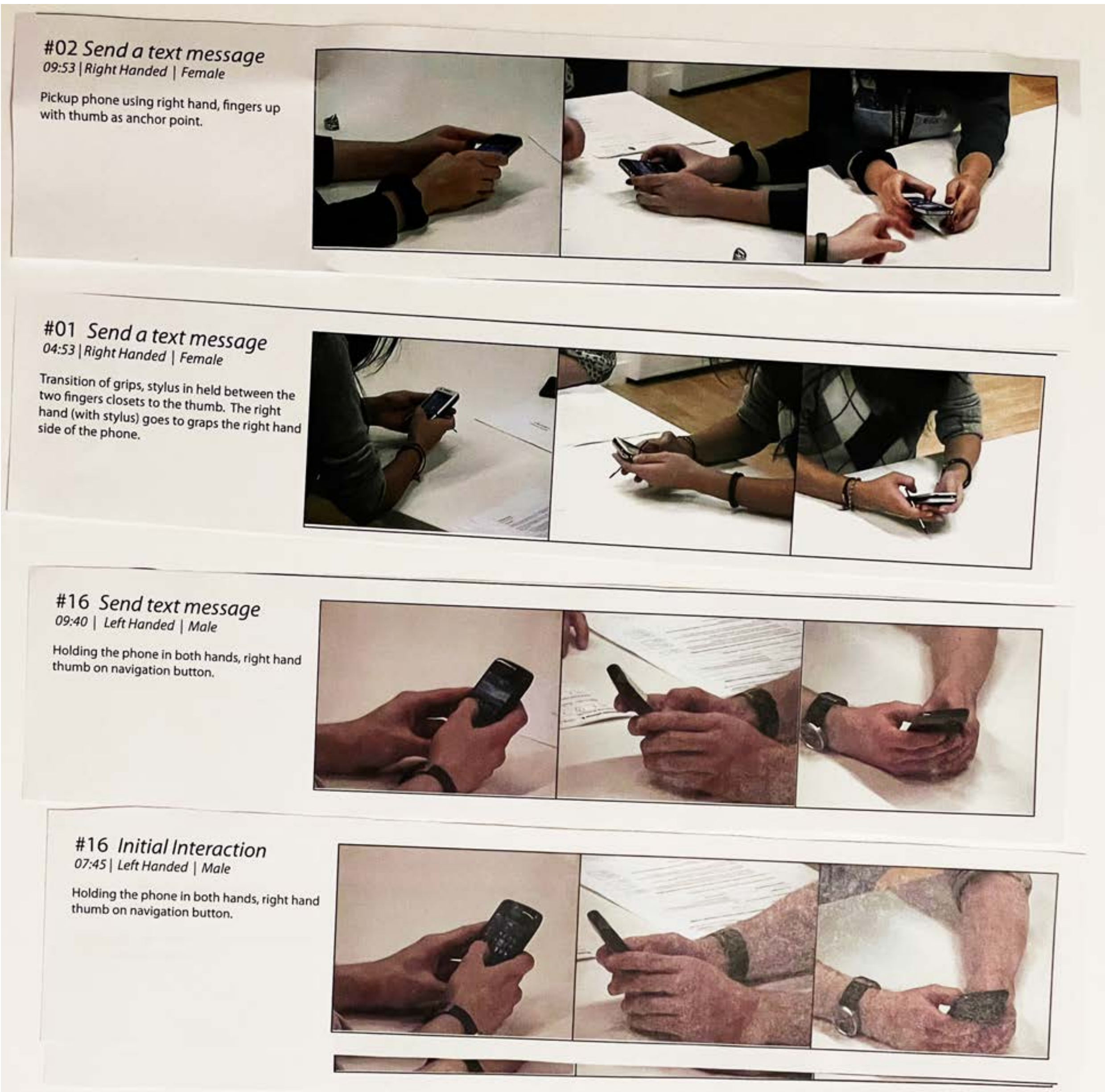
Yoo, H., Yoon, J. and Ji, H. (2015) 'Index finger zone: Study on touchable area expandability using thumb and index finger', in MobileHCI 2015 - Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct. New York, NY, USA: Association for Computing Machinery, Inc, pp. 803–810. doi: 10.1145/2786567.2793704.

Appendix A (Chapter 3)

A.1 Mobile HCI poster

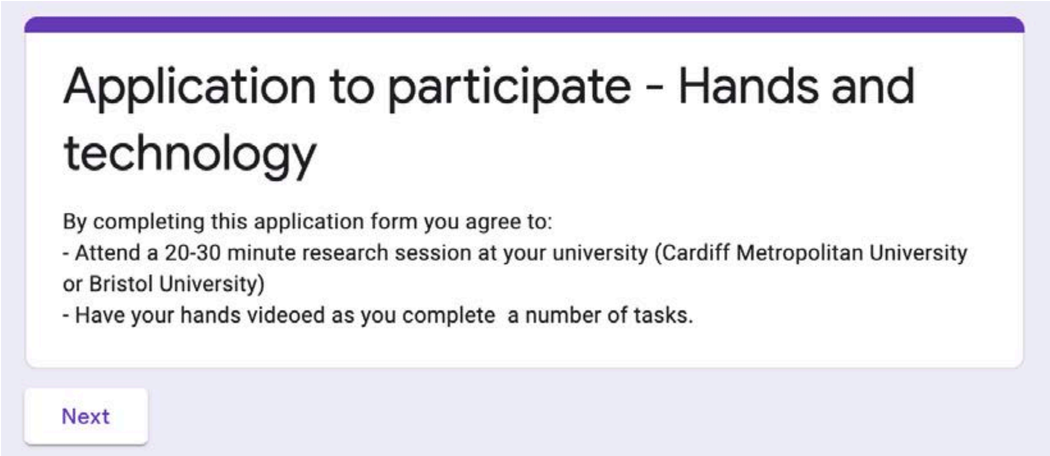


A.2 Examples of key moment printouts



Appendix B (Chapter 4)

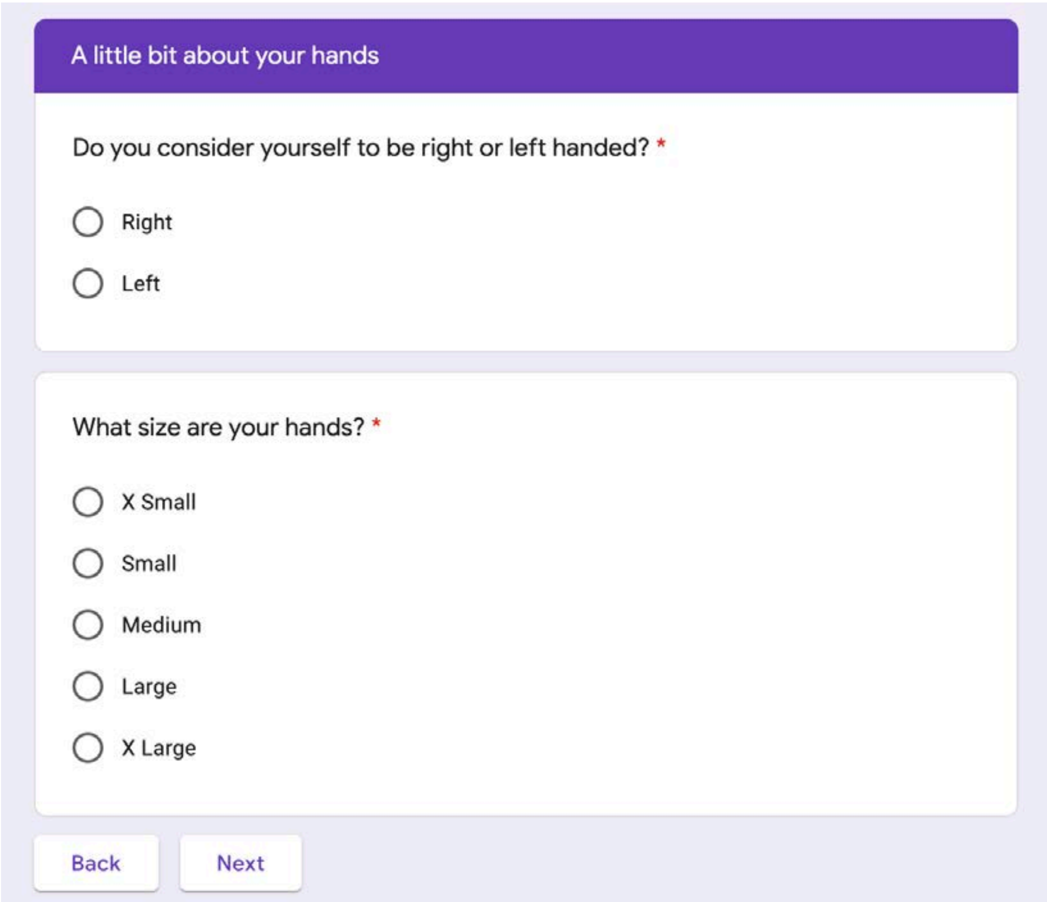
B.1 Recruitment questionnaire



Application to participate - Hands and technology

By completing this application form you agree to:
- Attend a 20-30 minute research session at your university (Cardiff Metropolitan University or Bristol University)
- Have your hands videoed as you complete a number of tasks.

Next



A little bit about your hands

Do you consider yourself to be right or left handed? *

Right

Left

What size are your hands? *

X Small

Small

Medium

Large

X Large

Back

Next

A little bit about your mobile phone use

What mobile phone do you use? *

Your answer

Do you use a mobile phone case? *

Your answer

How long have you had this mobile phone? *

Your answer

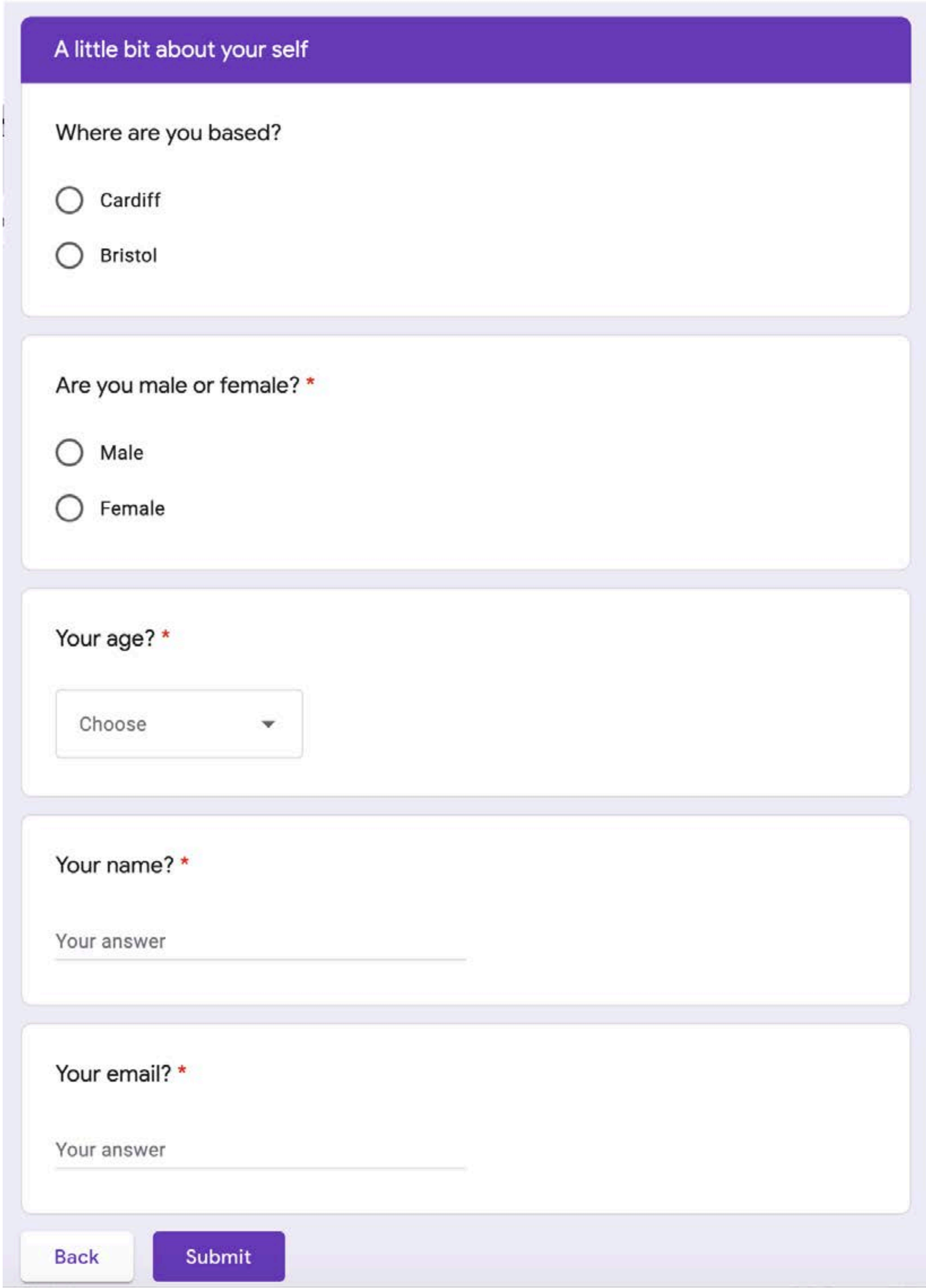
What are the top 3 things you use your mobile phone for? *

Your answer

Where are the top 3 places you use your mobile phone? (e.g. work, home, bus stop, on the train) *

Your answer

Back Next



A little bit about your self

Where are you based?

- Cardiff
- Bristol

Are you male or female? *

- Male
- Female

Your age? *

Choose

Your name? *

Your answer

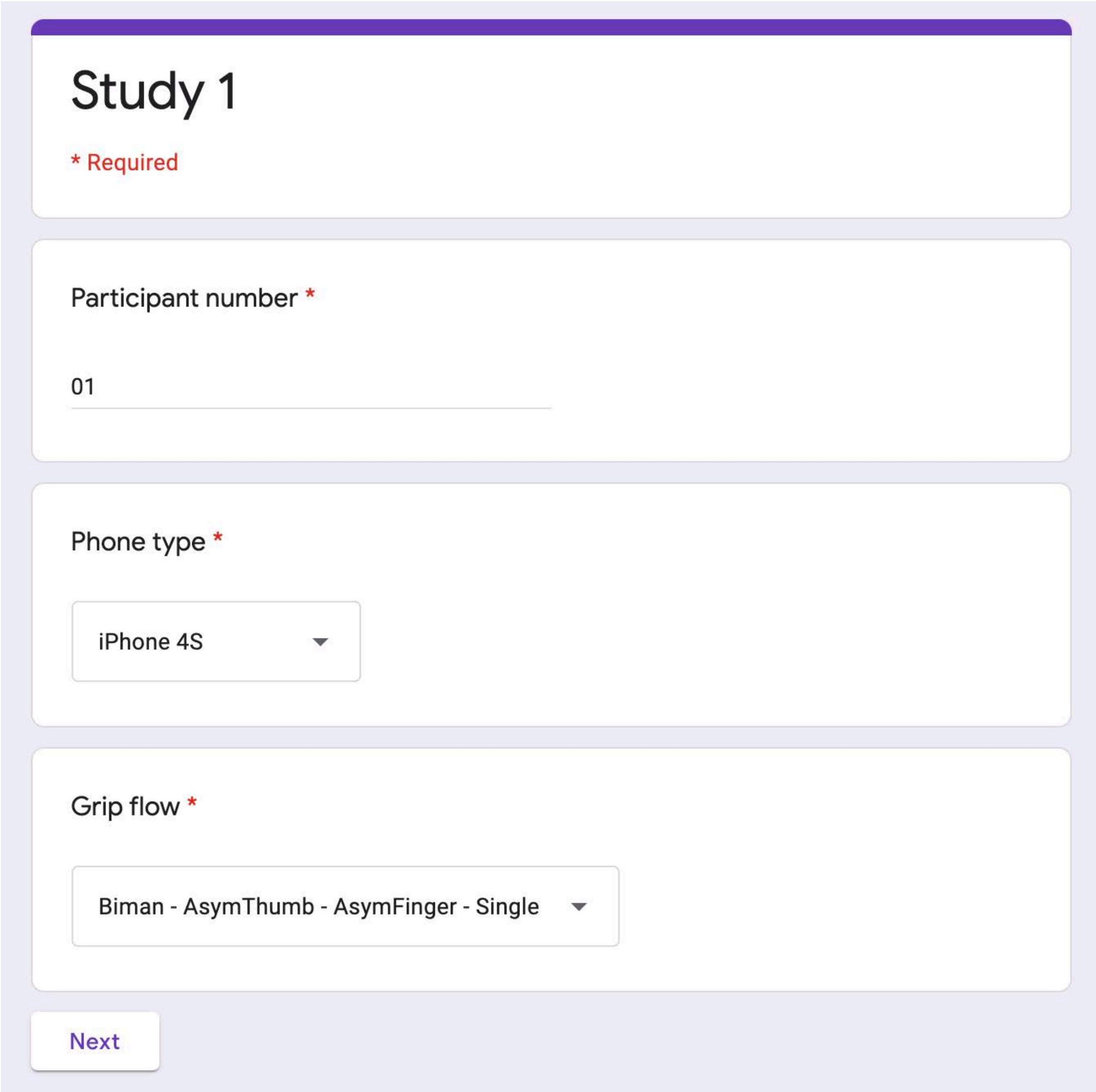
Your email? *

Your answer

Back

Submit

B.2 Feedback from (Admin)



Study 1

* Required

Participant number *

01

Phone type *

iPhone 4S

Grip flow *

Biman - AsymThumb - AsymFinger - Single

Next

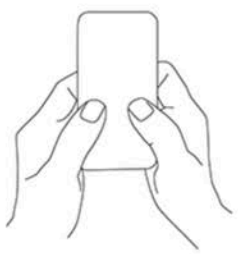
B.3 Feedback from (Participants)

Study 1

* Required

Grip 1/4

Biman - AsymThumb - AsymFinger - Single



How secure or un-secure did it feel holding the phone with the above grip? *

	1	2	3	4	5	6	7	
very unsecure	○	○	○	○	○	○	○	very secure

How comfortable or un-comfortable did it feel holding the phone with the above grip? *

	1	2	3	4	5	6	7	
very uncomfortable	○	○	○	○	○	○	○	very comfortable

Asked to complete this task with a grip of your choosing, this grip would be popular or un-popular? *

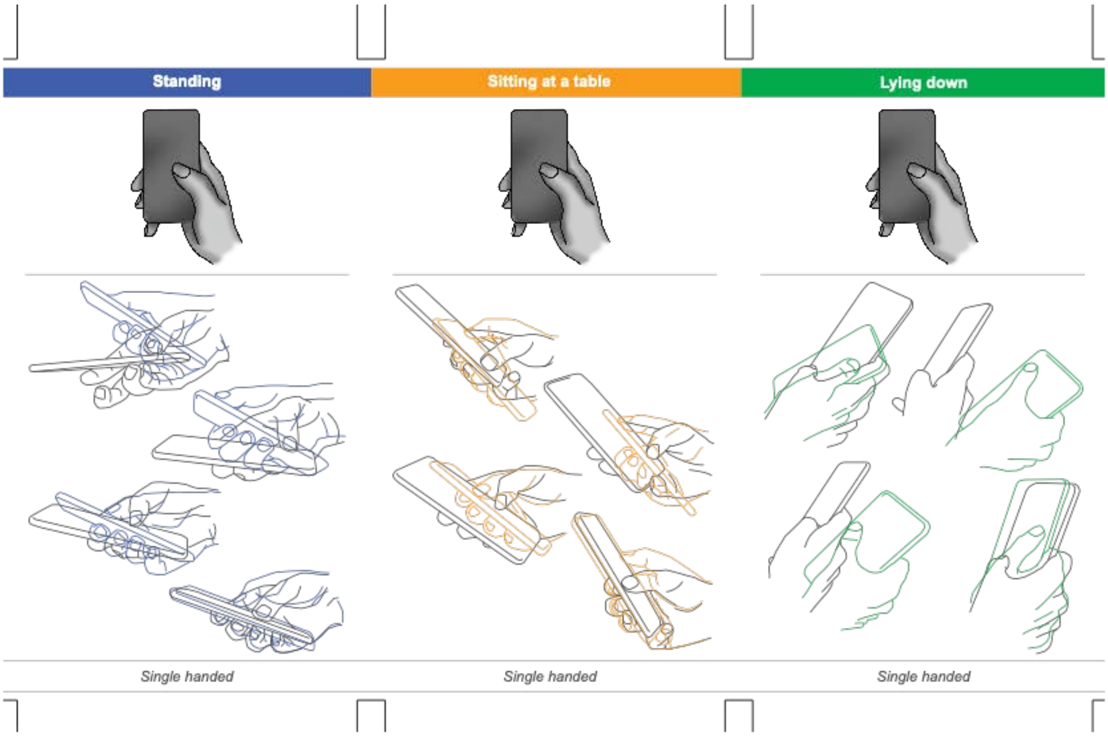
	1	2	3	4	5	6	7	
very unpopular	○	○	○	○	○	○	○	very popular

