SMARTWATCH INTERACTION TECHNIQUES SUPPORTING MOBILITY AND ENCUMBRANCE

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ABSTRACT

Smartwatches have evolved to the point of operating complex mobile apps and thus enable more versatile types and methods for accessing information, anytime and anywhere. However, by directly inheriting the traditional touch techniques as those used on smartphones, designers have missed a significant opportunity to leverage the full potential under which smartwatches are operated in, particularly when these are used on-the-go, or when the interaction is encumbered, i.e. when the users' hands are busy.

The goal of this thesis is to explore the effect of mobility on smartwatch use, and to design techniques to support mobility and encumbrance. In this thesis, I first explored the impact of mobility and encumbrance on common workspace navigation tasks. Based on the initial findings, I proposed a hypothetical design-space accumulating the factors that aim to reduce the efforts required for smartwatch interactions on-the-go. I developed a set of new interaction techniques for panning and zooming tasks in line with our design-space and evaluated their performance with a user experiment. Overall, the ultimate motivation of this thesis is to bring forward the full potential of smartwatch as a wearable device.

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INTRODUCTION

From portable health monitors to notification reminders and information portals, smartwatches have found a niche in giving users access to information on-the-go. After continuous evolution over decades, smartwatches now capture many of the capabilities that are included in smartphones. According to Allied Market Research (Bhawna Kohli 2017), the global smartwatch market is expected to reach $32.9 billion by 2020, registering a Compound Annual Growth Rate (CAGR) of 67.6% over the period of 2014-2020.

Despite overwhelming interest and technical advancements, the applicability of the smartwatch is still very limited as compared to smartphones. According to Chauhan et al. (Chauhan et al. 2016), the most popular application categories on smartwatch App Stores are Fitness, Productivity (Task, Time, and Photo Gallery Management), and Games. However, there are very few applications for Food, Social Networking, Financial Activities, and so on. It is evident from the survey by Chauhan et al. that users and developers do not desire to use smartwatches for applications that require viewing significant content or information. It is mainly due to their small screen size that limits the extent of information displayable on a smartwatch. In addition to this, not much work has been done on developing navigation techniques specifically for smartwatch use.

The same techniques as those used on mobile handheld devices have been directly ported to the smartwatch without any additional modification, undeterred by the fact that smartwatches have smaller screen sizes and serve entirely different purposes than a smartphone. The diminished screen size and prominent position on the wrist make smartwatches ideal for novel interaction paradigms than those currently available on existing portable devices. The new usage modes, methods of operation, and limitations, such as limiting the use of multiple fingers of the fat-finger problem (Siek, Rogers, and Connelly 2005), warrant re-examining how users interact with these for common tasks, such as workspace navigation.

Despite its small screen size that affords smaller information displays, smartwatches still have the potential to assist users under various situations, particularly when smartphone use is inconvenient. Ashbrook et al. (Ashbrook et al. 2008) demonstrate that the wrist is an ideal location for fast access to information. However, the time it takes to access information on a device is an important factor that influences the usability of the device (Starner et al. 2004; Cui, Chipchase, and Ichikawa 2007).

The smartwatch has perceived value in its ability to access information without suspending our daily tasks. For example, when walking, running, or having bags in hand. However, the direct transfer of traditional touch gestures has resulted in the user to stand still and pay full attention while using the smartwatch. To support usage situations, where we do not suspend our core activity, such as walking, running, or holding items, smartwatch interactions need to be redesigned to take into consideration how these scenarios impact existing interaction techniques.

1.1 TWO AXES OF ACTIVITY CONTEXTS

Mobility Levels	Encumbrance Levels: Two-handed	One-handed	Hands-busy
Still	Standing, sitting, everyday activities.	Writing a letter, holding an object etc.	Holding heavy object with both hands.
Walking	Walking out with friends.	Walking with a bag in one hand or briefcase at the office.	Riding shopping cart, carrying bags in both hands while walking.
Running	Jogging, racing etc.	Running at the railway station with briefcase in one hand.	Running with objects in both hands.

Table 1.1: The two main axes under investigation in my thesis: Mobility Levels and Encumbrance Levels.

While smartwatches provide access to information on the go, current interaction techniques do not necessarily account for the common activity contexts. Such activity contexts can be described along two axes: (i) the degree of user mobility and (ii) usage encumbrance. The degree of mobility can range from being inactive (standing or sitting), active (walking), to highly active (running). Usage encumbrance includes having both hands available for interaction, or having only one-hand or even no-hands, such as when holding items using two hands. Aspects of these two axes are defined in Table 1.1.

The Table 1.1 demonstrates the various different activities that we perform in our daily life ranging from standing still to running with bags in both hands. With smartwatches, it is now possible to access information on-the-go, but with current interaction techniques, smartwatches allow very limited interactivity, particularly in these scenarios. These include tap, flick, continuous swipes and stretch expand, for selecting, panning or zooming into workspaces. It is unclear how well these techniques transfer in contexts involving encumbrance, and whether new techniques need to be designed to suit these new contexts. My investigation sheds light on these above issues. Throughout the thesis, I refer to activity as meaning both mobility and encumbrance. When referring to either one of these axes, I explicitly mention it.

1.2 RHODES VISION FOR WEARABLES

Not just limiting to withstand mobile conditions, Rhodes (Rhodes 1997) envisioned that wearable devices should have the following main characteristics:

(i) Portable while Operational: the user can access and operate the wearable even while performing any dynamic task such as walking or running. This level of mobility distinguishes wearables from other handheld portable devices such as smartphones or laptops;

(ii) Hands Free Use: users must be able to interact with applications on wearables even when their hands are busy;

(iii) Embedded Sensors: users can get contextual information relevant to their surroundings through embedded sensors, including GPS, cameras and microphones;

(iv) Always Active: users can get information from wearables even when these are not actively in use, such as through alerts and notifications;

(v) Always On: wearables continuously monitor the user's surroundings and user state to gather information.

Realizing Rhodes' vision is one of the main objectives of my thesis. If wearables are to be used for information access, anytime and anywhere, they need to adapt to the input capabilities and activity contexts. Furthermore, by using the sensor capabilities of a smartwatch, such as built-in gyroscope, accelerometer, magnetometer, light and distance sensors, it is now possible to detect the activity state of the user and develop smarter and more effective user interactions. The smartwatch has a fixed position on the wrist of the user. It can be leveraged to accurately provide information about the hand orientation and wrist movements. This information can be used to develop smart interactions that adapt, depending on the activity level and hand orientation of the user. For example, depending on the user's mobility and encumbrance conditions, the internal parameters of gesture (e.g., scale factor for zooming) may change, allowing more control over the interaction in several activity contexts. This thesis also focuses on exploring the smartwatch's adaptive nature, along with its interactions by using inbuilt sensors.

1.3 research objective

The main objective of my thesis is to explore the design factors and interaction techniques that afford efficient information access on smartwatches unaffected by different mobility or encumbrance levels. To realize my main research objective, I underline a set of sub-objectives that lead towards the main goal. They are as follows:

(i) The first main sub-objective is to study the impact of encumbrance and mobility on current smartwatch interactions. There is a good amount of research focusing on the effect of different mobility levels on user interactions (Ng, Williamson, and Brewster 2015; Kjeldskov and Stage 2004; Lim and Feria 2012; Bergstrom-Lehtovirta, Oulasvirta, and Brewster 2011a; Schedlbauer and Heines 2007; Schildbach and Rukzio 2010; MacKay et al. 2005; Kane, Wobbrock, and Smith 2008). It is evident from the literature that mobility has a negative impact on interaction performances such as reaction time, completion time, and accuracy. All previous studies, however, have been performed on portable devices such as smartphones or tablets, with much wider screen sizes than a smartwatch. To our knowledge, no one has yet studied the effect of mobility and encumbrance on smartwatch touch-interactions.

(ii) Understand various aspects of smartwatch interactions under varied level of activity conditions. I summarize these findings and propose a design-space that aims to deliver guidelines for future smartwatch interaction design.

(iii) Devise new techniques based on the proposed design-space. To evaluate the effectiveness of the techniques under different activity conditions. I compare the performance with current interaction techniques and provide insights and design recommendations for smartwatch navigation techniques.

1.4 RESEARCH QUESTIONS

Our study intends to address the following main research questions as discussed below:

Research Question 1. What is the effect of encumbrance and mobility contexts on smartwatch interactions?

Research Question 2. What is the cause of difference in interaction performance under different activity levels?

Research Question 3. How can we design new interaction techniques that remain unaffected by mobility and encumbrance?

Research Question 4. How can interaction techniques adapt to activity contexts and what will be its effect on interaction performance?

This thesis seeks to address these four research questions. The first question is focused on determining the effect of mobility and encumbrance on current smartwatch interactions. We capture all the important parameters for each individual interaction task (such as completion time, accuracy, pan counts for panning, etc.) to analyze their effects on interaction performance.