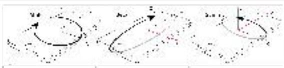
B.4 Example of the master Excel sheet

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1	Participar	HS (L)	HS (W)	HS (T)	HS(F)	Phon	graspor	grip	target	mouse1X	mou	mous	mouse	1X	1Y	2X	2Y	Visual e	Digital	was th	alpha	beta	gamm	Q1 Sec	Q2 Co	Q3 Po r
1672	14	173	85	59	81	1	2	4	2	38	38	280	441	44	44	276	436	0	1	1	11	-8	-11	6	6	6
1673	14	173	85	59	81	1	2	1	2	40	32	280	445	44	44	276	436	2	1	1	-14	-6	-25	6	5	5
1674	14	173	85	59	81	1	2	2	3	289	452	36	40	276	436	44	44	1	0	1	3	2	-5	5	5	6
1675	14	173	85	59	81	1	2	3	3	274	439	31	29	276	436	44	44	1	0	1	5	12	13	6	6	6
1676	14	173	85	59	81	1	2	4	3	279	419	53	38	276	436	44	44	0	1	1	-3	4	5	6	6	6
1677	14	173	85	59	81	1	2	1	3	281	463	37	20	276	436	44	44	2	1	1	6	11	32	6	5	5
1678	14	173	85	59	81	1	2	2	4	43	440	269	34	44	436	276	44	1	0	1	4	11	14	5	5	6
1679	14	173	85	59	81	1	2	3	4	29	431	266	44	44	436	276	44	1	0	1	-1	2	2	6	6	6
1680	14	173	85	59	81	1	2	4	4	44	432	277	29	44	436	276	44	0	1	1	0	0	0	6	6	6
1681	14	173	85	59	81	1	2	1	4	38	430	292	59	44	436	276	44	2	1	1	-2	-3	9	6	5	5
1682	14	173	85	59	81	1	2	2	5	27	169	275	316	44	175	276	305	1	0	1	0	-2	0	5	5	6
1683	14	173	85	59	81	1	2	3	5	40	173	279	320	44	175	276	305	1	0	1	-1	-3	-3	6	6	6
1684	14	173	85	59	81	1	2	4	5	51	191	281	314	44	175	276	305	0	1	1	2	-3	-3	6	6	6
1685	14	173	85	59	81	1	2	1	5	44	177	289	313	44	175	276	305	2	1	1	-5	-1	-21	6	5	5
1686	14	173	85	59	81	1	2	2	6	279	167	32	302	276	175	44	305	1	0	1	0	-4	0	5	5	6
1687	14	173	85	59	81	1	2	3	6	279	167	22	312	276	175	44	305	1	0	1	0	0	0	6	6	6
1688	14	173	85	59	81	1	2	4	6	294	165	53	307	276	175	44	305	0	1	1	0	0	0	6	6	6
1689	14	173	85	59	81	1	2	1	6	273	186	20	311	276	175	44	305	2	1	1	1	1	4	6	5	5
1690	14	173	85	59	81	1	2	2	7	284	298	32	173	276	305	44	175	1	0	1	1	1	-1	5	5	6
1691	14	173	85	59	81	1	2	3	7	268	311	45	172	276	305	44	175	1	0	1	0	2	3	6	6	6
1692	14	173	85	59	81	1	2	4	7	291	324	31	166	276	305	44	175	0	1	1	-4	2	3	6	6	6
1693	14	173	85	59	81	1	2	1	7	275	301	49	182	276	305	44	175	2	1	1	-2	-4	9	6	5	5
1694	14	173	85	59	81	1	2	2	8	42	328	279	159	44	305	276	175	1	0	1	0	-1	1	5	5	6
1695	14	173	85	59	81	1	2	3	8	22	322	277	166	44	305	276	175	1	0	1	0	0	-1	6	6	6
1696	14	173	85	59	81	1	2	4	8	42	314	286	169	44	305	276	175	0	1	1	-1	0	0	6	6	6
1697	14	173	85	59	81	1	2	1	8	41	305	282	181	44	305	276	175	2	1	1	0	-2	-4	6	5	5
1698	14	173	85	59	81	2	3	1	1	276	32	24	529	276	44	44	524	3	1	1	10	-35	-17	4	3	3
1699	14	173	85	59	81	2	3	2	1	280	46	34	521	276	44	44	524	2	0	1	6	-15	-17	6	6	6
1700	14	173	85	59	81	2	3	3	1	284	32	45	534	276	44	44	524	3	1	1	4	-9	-12	5	5	5
1701	14	173	85	59	81	2	3	4	1	282	22	39	517	276	44	44	524	6	0	2	0	0	0	5	5	4
1702	14	173	85	59	81	2	3	1	2	30	35	303	534	44	44	276	524	3	1	1	31	-21	-29	4	3	3
1703	14	173	85	59	81	2	3	2	2	37	33	271	545	44	44	276	524	2	0	1	-11	-4	10	6	6	6
1704	14	173	85	59	81	2	3	3	2	22	28	286	528	44	44	276	524	3	1	1	-4	-1	7	5	5	5
1705	14	173	85	59	81	2	3	4	2	43	18	285	536	44	44	276	524	6	0	2	0	-1	-1	5	5	4
1706	14	173	85	59	81	2	3	1	3	286	534	17	45	276	524	44	44	3	1	1	9	-1	-6	4	3	3
1707	14	173	85	59	81	2	3	2	3	284	527	34	47	276	524	44	44	2	0	1	7	7	-11	6	6	6
1708	14	173	85	59	81	2	3	3	3	286	513	55	21	276	524	44	44	3	1	1	0	4	1	5	5	5
1709	14	173	85	59	81	2	3	4	3	292	533	24	26	276	524	44	44	6	0	2	0	1	2	5	5	4
1710	14	173	85	59	81	2	3	1	4	40	527	272	54	44	524	276	44	3	1	1	-2	12	6	4	3	3
1711	14	173	85	59	81	2	3	2	4	55	509	280	46	44	524	276	44	2	0	1	-5	8	16	6	6	6
1712	14	173	85	59	81	2	3	3	4	42	522	273	41	44	524	276	44	3	1	1	-11	16	20	5	5	5
1713	14	173	85	59	81	2	3	4	4	40	519	283	47	44	524	276	44	6	0	2	-2	3	2	5	5	4
1714	14	173	85	59	81	2	3	1	5	39	201	287	377	44	204	276	364	3	1	1	4	-2	-6	4	3	3

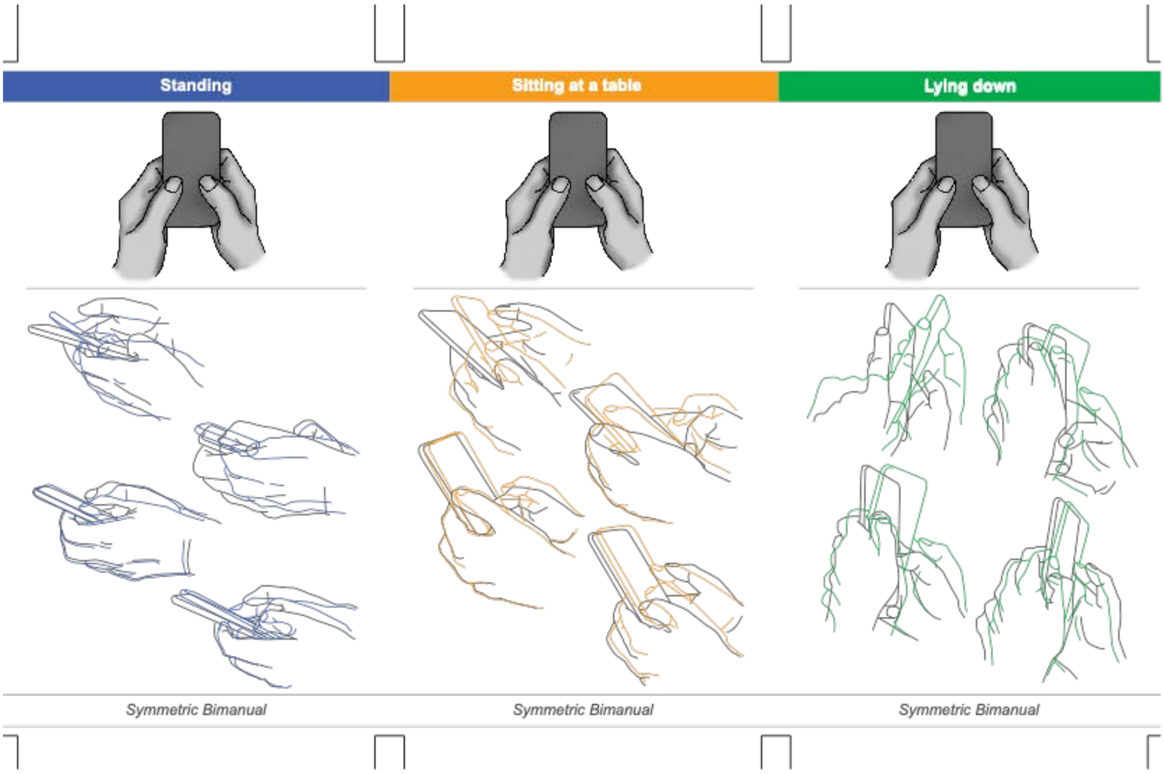
Appendix C (Chapter 6)

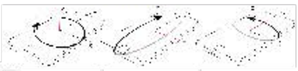
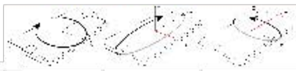
C.1 Data cards presented to the workshop participants



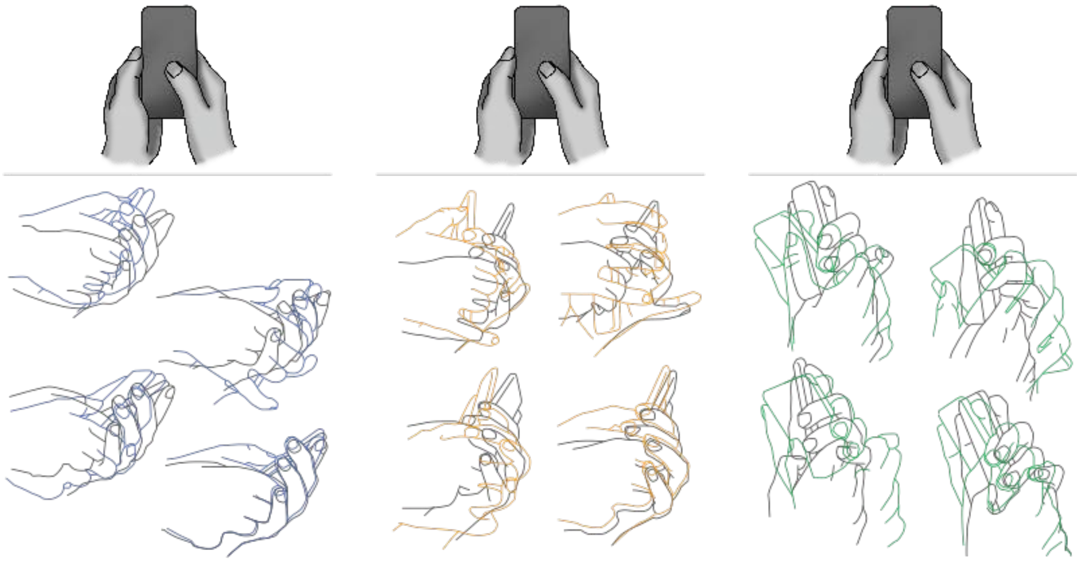


Standing			Sitting at a table			Lying down		
7.6°	15.5°	25.9°	10.4°	18.5°	35.6°	45.8°	24.3°	46.3°
6.8°	15.9°	28.6°	9.9°	16.7°	42.4°	71.0°	32.4°	63.4°
6.8°	18.4°	9.6°	9.3°	17.7°	17.3°	46.1°	17.2°	46.9°
7.2°	15.9°	9.6°	7.8°	15.2°	16.7°	50.4°	15.0°	44.9°
5.6°	8.4°	15.1°	5.1°	8.8°	21.0°	40.8°	16.6°	44.3°
4.7°	9.4°	14.7°	4.2°	9.6°	19.5°	50.7°	19.1°	48.6°
1.5°	2.6°	4.1°	1.8°	2.9°	4.2°	19.5°	2.3°	20.7°
1.7°	2.9°	3.8°	2.3°	3.0°	5.7°	13.3°	2.9°	13.4°
Single handed			Single handed			Single handed		

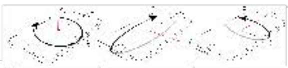


Standing			Sitting at a table			Lying down		
								
3.0°	5.8°	7.9°	5.2°	7.7°	10.8°	30.5°	13.7°	31.4°
4.4°	6.2°	7.4°	8.4°	6.2°	11.2°	26.7°	12.3°	24.8°
2.9°	8.8°	11.1°	4.3°	11.1°	12.1°	18.7°	12.7°	16.6°
2.3°	7.6°	10.1°	6.6°	11.1°	12.3°	25.2°	14.1°	27.4°
0.8°	1.6°	2.4°	1.2°	2.1°	3.4°	8.7°	2.9°	10.1°
0.7°	1.2°	2.4°	1.6°	2.7°	2.4°	12.6°	2.8°	14.2°
0.9°	2.7°	3.8°	1.1°	2.9°	4.4°	13.2°	3.9°	14.4°
1.2°	2.2°	3.5°	1.4°	2.8°	3.1°	13.1°	2.3°	14.3°
Symmetric Bimanual			Symmetric Bimanual			Symmetric Bimanual		

Standing	Sitting at a table	Lying down



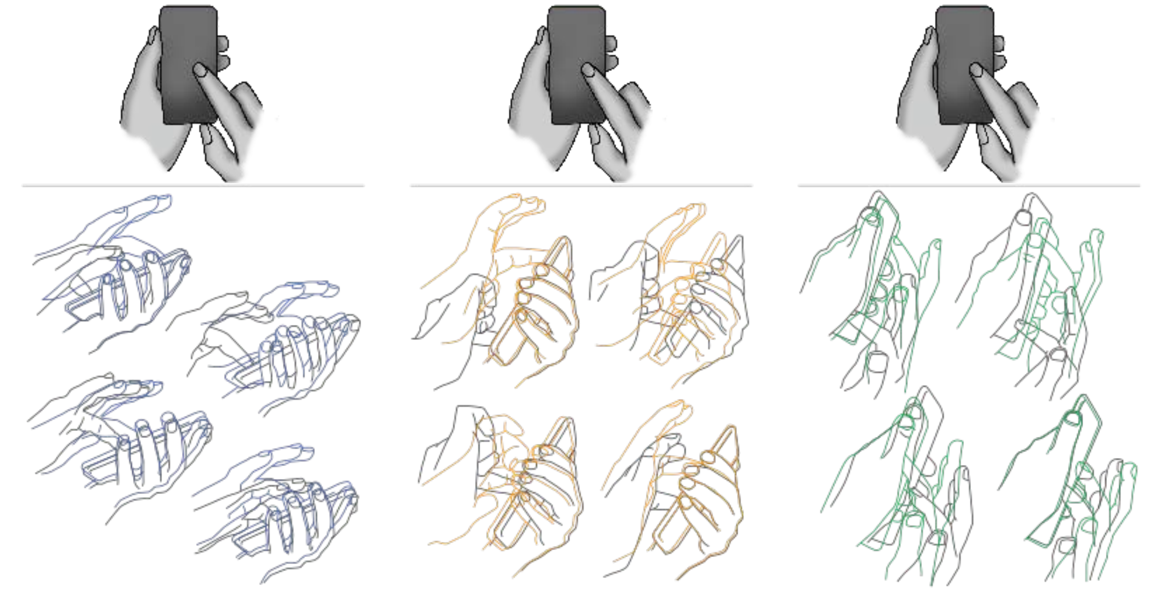
Asymmetric Bimanual with the thumb	Asymmetric Bimanual with the thumb	Asymmetric Bimanual with the thumb



Standing			Sitting at a table			Lying down		
6.4°	13.3°	26.3°	13.8°	19.1°	33.8°	37.3°	21.2°	35.2°
5.8°	11.9°	26.0°	11.6°	19.6°	32.0°	27.3°	23.0°	42.6°
5.0°	8.3°	7.4°	11.7°	12.9°	17.2°	20.5°	14.4°	18.9°
4.9°	7.7°	8.1°	8.0°	10.4°	13.8°	29.3°	13.4°	27.7°
2.6°	6.7°	14.1°	4.4°	8.3°	17.1°	15.3°	9.6°	23.5°
2.6°	6.8°	14.2°	4.3°	9.4°	16.6°	12.3°	9.8°	18.4°
1.0°	1.1°	2.7°	1.6°	1.2°	1.7°	11.2°	2.4°	13.7°
0.6°	1.1°	2.2°	0.7°	1.3°	2.2°	3.9°	2.1°	4.9°

Asymmetric Bimanual with the thumb	Asymmetric Bimanual with the thumb	Asymmetric Bimanual with the thumb

Standing	Sitting at a table	Lying down



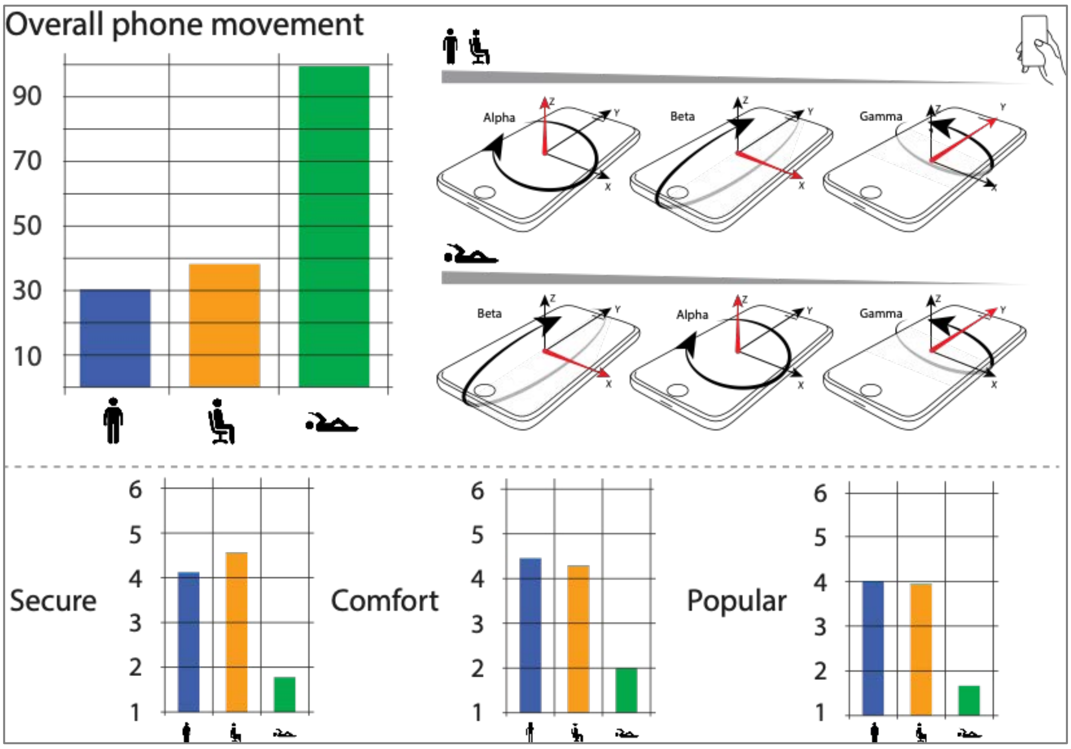
Asymmetric Bimanual with a finger | Asymmetric Bimanual with a finger | Asymmetric Bimanual with a finger

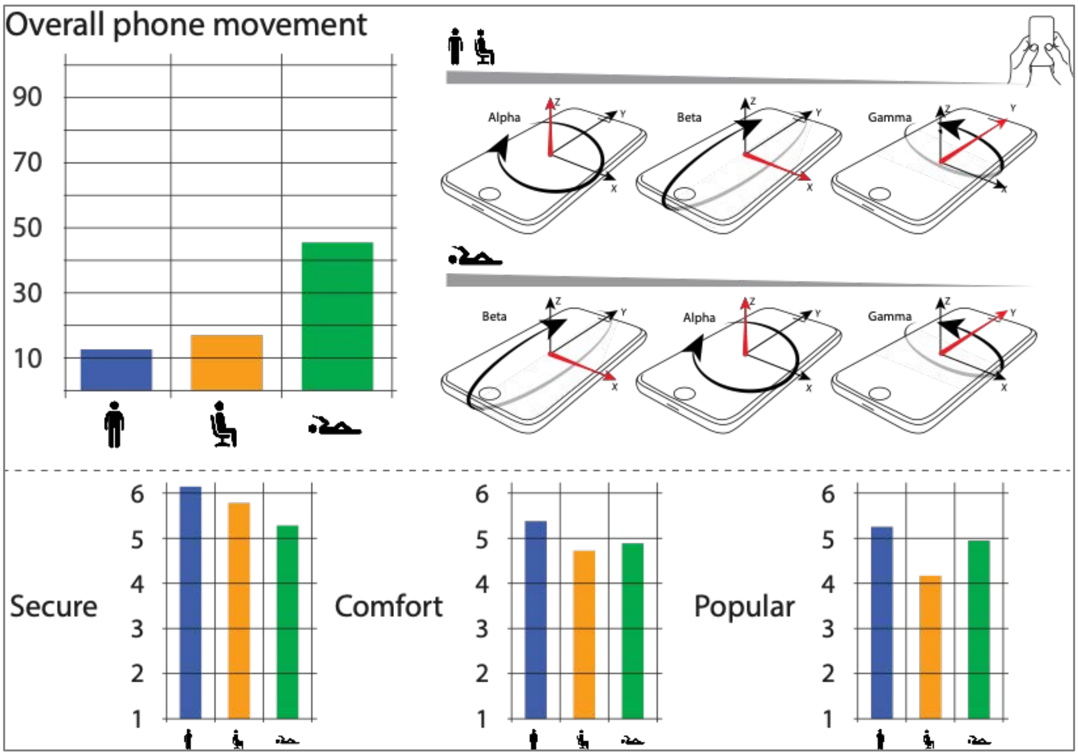
Standing			Sitting at a table			Lying down		
4.4°	3.4°	5.2°	8.2°	6.1°	11.4°	26.7°	6.4°	25.3°
3.2°	3.1°	4.4°	8.4°	5.0°	11.7°	31.5°	7.9°	28.2°
1.6°	1.4°	1.2°	3.2°	2.6°	3.7°	11.4°	2.9°	9.8°
1.6°	1.6°	1.3°	2.6°	2.2°	3.2°	11.8°	2.4°	10.3°
1.6°	1.2°	3.0°	3.6°	3.1°	6.9°	11.4°	3.7°	12.6°
1.9°	1.2°	2.7°	2.6°	2.7°	5.3°	27.1°	4.8°	25.3°
0.4°	0.5°	0.7°	0.8°	0.7°	1.0°	12.2°	1.5°	12.2°
0.2°	0.3°	0.8°	0.4°	0.5°	0.7°	3.7°	0.3°	3.2°

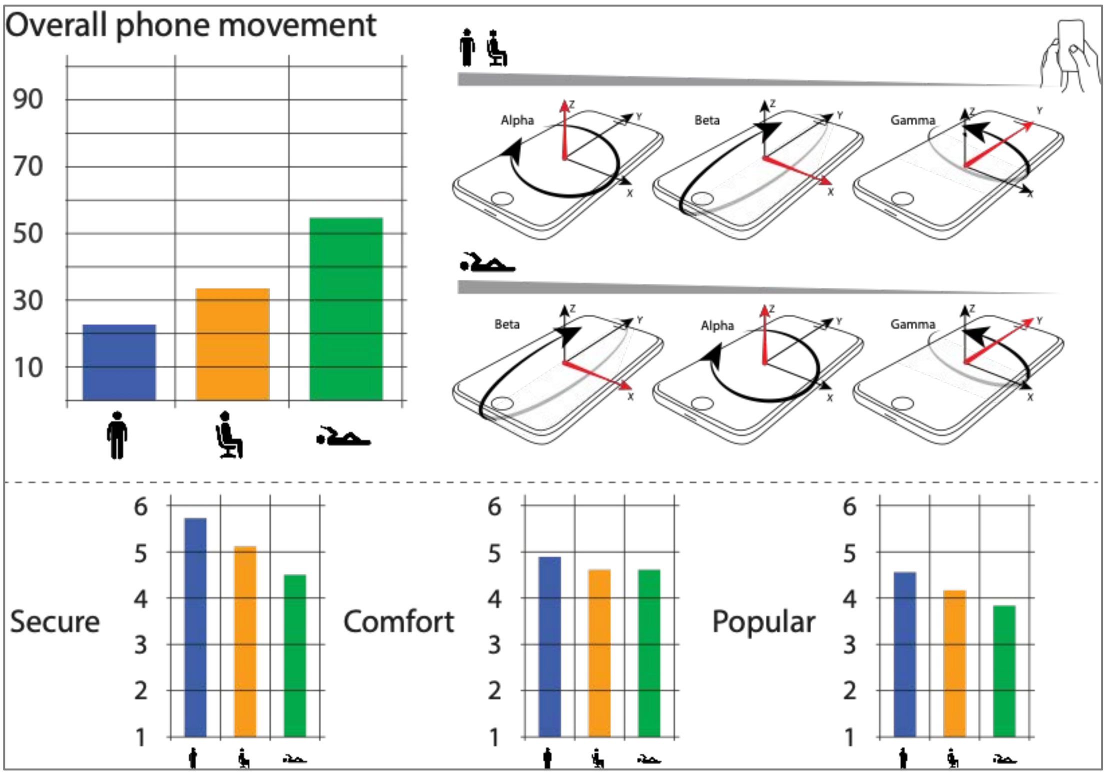
Asymmetric Bimanual with a finger | Asymmetric Bimanual with a finger | Asymmetric Bimanual with a finger

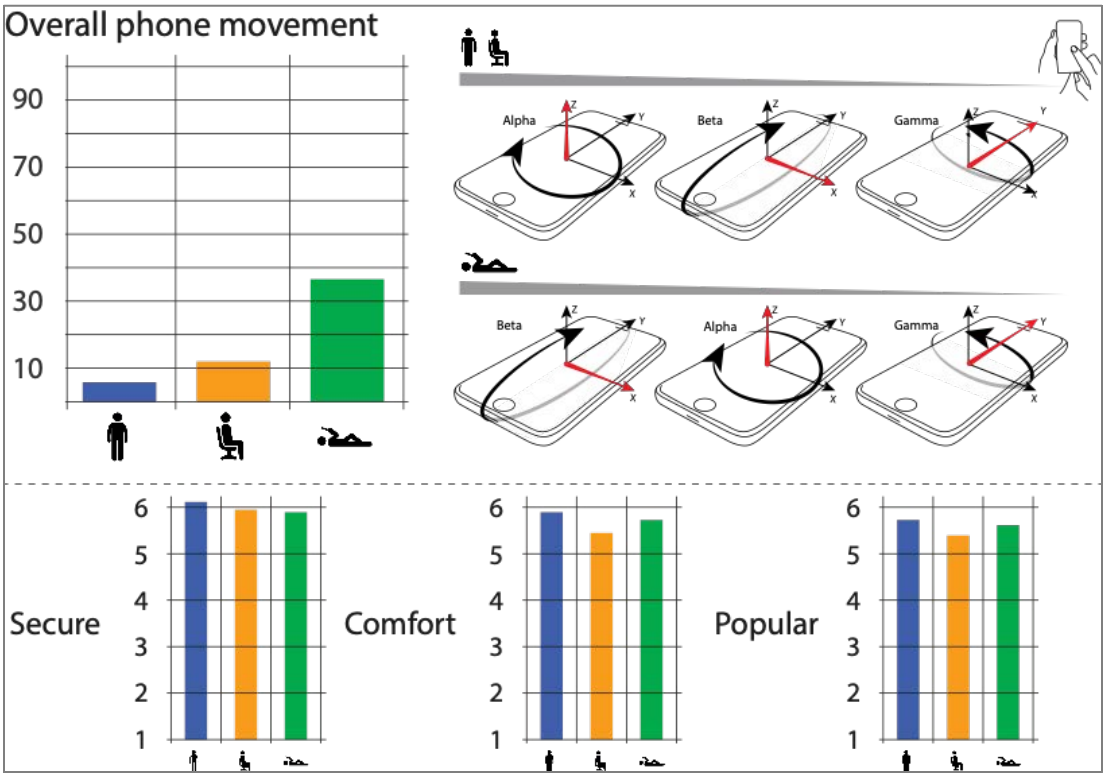
Appendix D (Chapter 7)

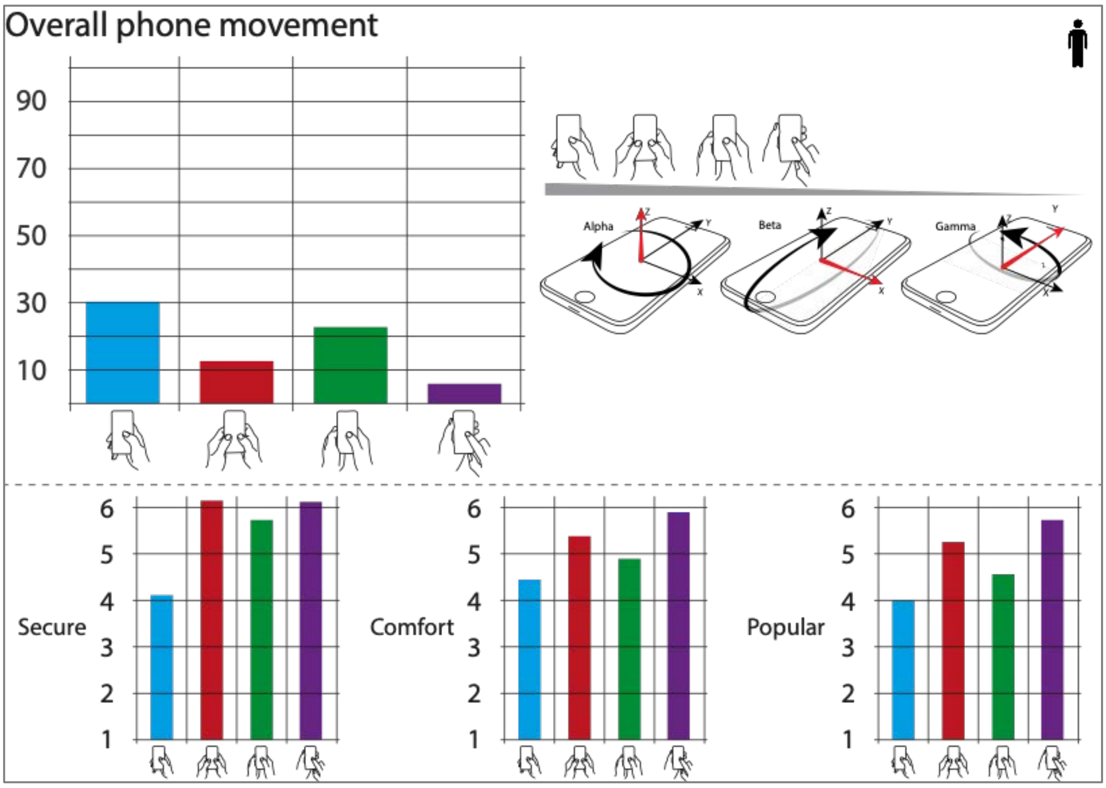
D.1 A4 sheets comparing the body posture and hand grips

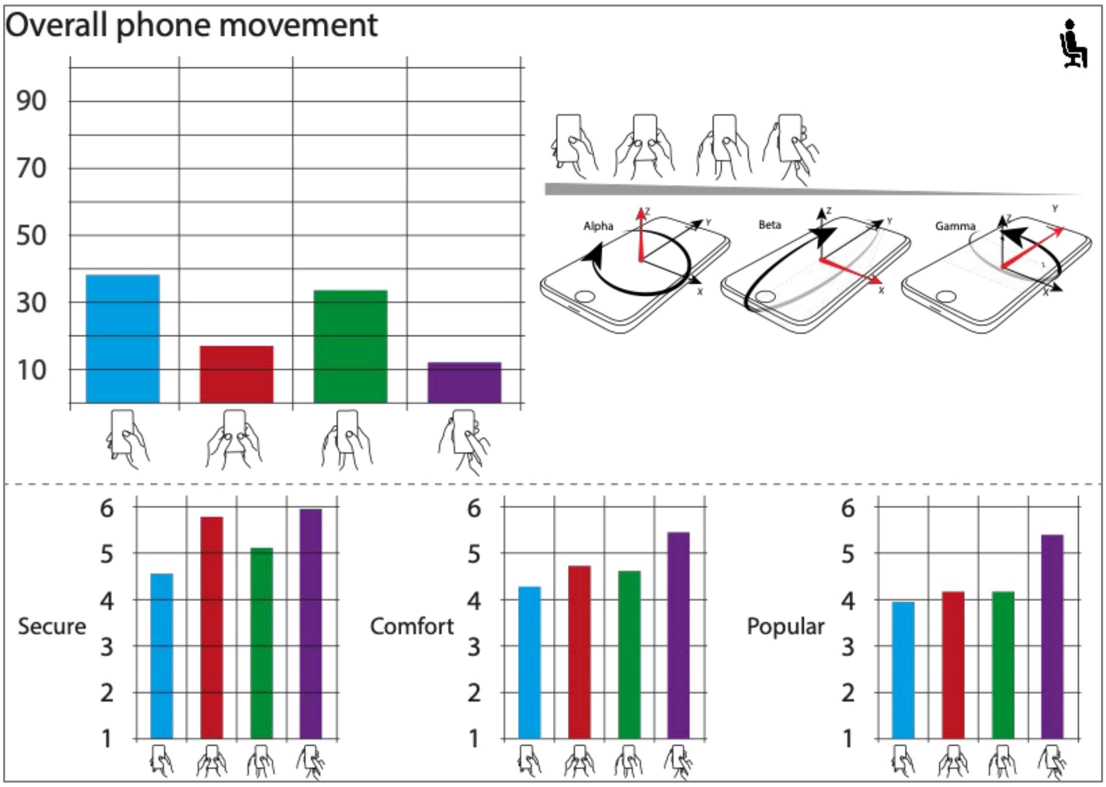


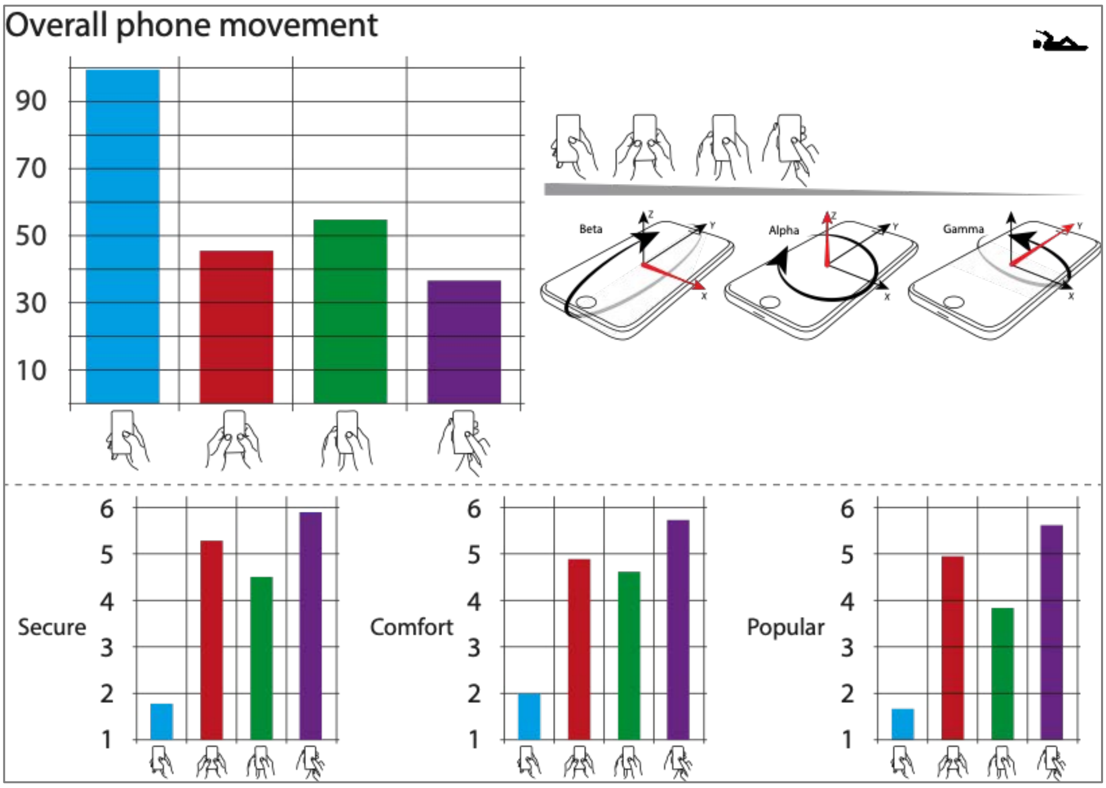



Overall phone movement
90
70
50
30
10
Alpha
Beta
Gamma
Beta
Alpha
Gamma
Secure
Comfort
Popular
6
5
4
3
2
1

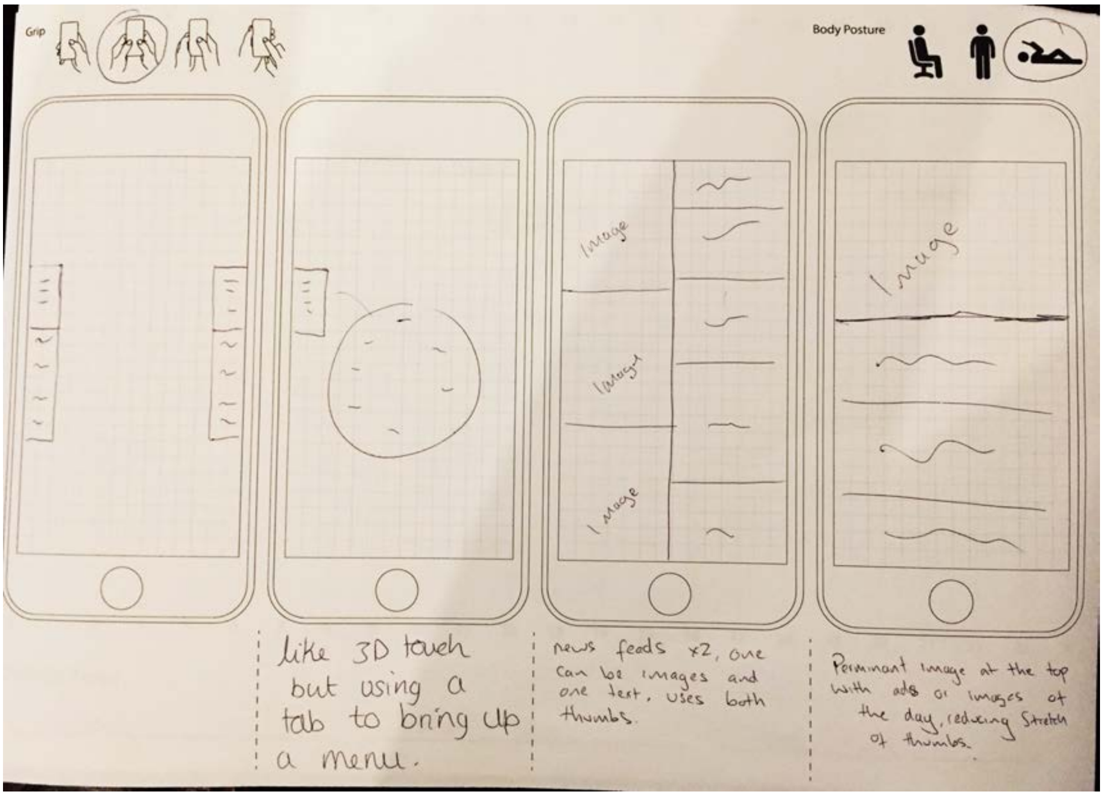

Overall phone movement
90
70
50
30
10
Alpha
Beta
Gamma
Beta
Alpha
Gamma
Secure
Comfort
Popular
6
5
4
3
2
1

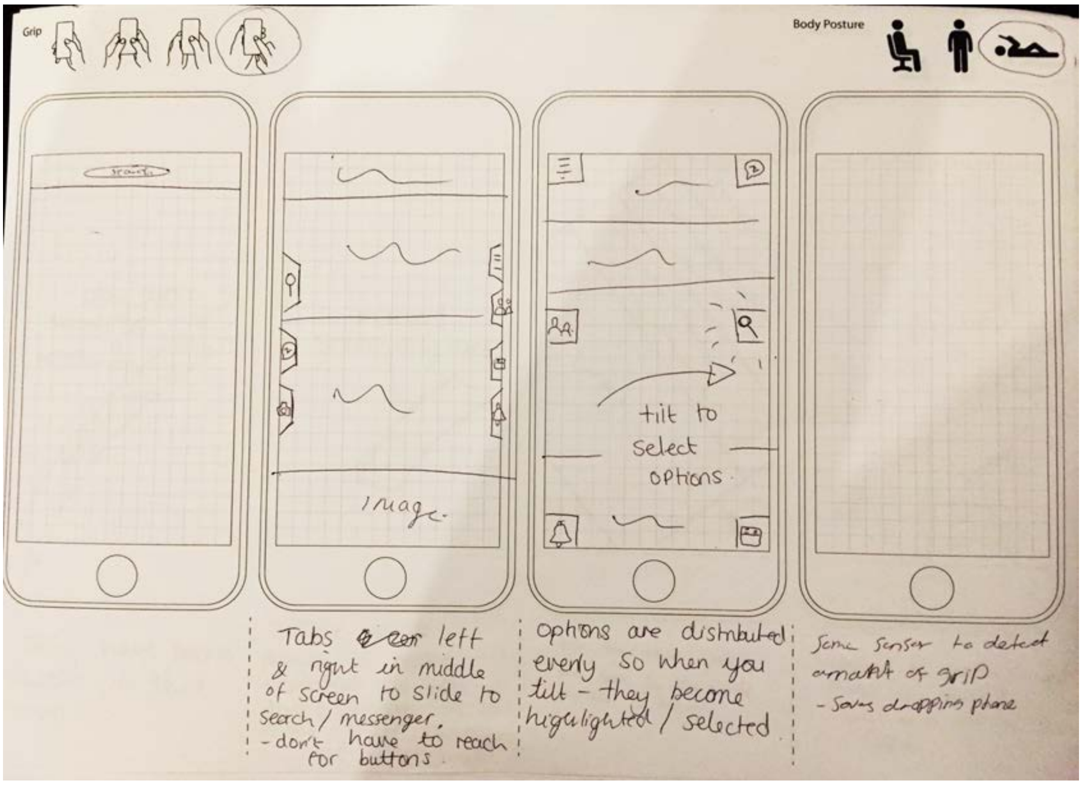

Overall phone movement
90
70
50
30
10
Alpha
Beta
Gamma
Secure
Comfort
Popular
6
5
4
3
2
1

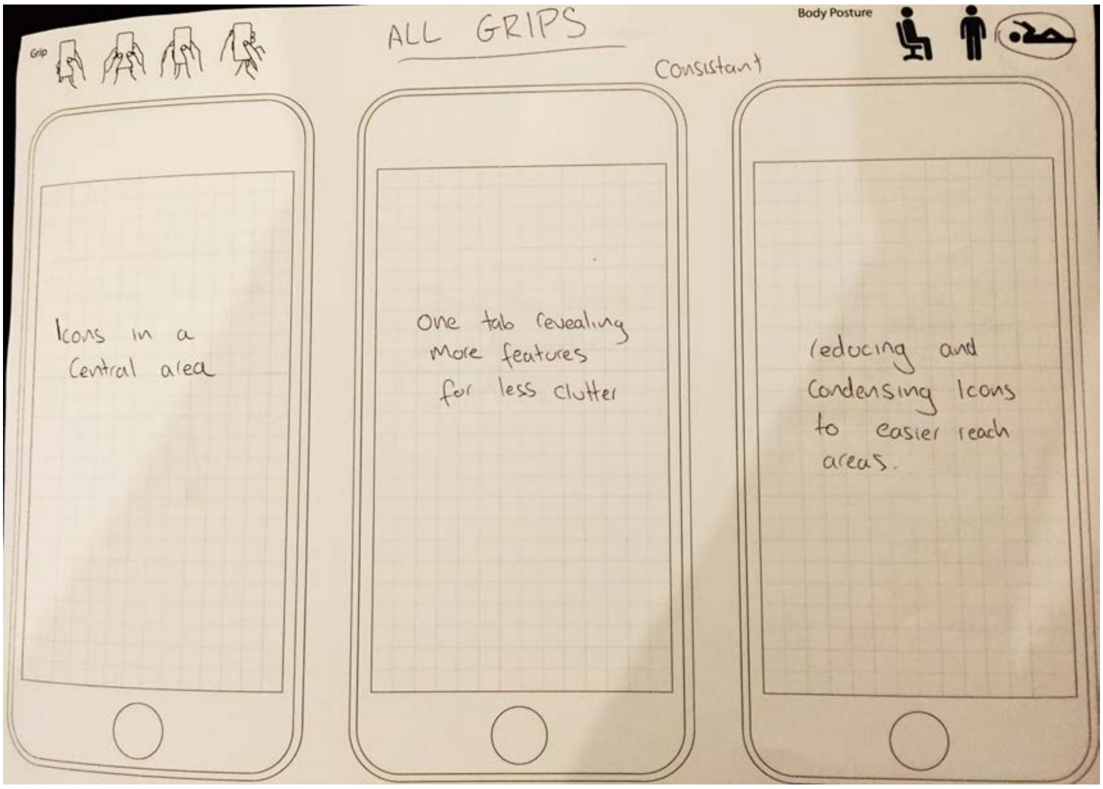

Overall phone movement
90
70
50
30
10
Alpha
Beta
Gamma
Secure
Comfort
Popular
6
5
4
3
2
1


Overall phone movement
90
70
50
30
10
Beta
Alpha
Gamma
Secure
Comfort
Popular
6
5
4
3
2
1

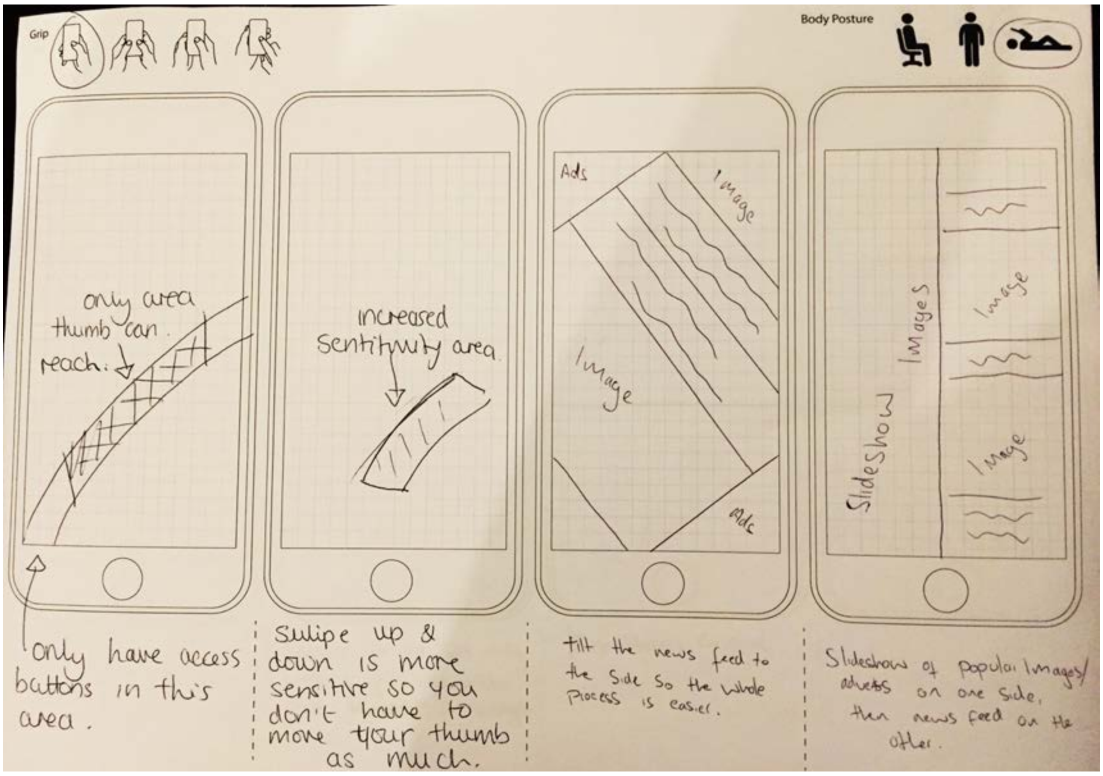
D.2 Participant sketches (Grip workshop)



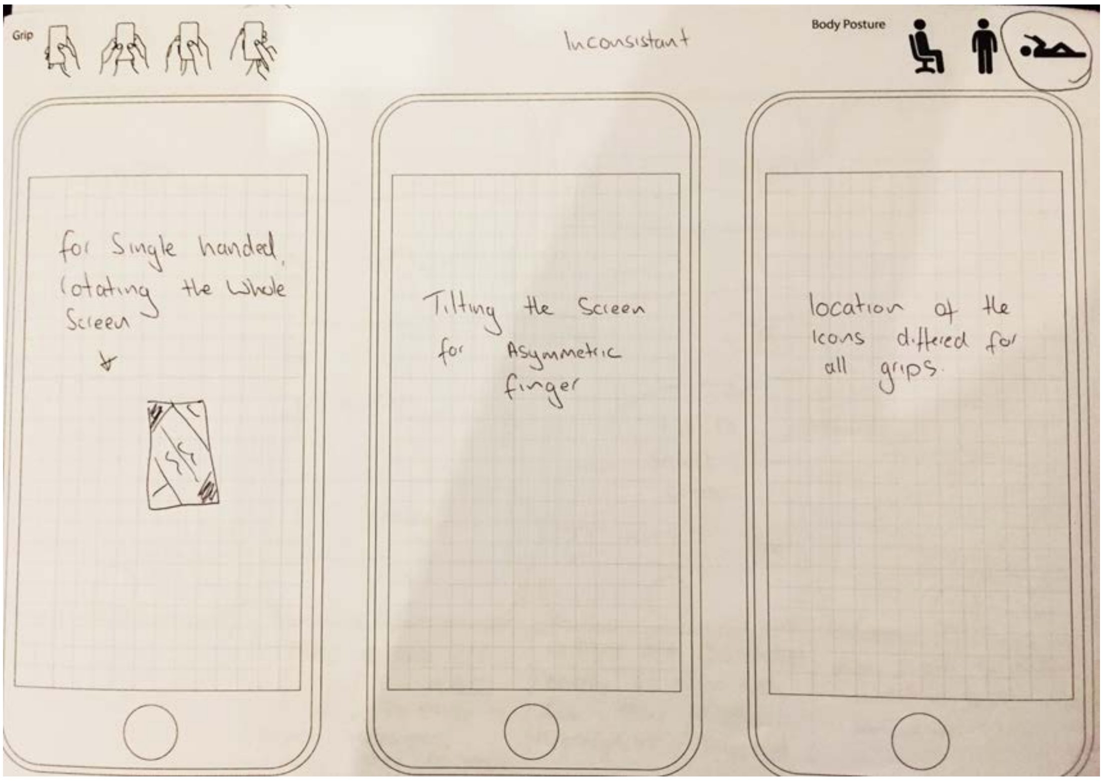


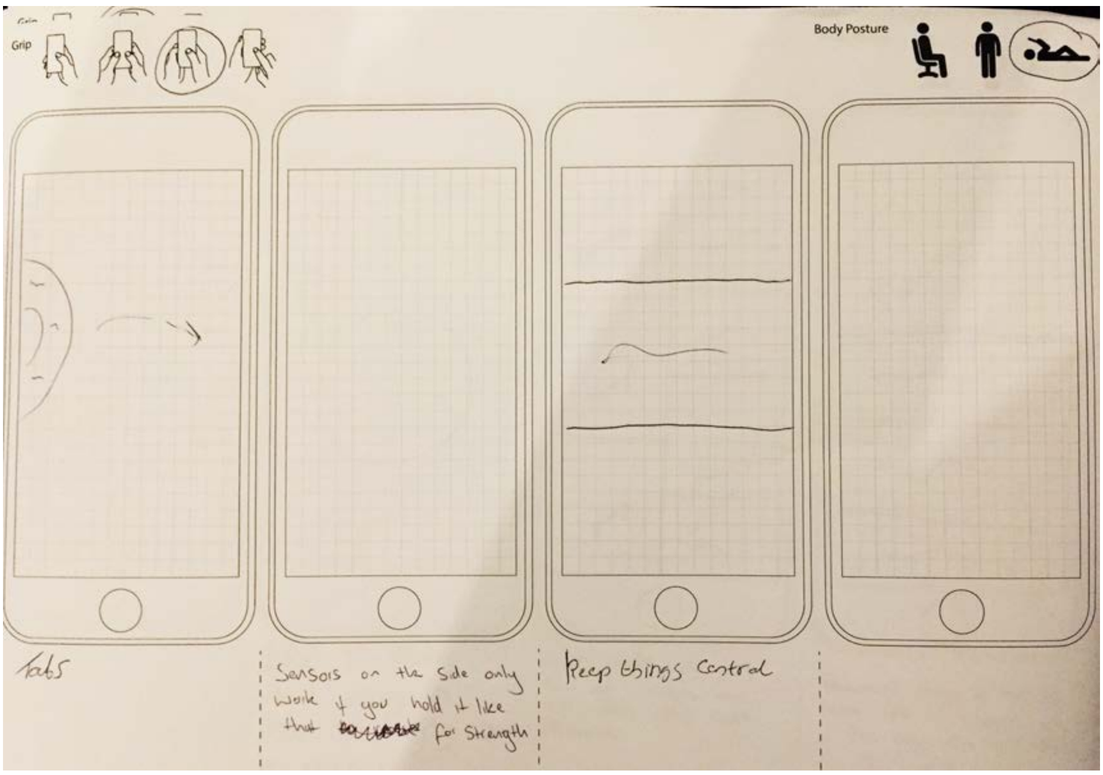


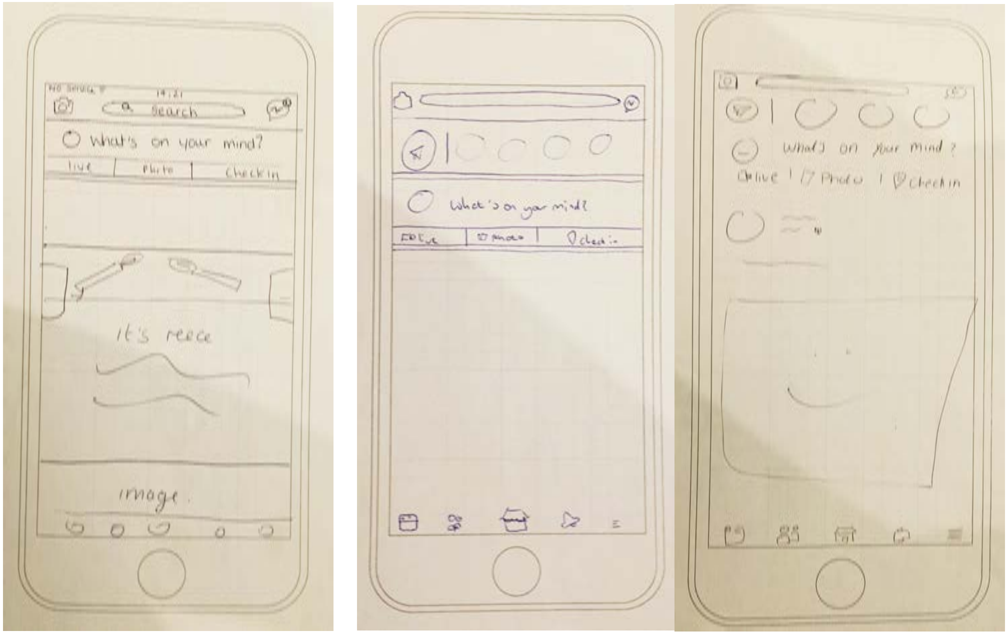
Grip
ALL GRIPS
Consistant
Body Posture
Icons in a Central area
One tab revealing more features for less clutter
reducing and Condensing Icons to easier reach areas.

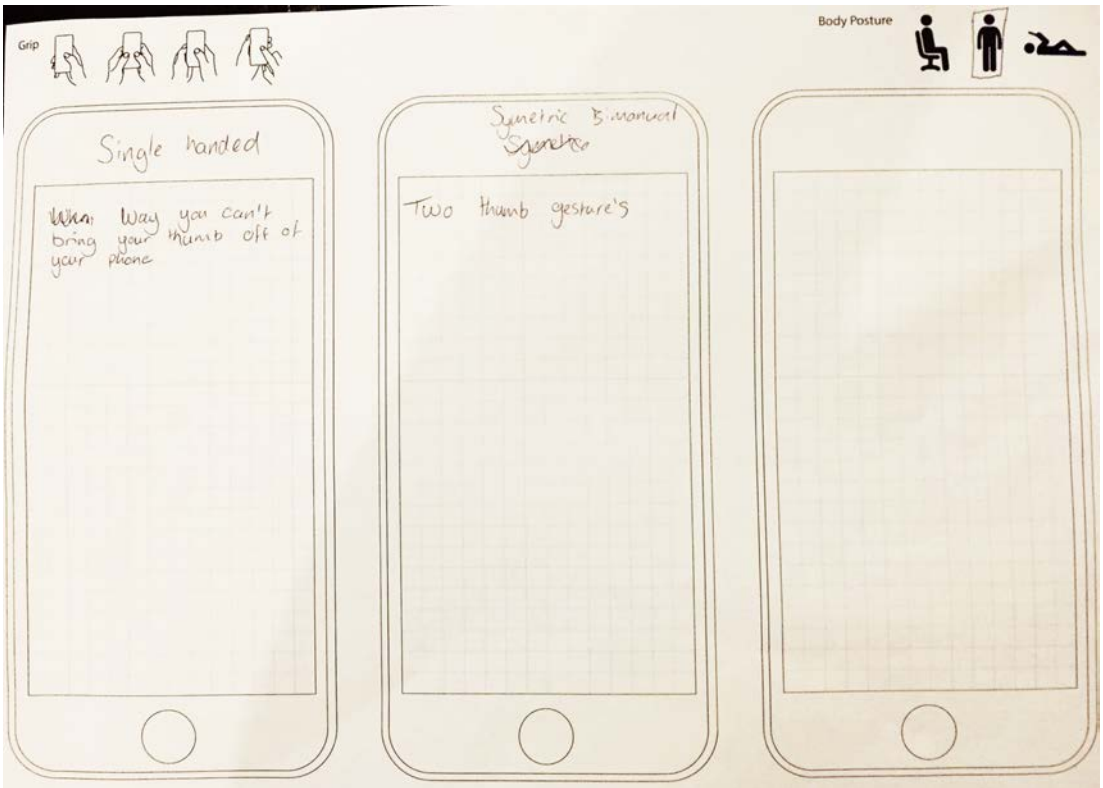


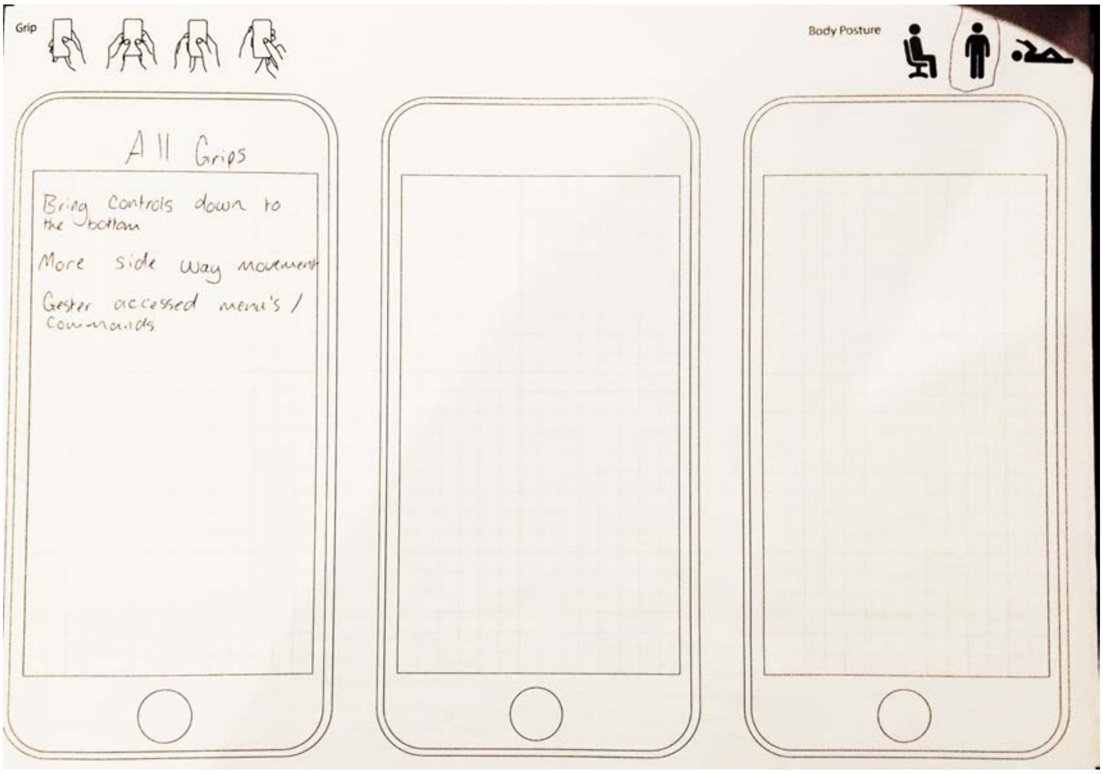
Grip
Body Posture
only area thumb can reach.
increased sentitivity area
Ads
Image
Image
Ads
Slideshow
Images
Image
Image
only have access buttons in this area.
Swipe up & down is more sensitive so you don't have to move your thumb as much.
tilt the news feed to the side so the whole process is easier.
Slideshow of popular Images/adverts on one Side, then news feed on the other.

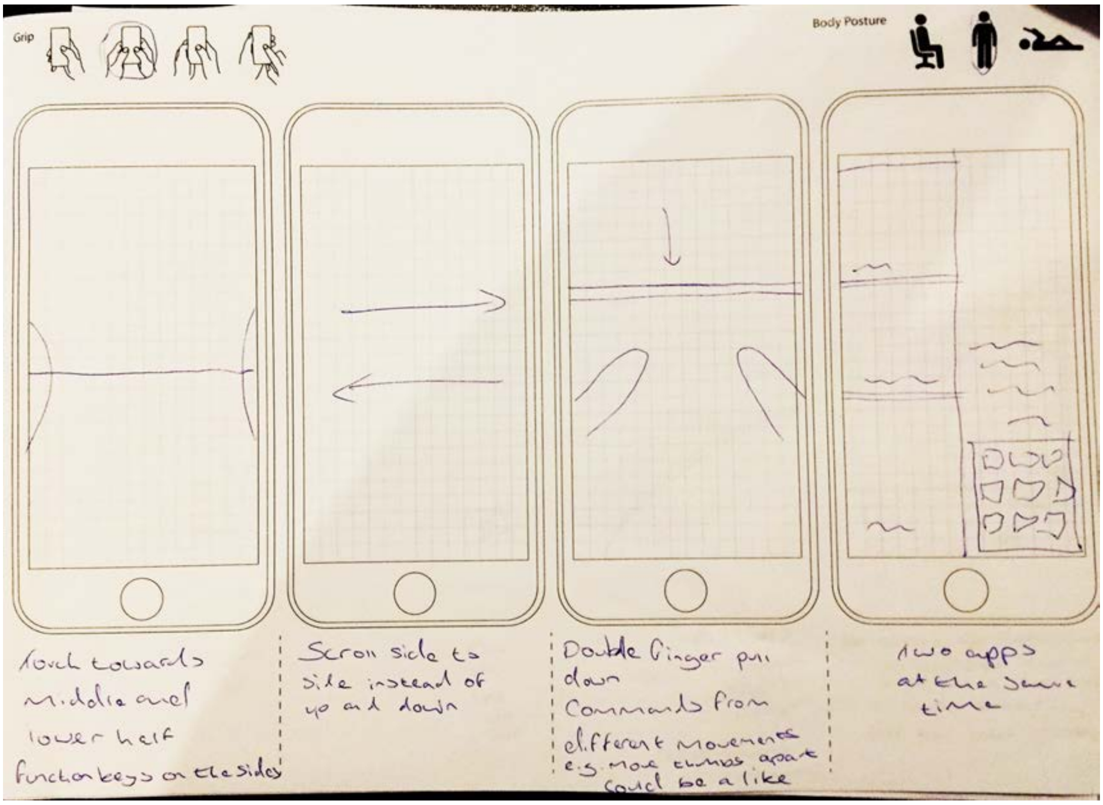

Grip
Inconsistant
Body Posture
for Single handed, rotating the Whole Screen
Tilting the Screen for Asymmetric finger
location of the icons differed for all grips.

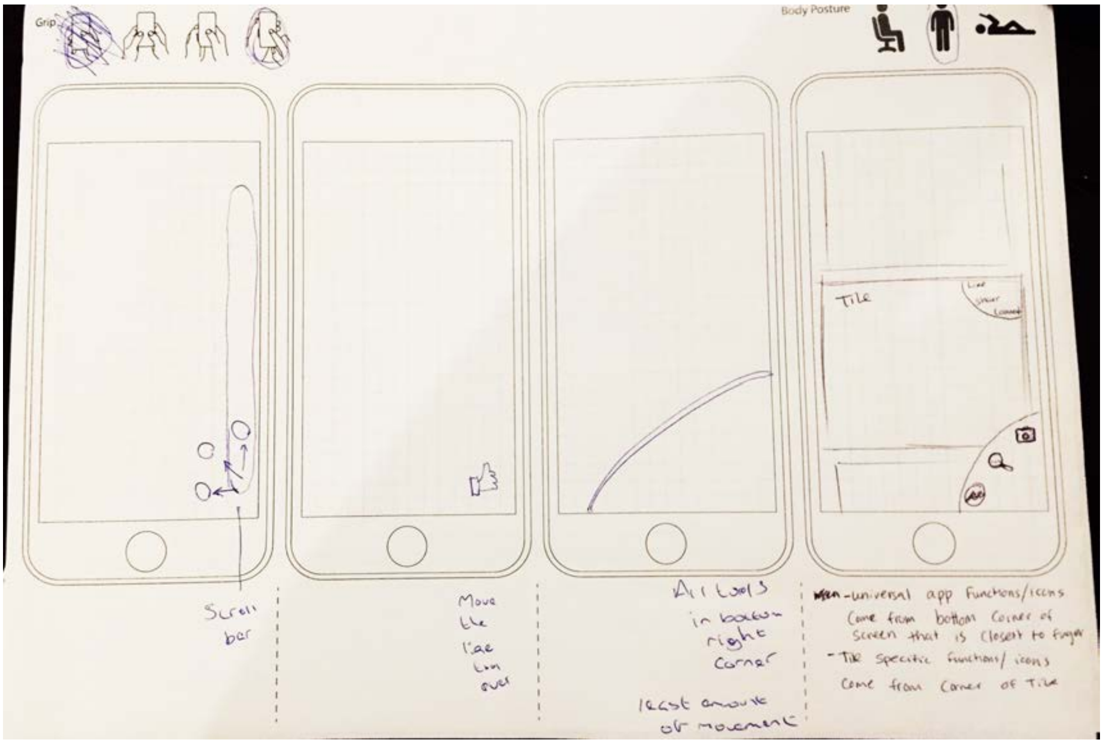

Grip
Body Posture
Tabs
Sensors on the side only work if you hold it like that for Strength
Keep things Central

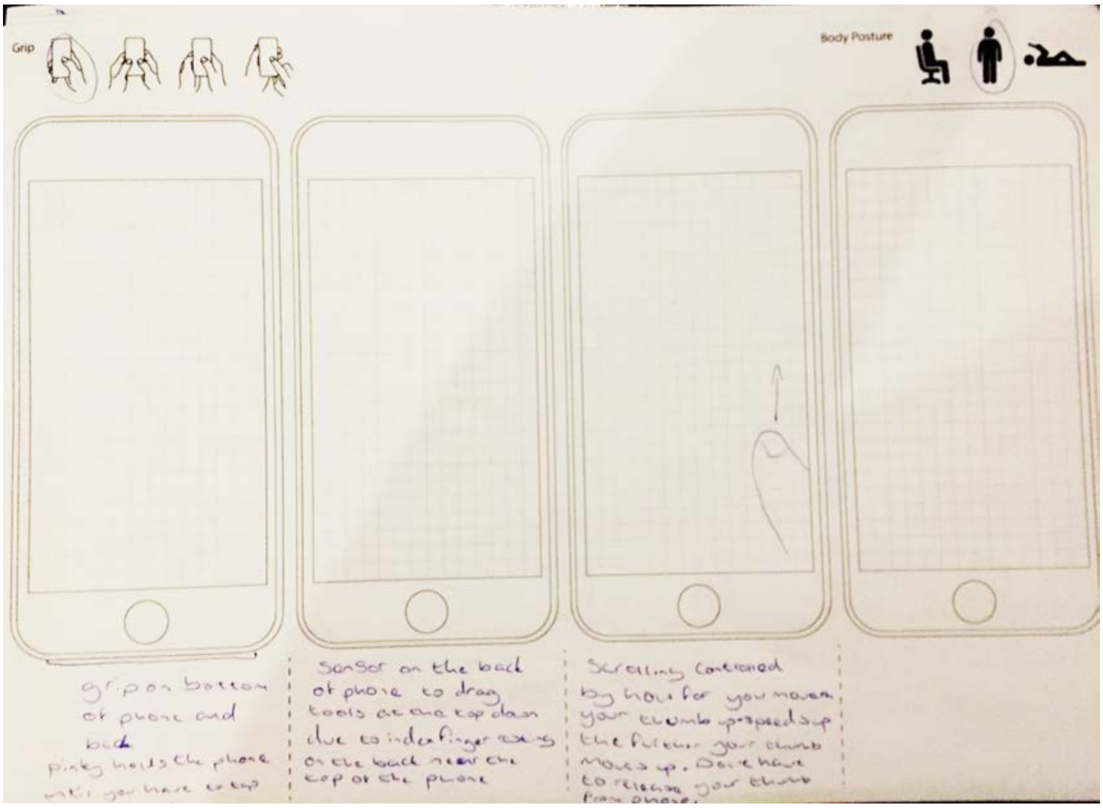

Search
What's on your mind?
live
Photo
Check in
it's reece
image
What's on your mind?
Photo
Check in

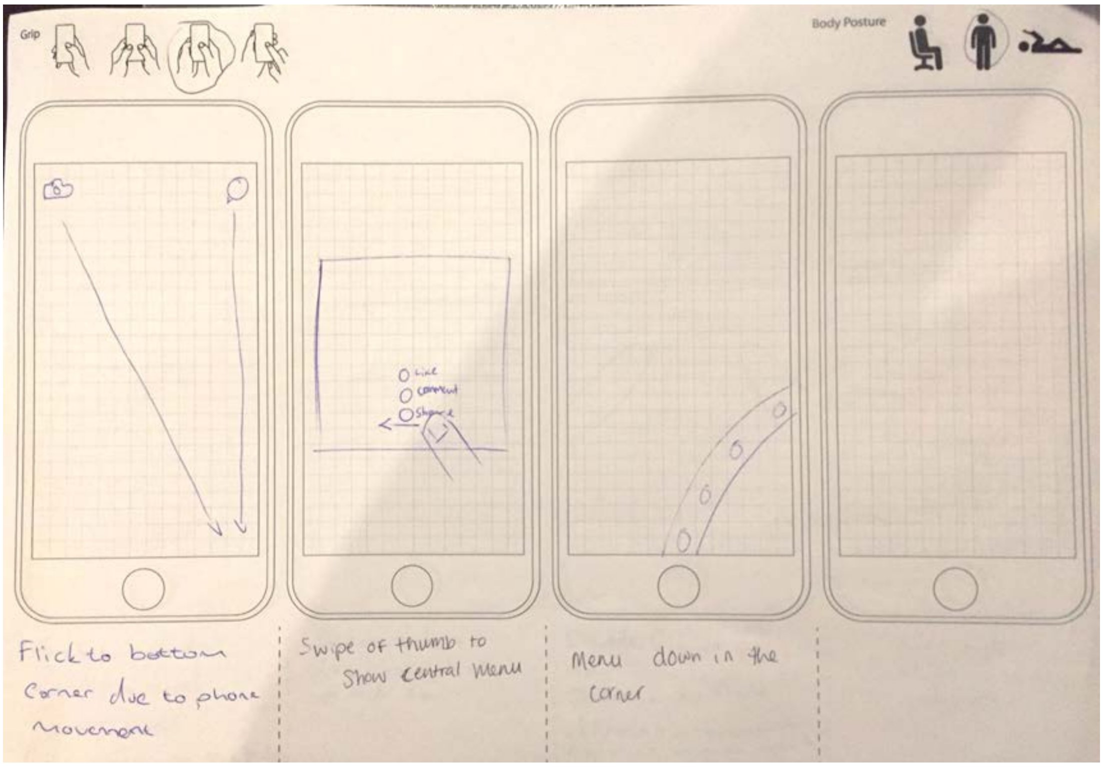

Grip
Body Posture
Single handed
When way you can't bring your thumb off of your phone
Symetric Bimanual
Two thumb gesture's

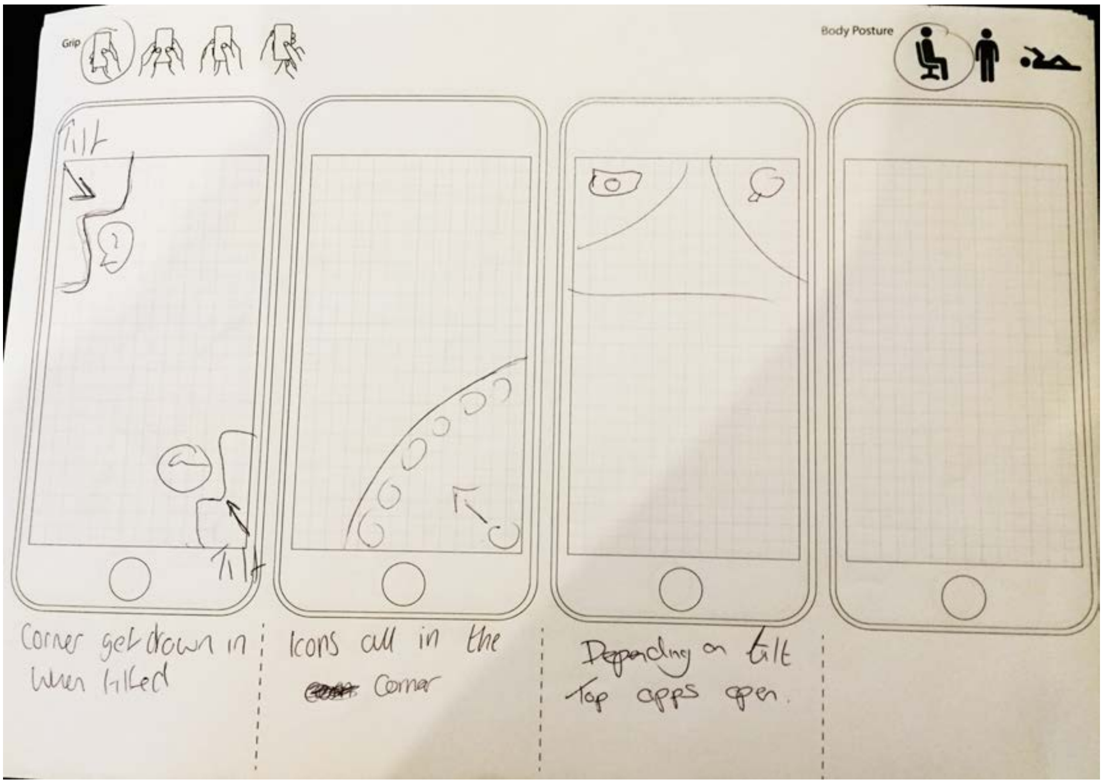

Grip
Body Posture
All Grips
Bring controls down to the bottom
More side way movement
Gester accessed menu's / commands

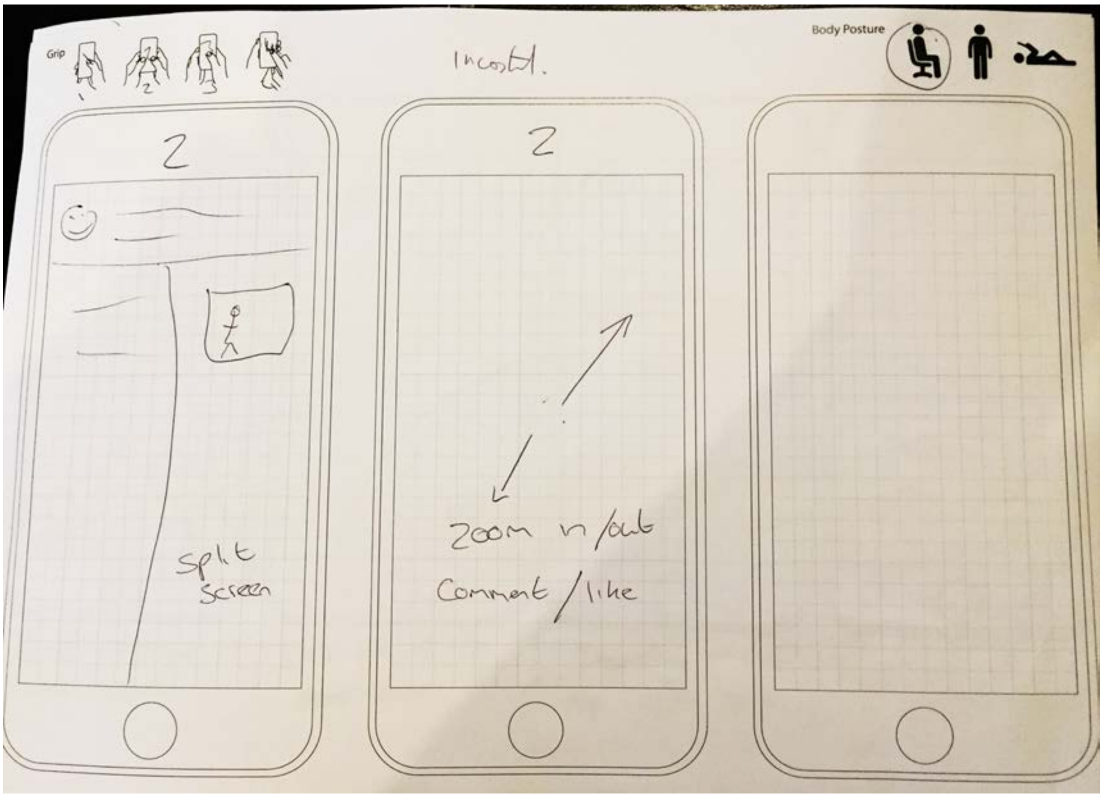

Grip
Body Posture
Touch towards middle and lower half
Function keys on the sides
Scroll side to side instead of up and down
Double finger pull down
Commands from different movements
e.g. move thumbs apart could be a like
Two apps at the same time

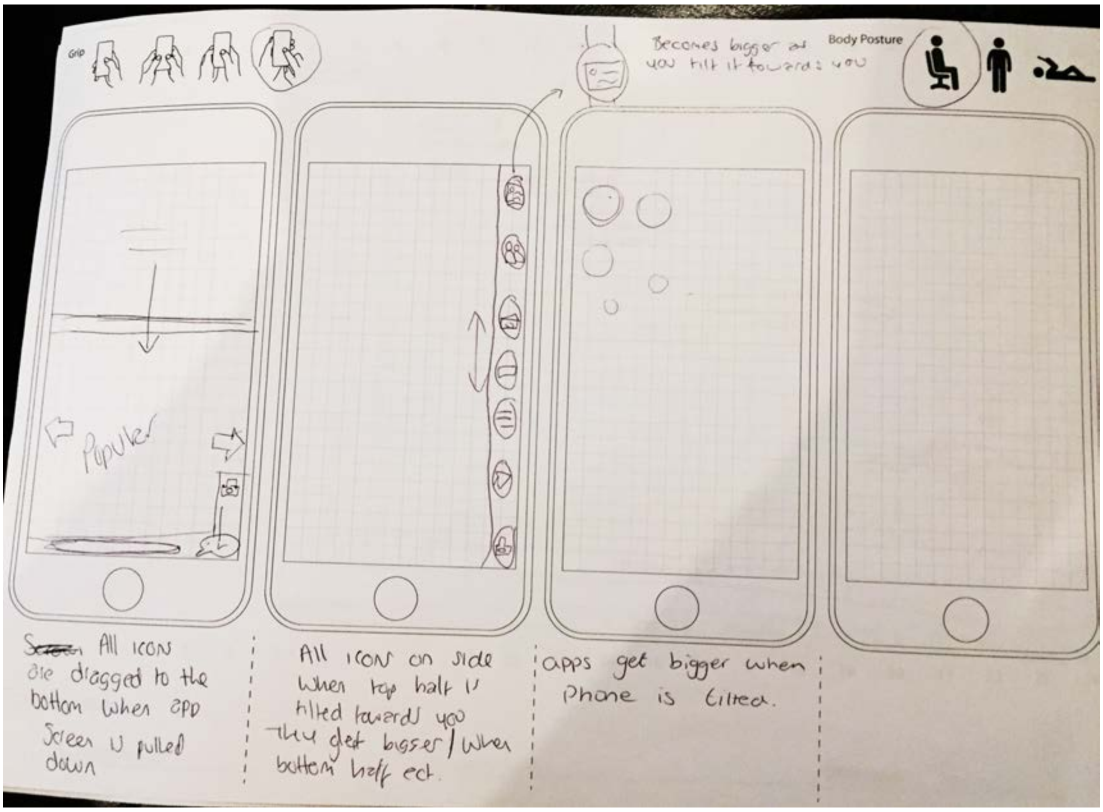

Grip
Body Posture
Tile
Scroll bar
Move the like icon over
All tools in bottom right corner
least amount of movement
-universal app functions/icons come from bottom corner of screen that is closest to finger
-Tile specific functions/icons come from corner of tile

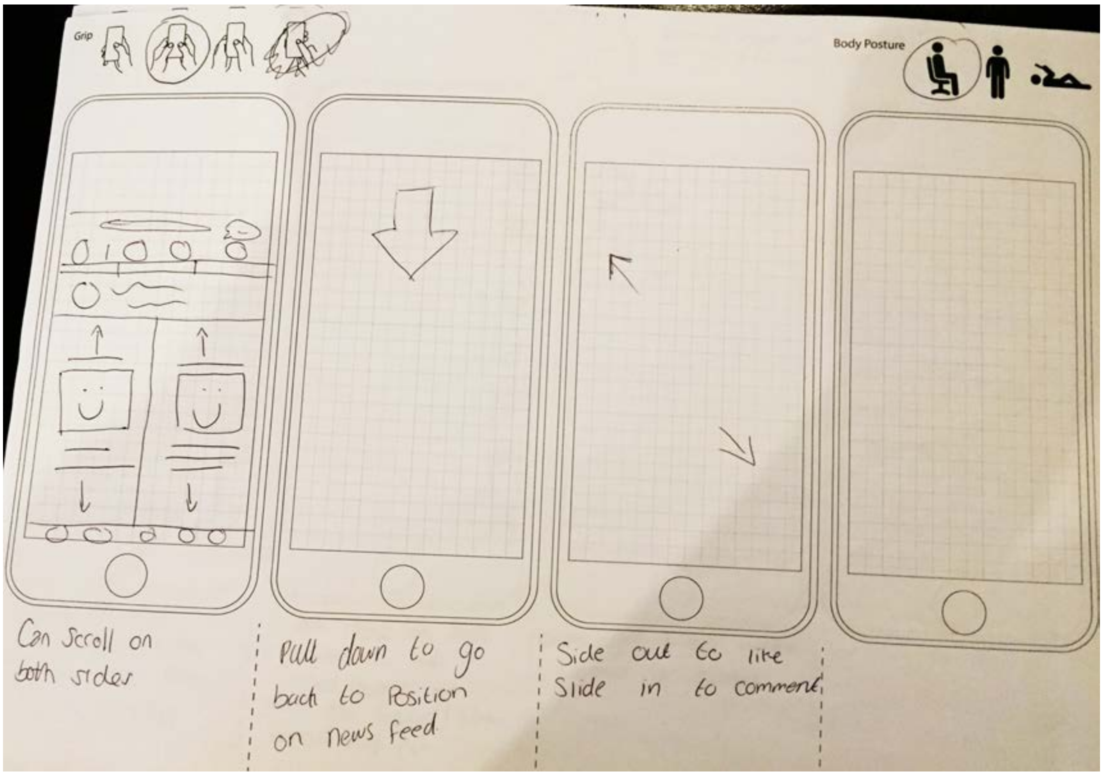

Grip
Body Posture
grip on bottom of phone and back
Pinky holds the phone
Sensor on the back of phone to drag tools at the top down due to index finger resting on the back near the top of the phone
Scrolling controlled by how far you move your thumb up - speeds up the further your thumb moves up. Don't have to release your thumb from phone.

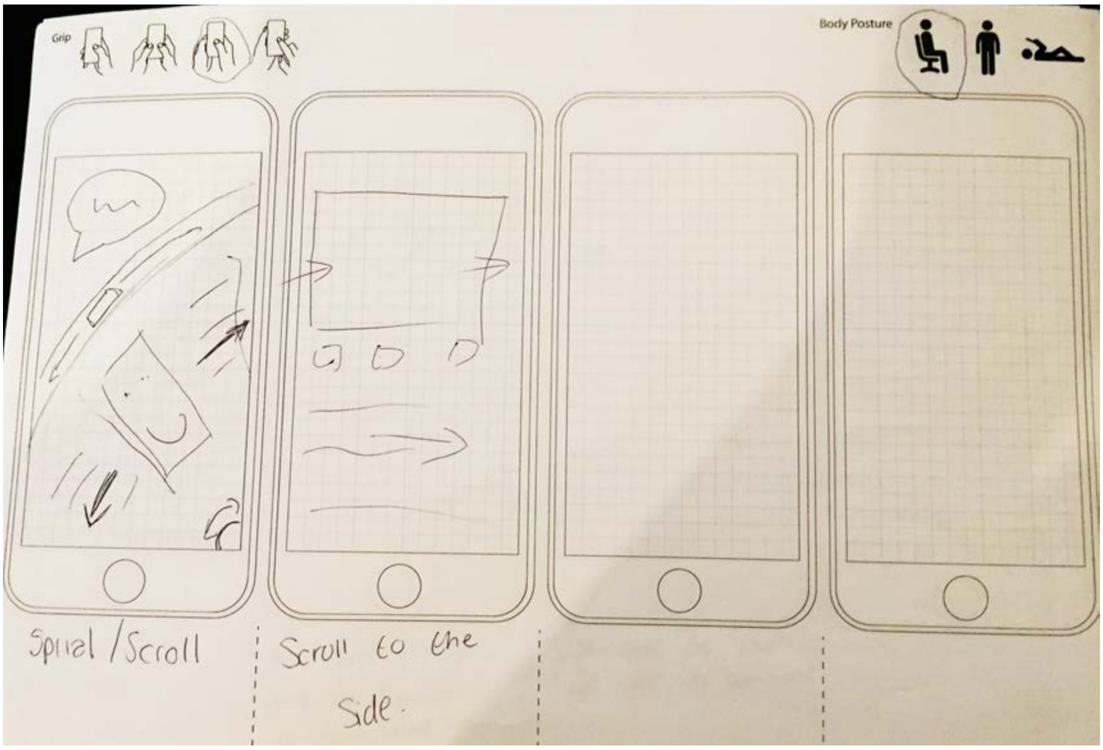

Grip
Body Posture
like
comment
Share
Flick to bottom corner due to phone movement
Swipe of thumb to show central menu
Menu down in the corner

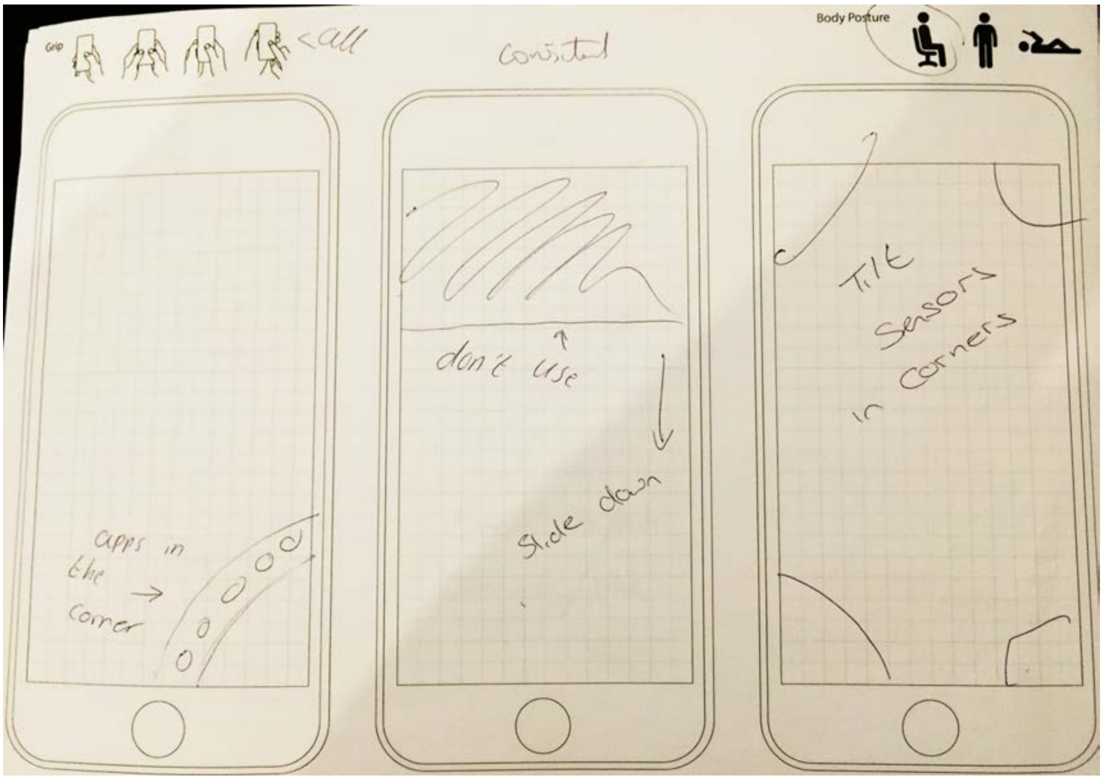

Grip
Body Posture
Tilt
Tilt
Corner get down in when tilted
Icons all in the Corner
Depending on tilt Top apps open.


Grip
Body Posture
2
2
Split screen
Zoom in/out
Comment / like

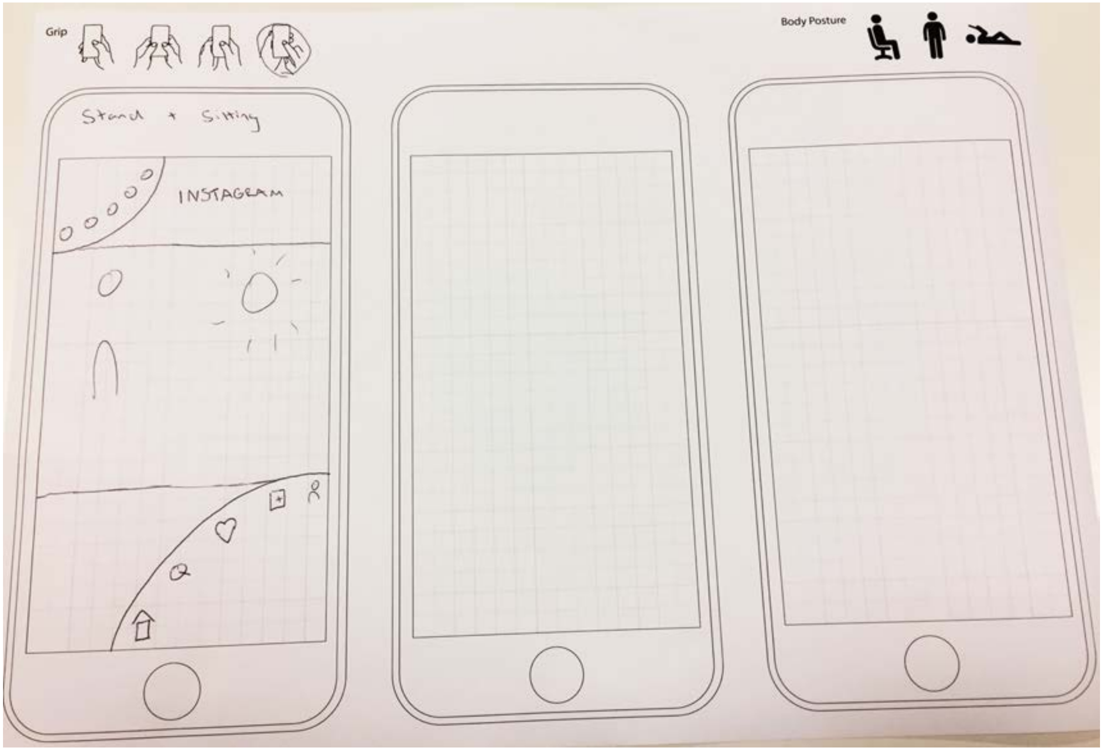

Grip
Becomes bigger as you tilt it towards you
Body Posture
Popular
~~Screen~~ All icon are dragged to the bottom when app screen is pulled down
All icon on side when top half is tilted towards you they get bigger / when bottom half ect.
apps get bigger when phone is tilted.

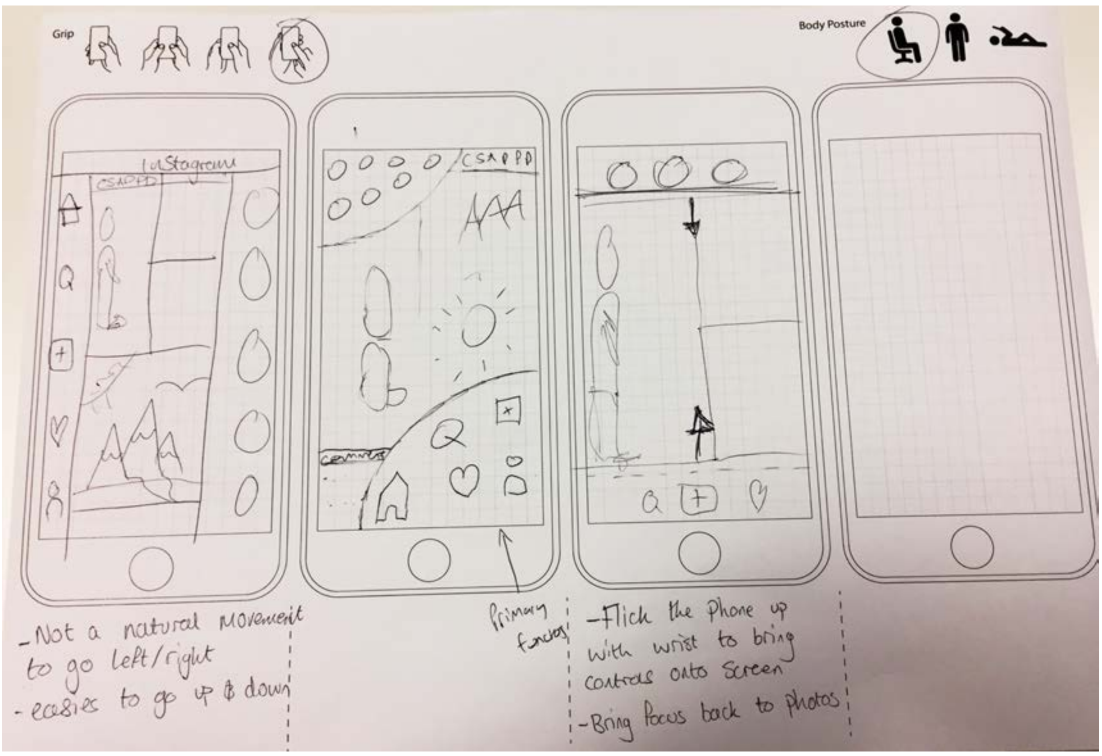

Grip
Body Posture
Can scroll on both sides
Pull down to go back to Position on news feed
Side out to like
Slide in to comment

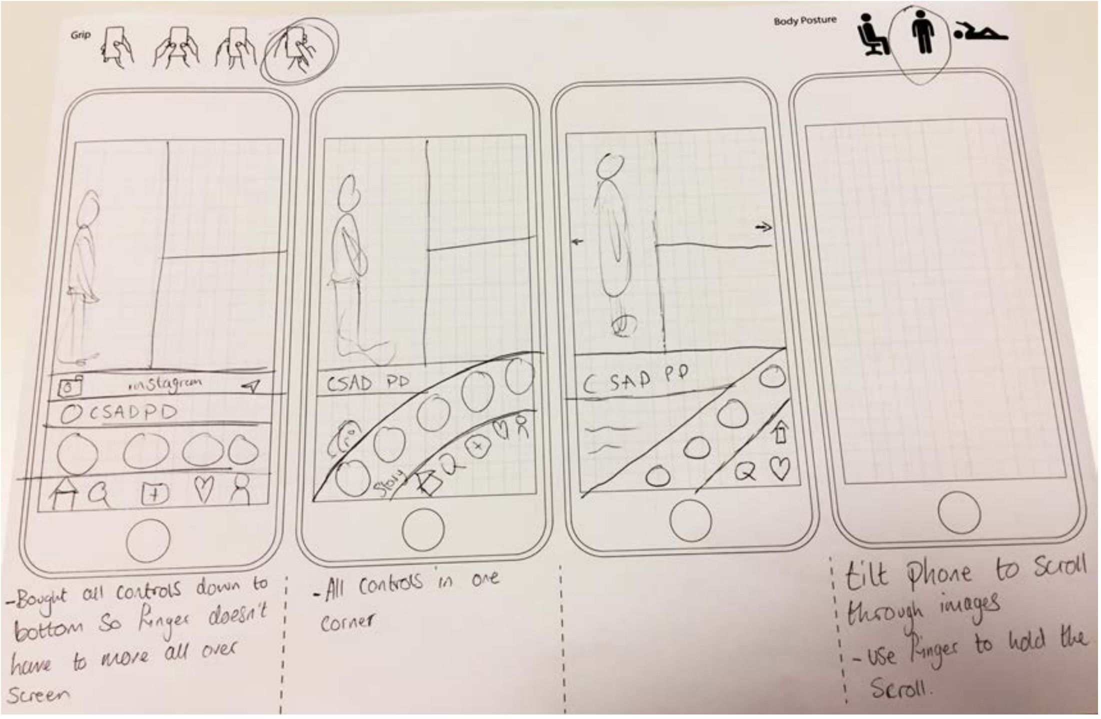

Grip
Body Posture
Spiral / Scroll
Scroll to the Side.

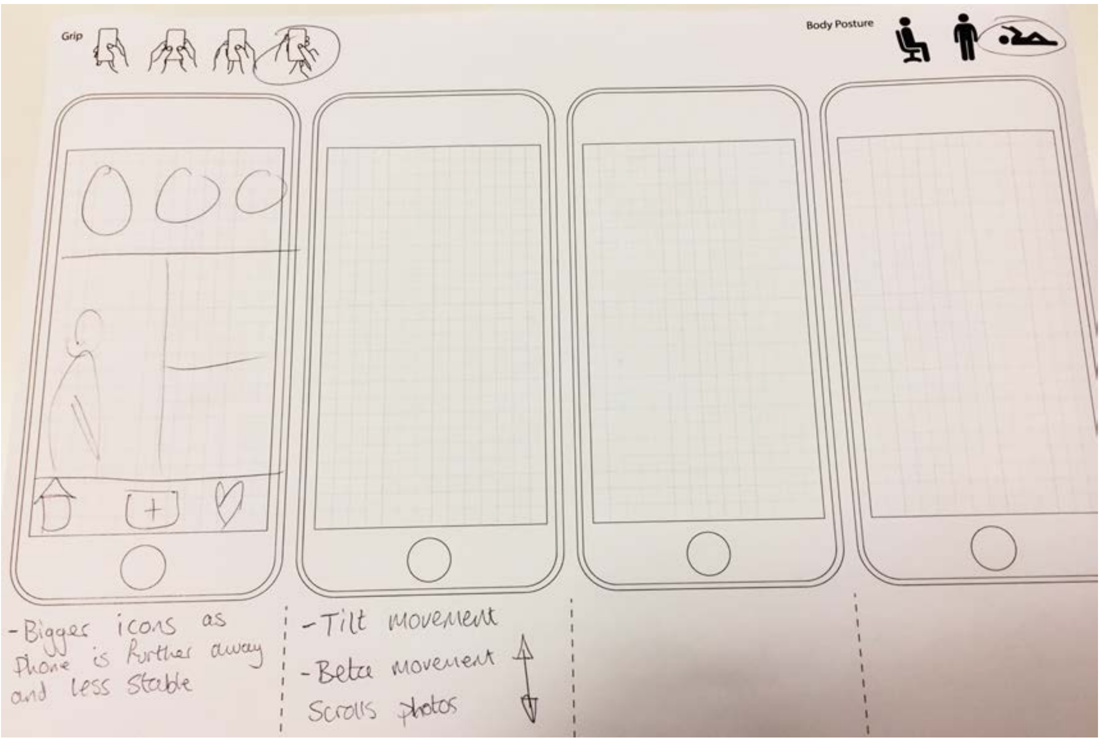

Grip
<all
Consistent
Body Posture
apps in the corner
don't use
Slide down
Tilt Sensors in Corners

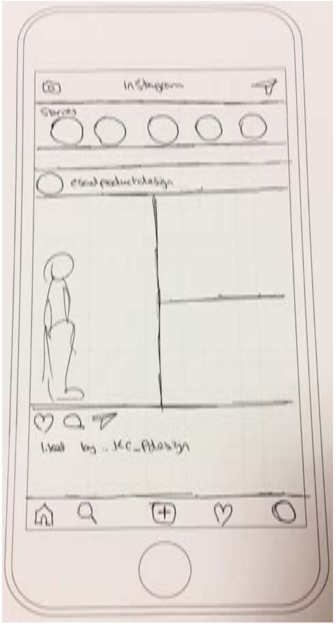
D.3 Participant sketches (Body posture workshop)

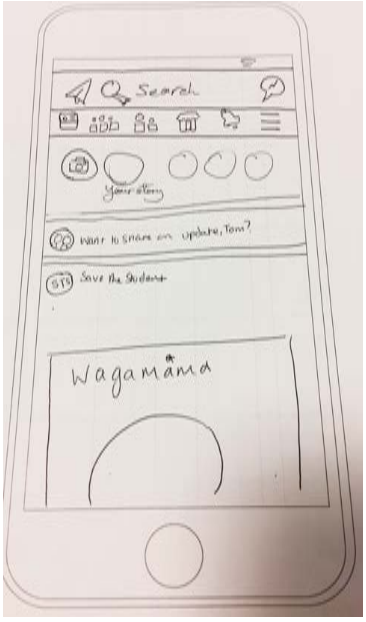


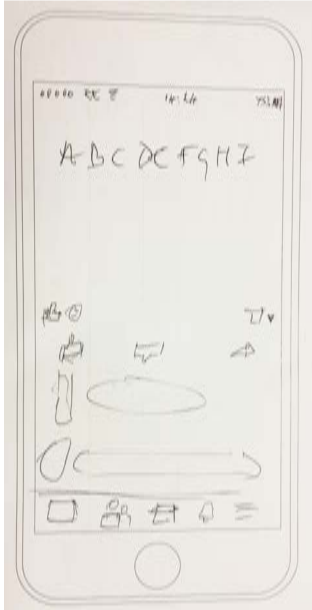


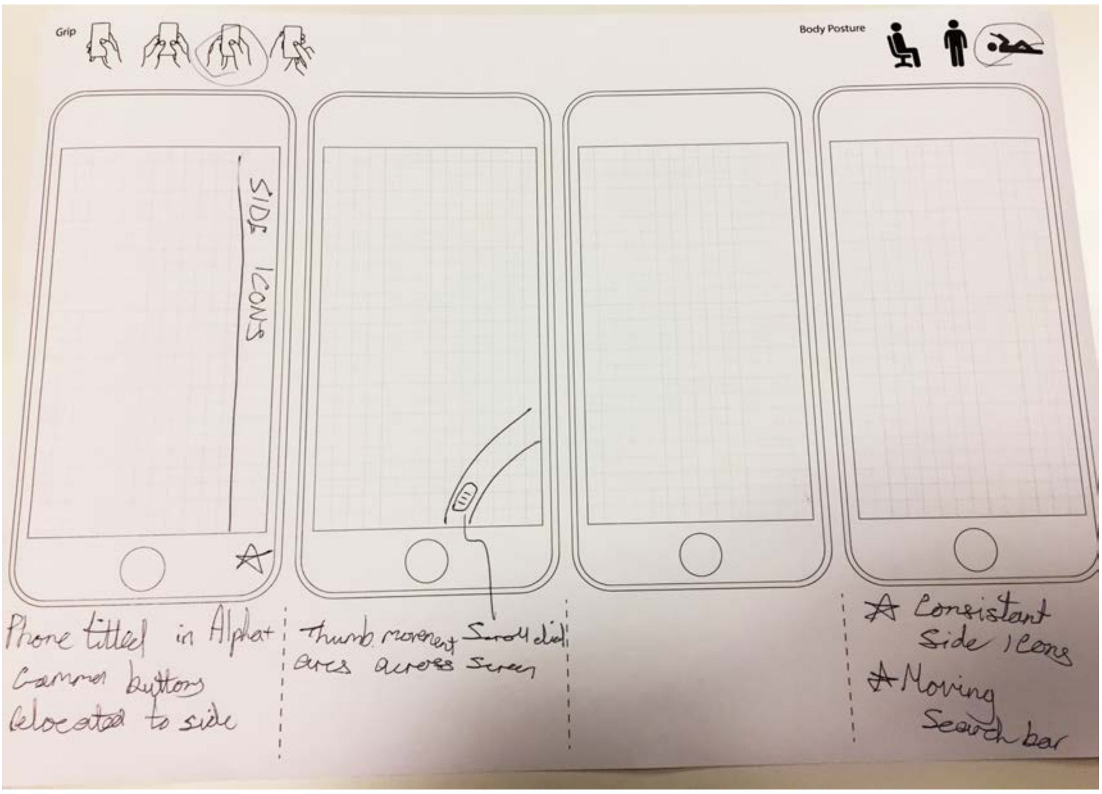

Grip
Body Posture
instagram
CSADPD
CSAD PD
C SAD PD
-Bought all controls down to bottom So finger doesn't have to move all over Screen
-All controls in one Corner
tilt phone to Scroll through images
-use finger to hold the Scroll.

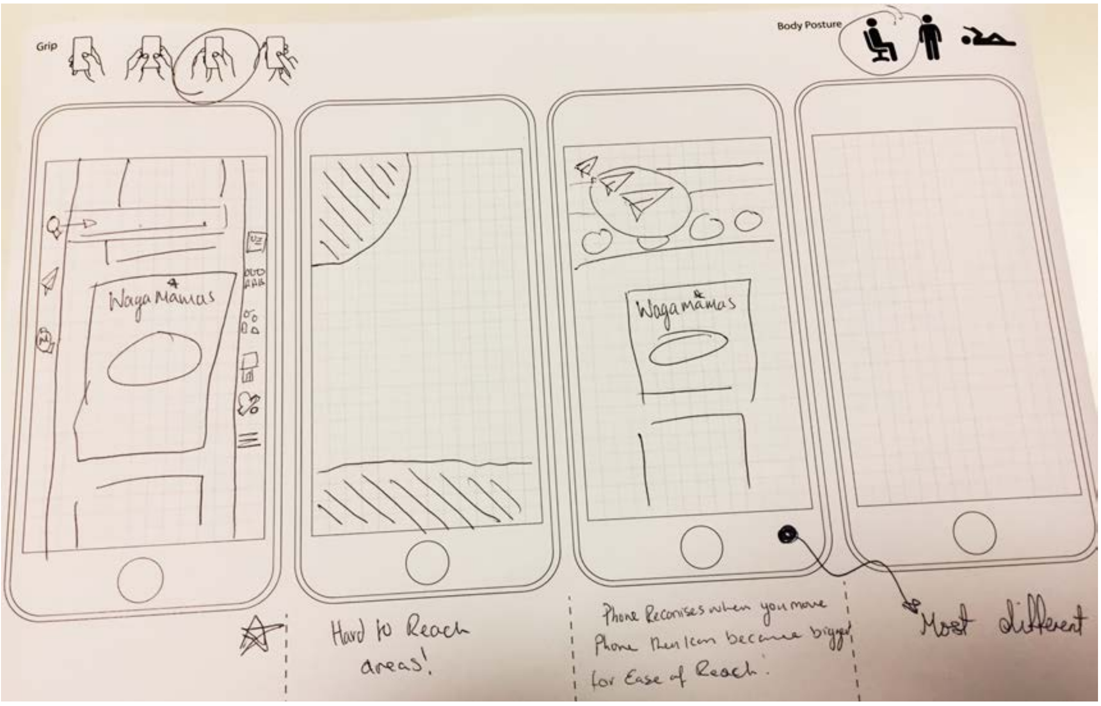

Grip
Body Posture
-Bigger icons as Phone is further away and less Stable
-Tilt movement
-Beta movement Scrolls photos

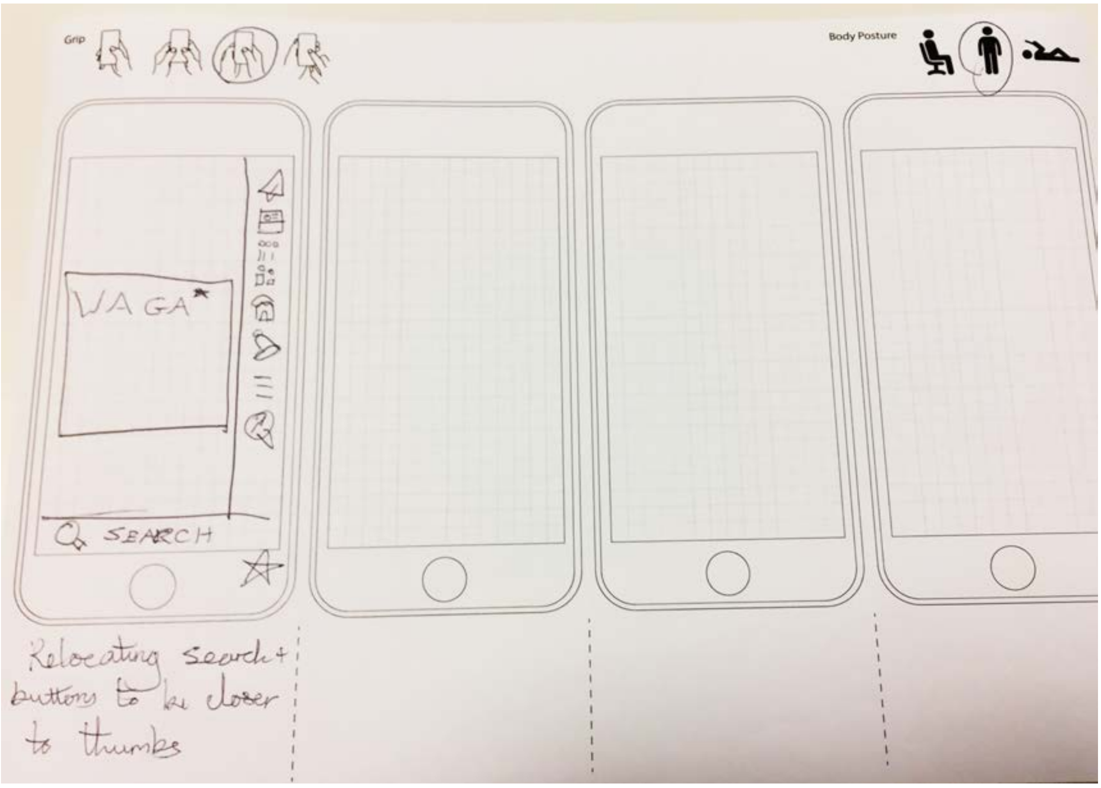

Instagram
Stories

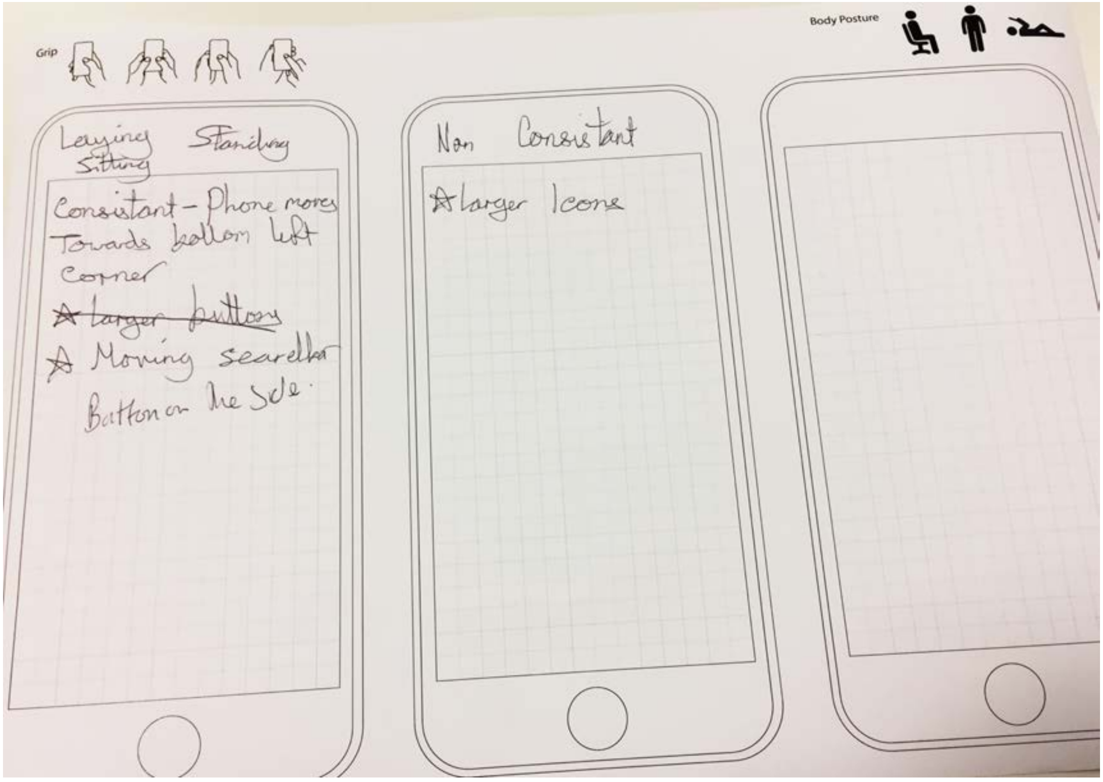

Search
Your story
Want to share an update, Tom?
Save the Student
Wagamama

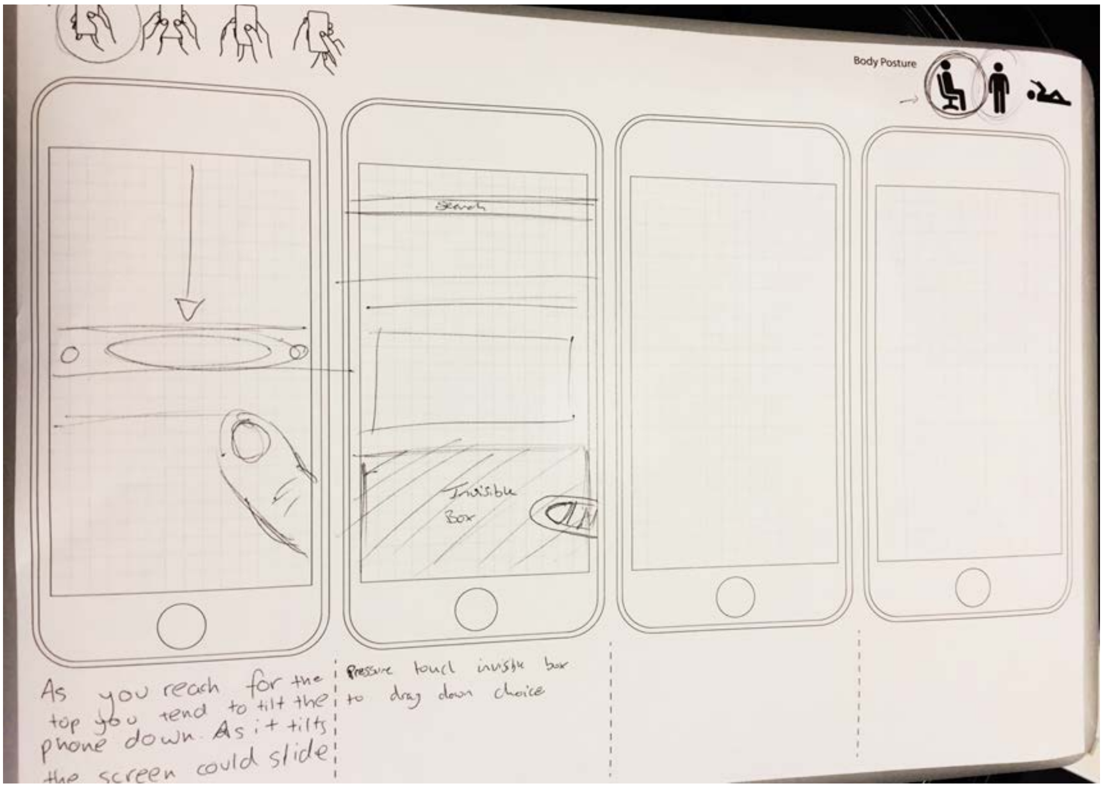

ABCDEFGHI

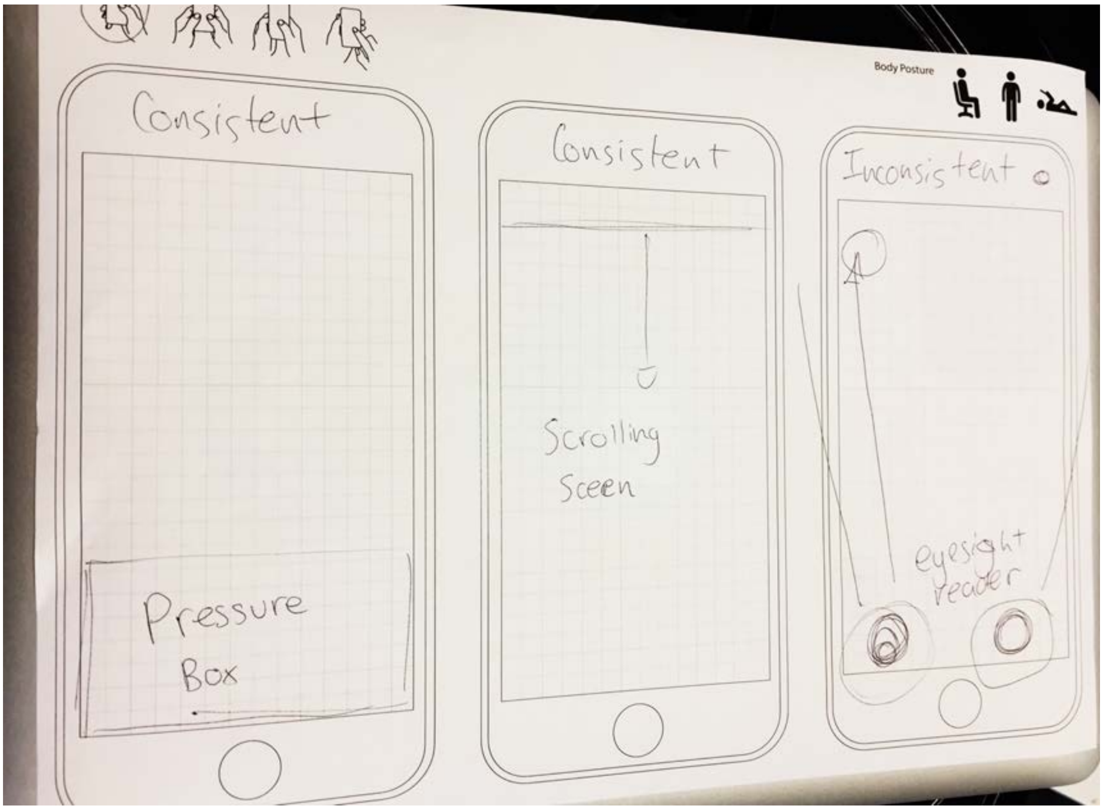

Grip
Body Posture
SIDE ICONS
Phone tilted in Alpha+
Camera buttons relocated to side
Thumb movement arcs across screen
Scroll dial
Consistant Side Icons
Moving Search bar

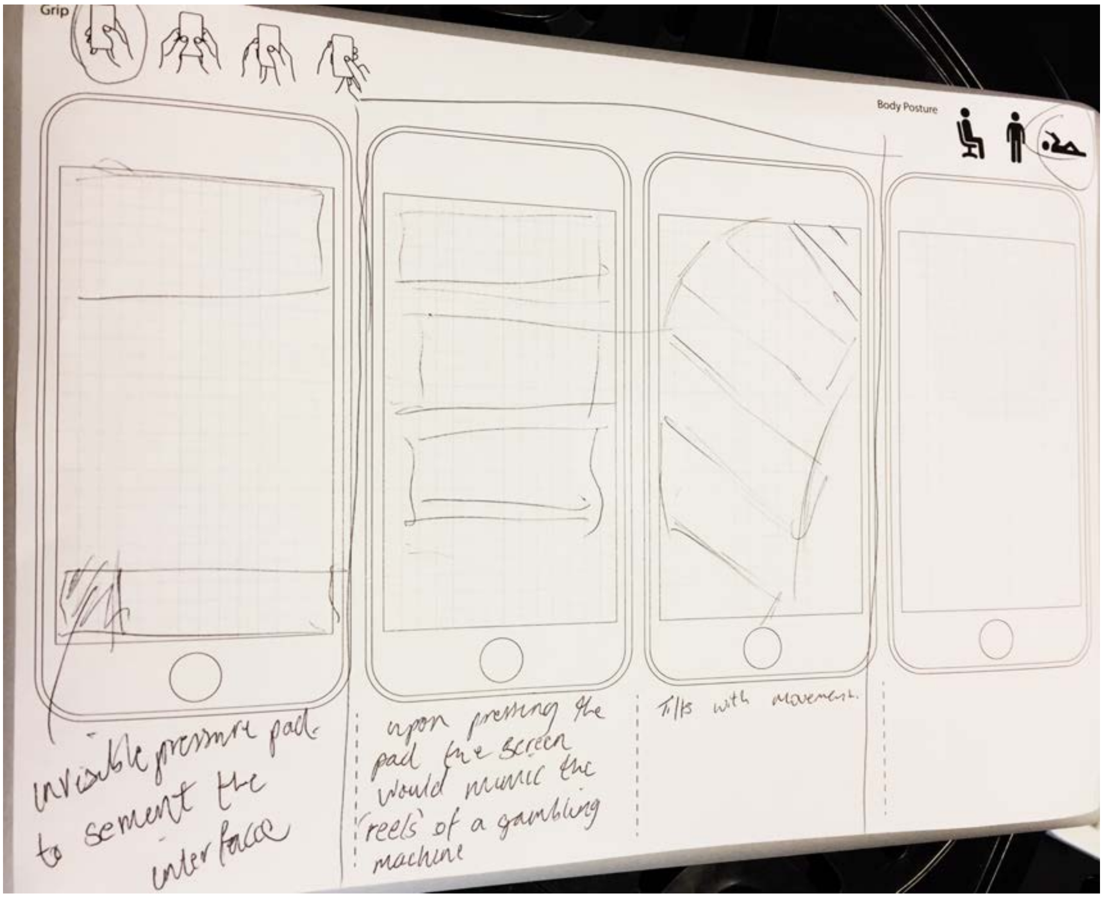

Grip
Body Posture
Waga Mamas
Hard to Reach areas!
Phone Reconises when you move Phone then Icon became bigger for Ease of Reach.
Most different

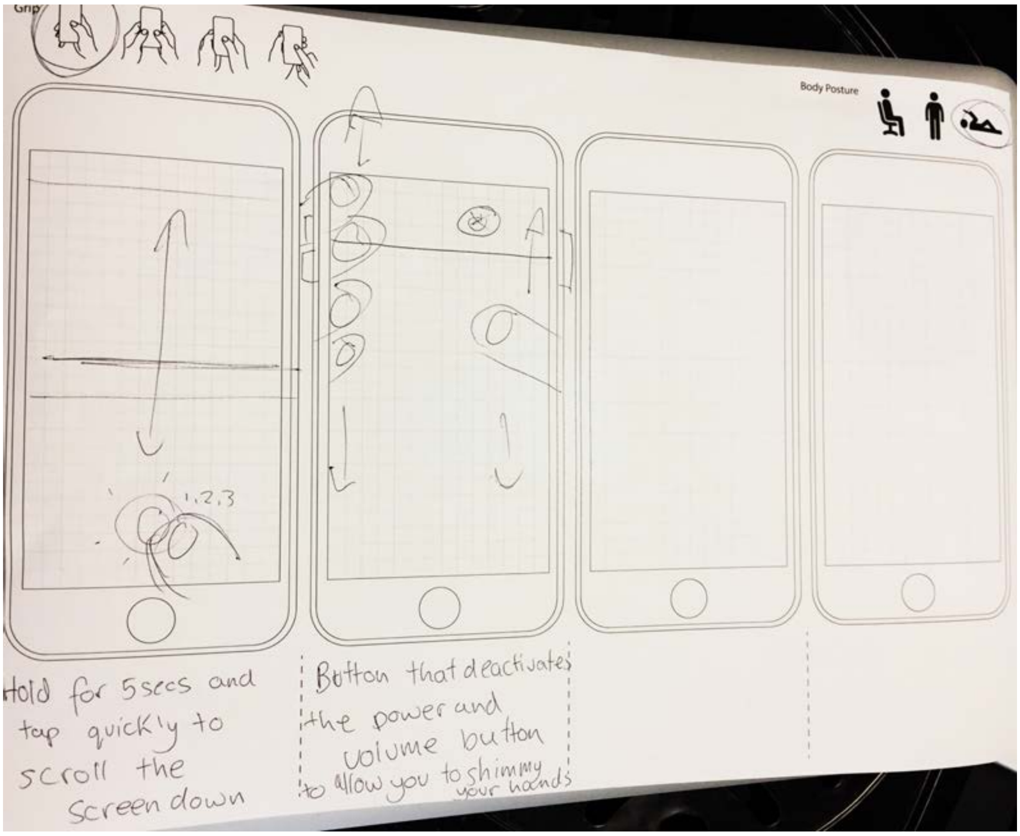

Grip
Body Posture
WAGA
SEARCH
Relocating search + buttons to be closer to thumbs

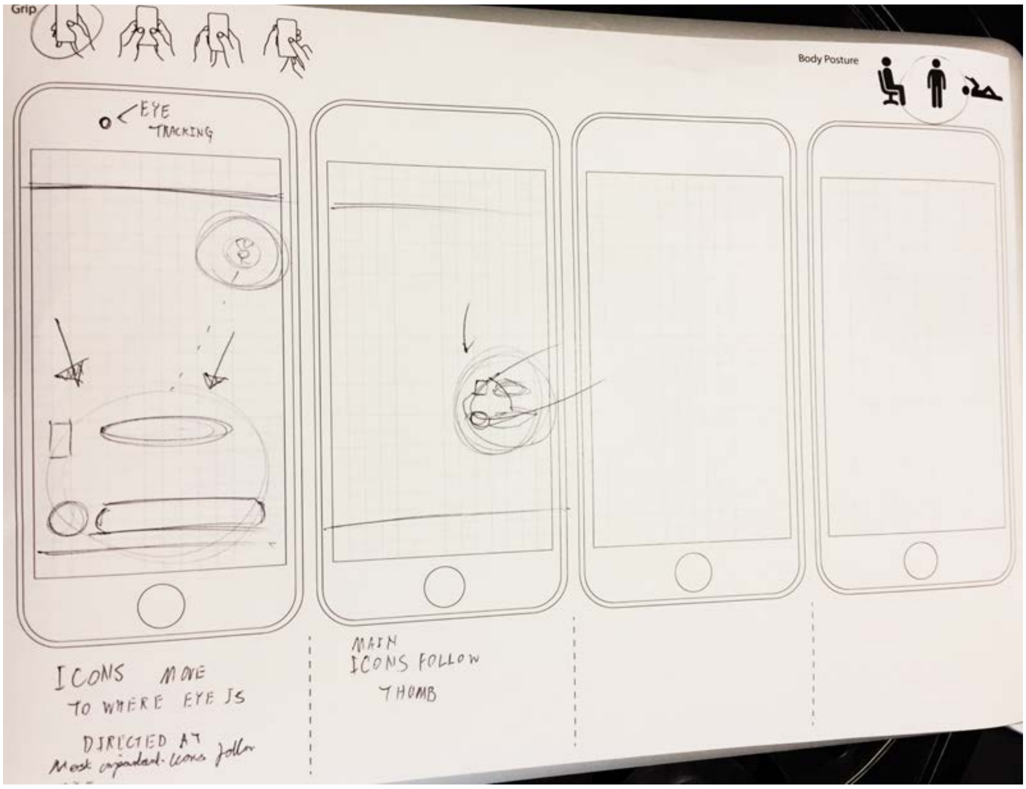

Grip
Body Posture
Laying Sitting Standing
Consistant - Phone moves Towards bottom left Corner
~~A Larger buttons~~
A Moving searchbar Button on the side.
Non Consistant
A Larger Icons

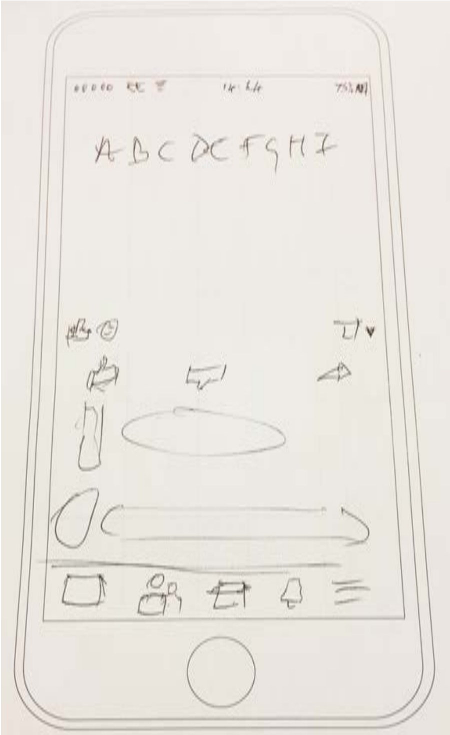

Body Posture
Search
Invisible Box
As you reach for the top you tend to tilt the phone down. As it tilts the screen could slide
Pressure touch inside box to drag down choice

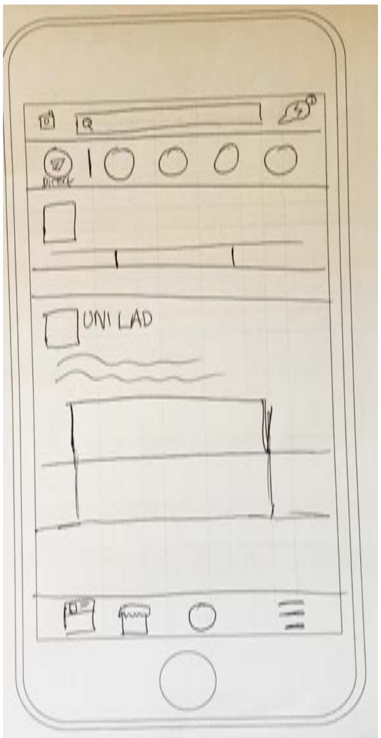

Body Posture
Consistent
Pressure
Box
Consistent
Scrolling
Sceen
Inconsistent
eyesight
reader

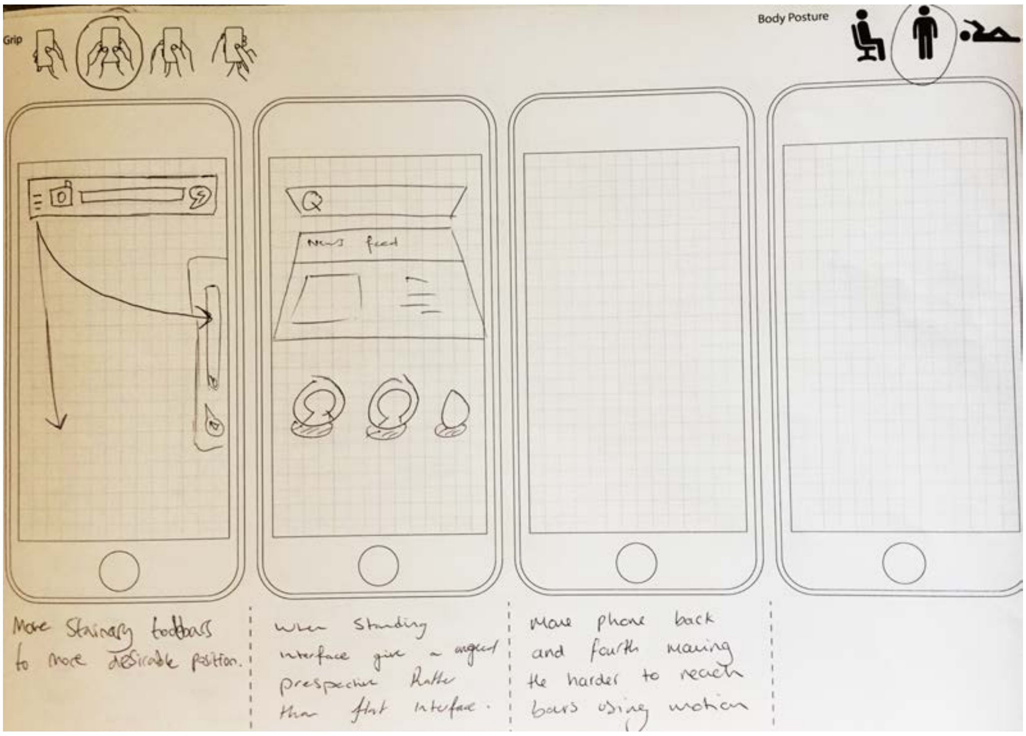

Grip
Body Posture
invisible pressure pad to sement the interface
upon pressing the pad the screen would mimic the 'reels' of a gambling machine
Tilts with movement.

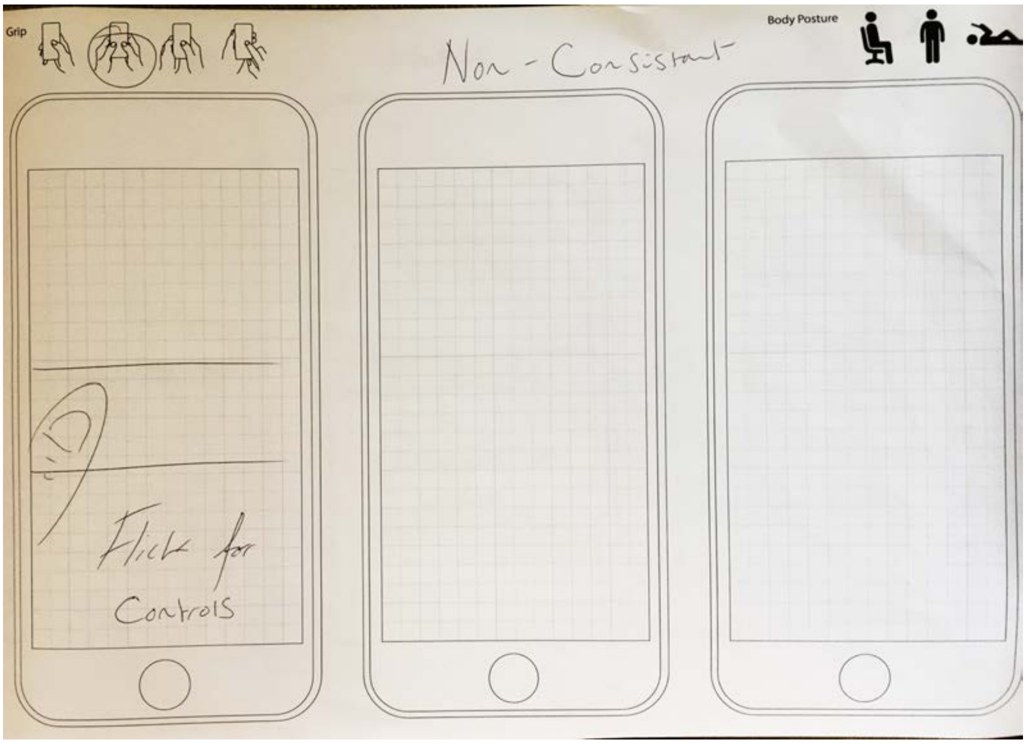

Grip
Body Posture
1,2,3
Hold for 5secs and tap quickly to scroll the screen down
Button that deactivates the power and volume button to allow you to shimmy your hands


Grip
Body Posture
EYE TRACKING
ICONS MOVE TO WHERE EYE IS DIRECTED AT
MAIN ICONS FOLLOW THUMB

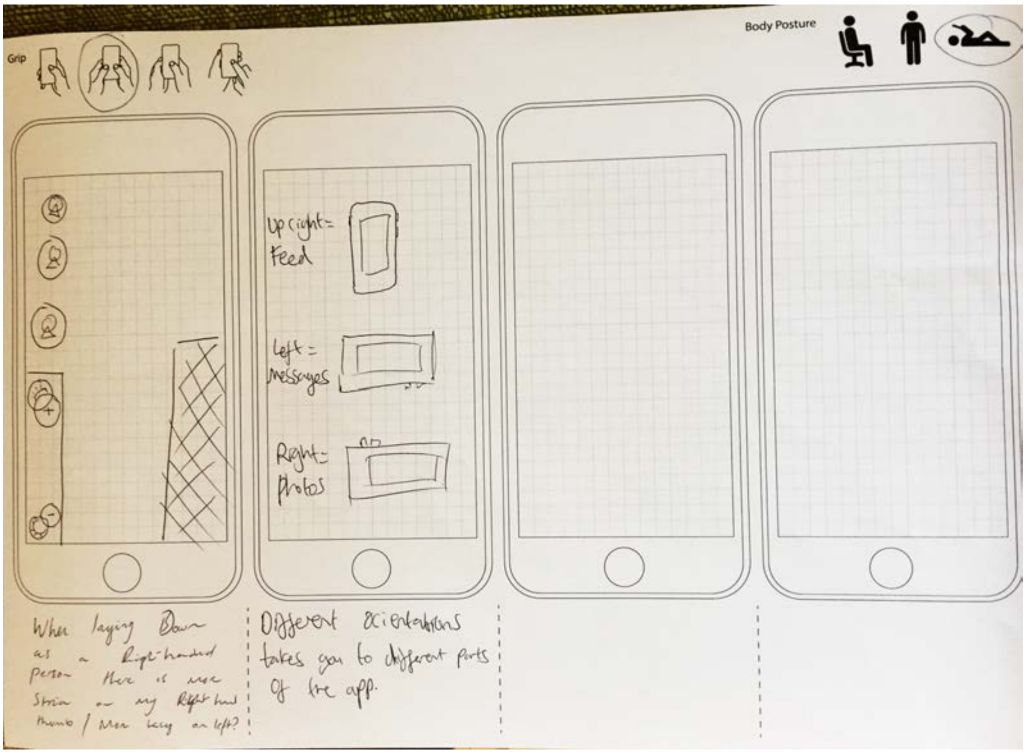



UNI LAD

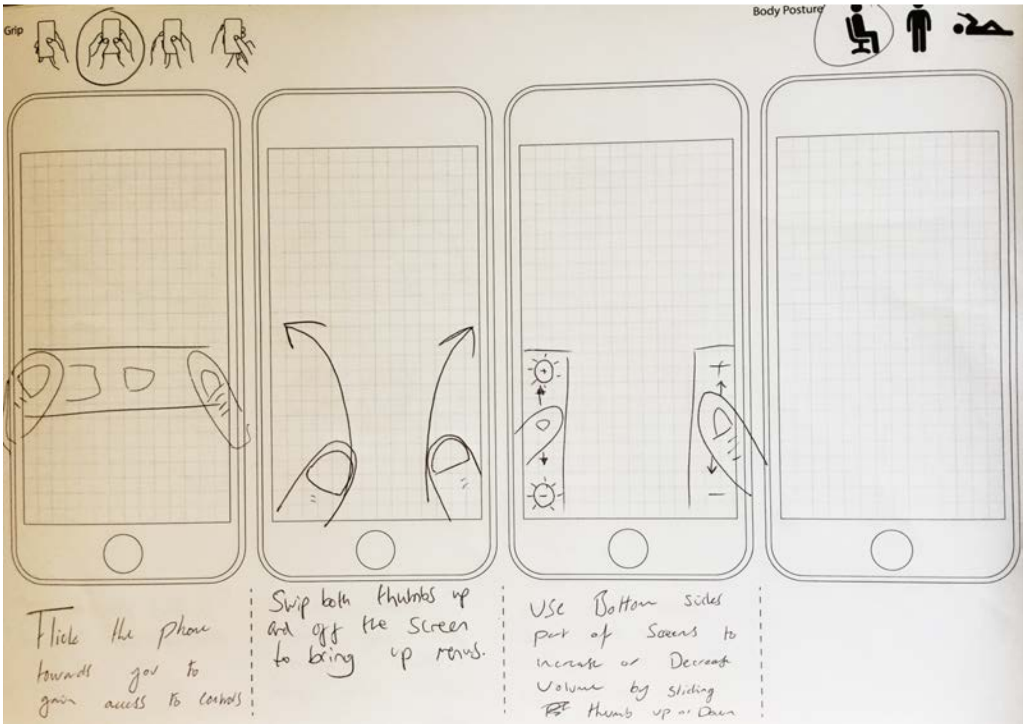

Grip
Body Posture
News feed
Move Stationary toolbars to more desirable position.
When Standing interface give a angled prespective Rather than flat interface.
Move phone back and fourth making the harder to reach bars using motion

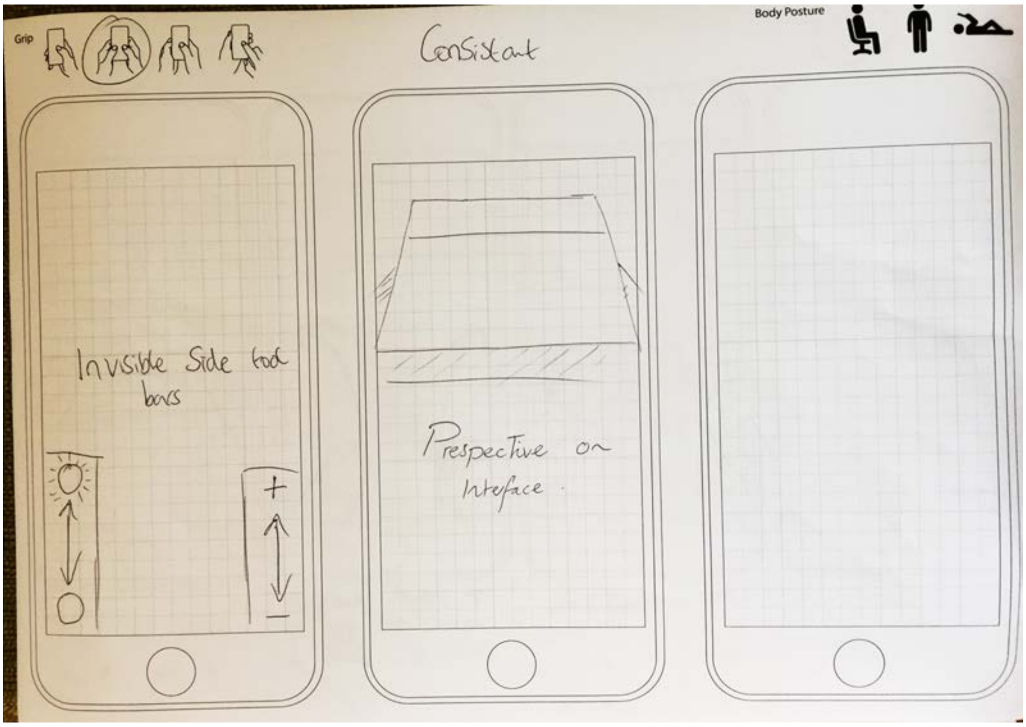


Grip
Non - Consistant
Body Posture
Flick for Controls



Body Posture
Grip
Upright = Feed
Left = messages
Right = photos
When laying Down as a Right-handed person there is more Strain on my Right hand thumb / More leaning on left?
Different orientations takes you to different parts of the app.


Grip
Body Posture
Flick the phone towards you to gain access to controls
Swip both thumbs up and off the screen to bring up menus.
Use Bottom sides part of Screens to increase or Decrease Volume by sliding thumb up or Down
+
−


Grip
Body Posture
Consistant
Invisible Side tool bars
+
−
Prespective on Inteface.