The second research question is directly linked to our first question. We investigate the underlying causes that affects smartwatch interactions under activity contexts by studying the nature of interactions and their corresponding parameters. Based upon the findings, we propose a design-space that aids to develop smartwatch interactions which are more resistive to the effects of activity contexts. We capture elements of the design-space to devise novel smartwatch navigation techniques and compare their performance with current smartwatch interactions.

1.5 CONTRIBUTIONS

The following are five major contributions of my thesis:

(i) an investigation on the impact of activity contexts on smartwatch use in terms of encumbrance and mobility and a presentation of insights that underline the actual cause of performance change under activity contexts.

(ii) a design-space that aids in the design of potentially new smartwatch navigation techniques, unaffected by mobility and encumbrance contexts.

(iii) novel interaction techniques for panning and zooming on a smartwatch.

(iv) a validation of the adaptive nature of interactions that adjust based upon the activity contexts users may be involved in.

(v) an evaluation of the new interaction techniques with respect to current smartwatch interactions, and design recommendations for their use in future smartwatch applications.

1.6 THESIS OUTLINE

This thesis consists of seven main chapters:

Chapter 1: Introduction - It introduces the research topic through a brief overview of desirable smartwatch characteristics. This chapter proceeds to discuss the objective of the research, main research questions, and contributions this thesis has made to its field.

Chapter 2: Background Literature - This chapter reviews the literature from various different aspects to support the purpose of this thesis. The main literature topics covered in this chapter are as follows:

(i) Evolution of touch interactions and new interactions for zooming and panning.

(ii) Effect of mobility on touch interactions.

(iii) Effect of encumbrance on touch interactions.

(iv) Interactions that support mobility and encumbrance.

(v) Evaluation methods for examining effect of mobility and encumbrance.

Chapter 3: Effect of Mobility and Encumbrance on Smartwatch Interactions - It focuses on investigating the effect of mobility and encumbrance on current smartwatch interactions with a user experiment. It describes scenarios, experimental design, and interaction tasks that are included in the experiment. This chapter ends with the result for each interaction task, comparative discussion, participant's input and conclusion.

Chapter 4: Interaction Design for Activity Contexts - The main contribution of this chapter is the creation of a design-space and development of new interaction techniques for zooming and panning. It starts with an observational study and proceeds to use knowledge from observational studies and the first user experiment to devise the design-space. It discusses different design factors and vital components of the design-space. Based on the design-space, it proposes two new interaction techniques for each: zooming and panning. It also introduces the concept of adaptive interactions for varied levels of activity contexts.

Chapter 5: Evaluation of the Design-Space - The main objective of this chapter is to evaluate the performance of new techniques with a user experiment. It presents the hypothesis, experimental design, and the techniques that are included in the user experiment. This chapter ends with the result and conclusions.

Chapter 6: Conclusions and Future Work - It highlights the main contributions and conclusions of this thesis. A big section in this chapter is dedicated to future work. This chapter ends with the design guidelines and recommendations for future smartwatch interactions.

2

BACKGROUND LITERATURE

Interaction techniques for smartwatches cannot remain the same as the ones proposed for smartphones due to the "always active" nature of its users accessing information on-the-go. Indeed, porting traditional interaction techniques directly to the smartwatch would hinder the opportunity to exploit the potential of wearables to their full extent. With access to sensor and touch capabilities, interaction techniques need to support different activity levels, i.e. mobility and encumbrance. Ng et al. (Ng, Brewster, and Williamson 2013) define "*encumbrance*" as a situation in which the user is impeded by holding different types of objects while interacting with mobile devices.

We review the literature to discuss the touch interactions and the effect of mobility levels and encumbrance on mobile application usage. In section 2.1, we proceed to briefly overview the history of touch interactions and new interactions for navigation tasks, such as panning and zooming. In section 2.2, we discuss the effects of mobility on touch interactions. In section 2.3, we discuss the impact of encumbrance on mobile device interactions. In section 2.4, we discuss interaction techniques to support mobility and encumbrance contexts. In section 2.5, we discuss the evaluation methods employed to date in order to evaluate interaction techniques under mobility and encumbrance contexts.

2.1 EVOLUTION OF TOUCH INTERACTIONS

Currently, the most common form of interactions on smartwatches are touch-based interactions. Touch is the most intuitive way of interacting with a smartwatch. As our research aims to deliver new touch interactions that are resistant to the effects of encumbrance and mobility, we start our discussion with a brief history of touch interactions i.e. how the touch-displays and touch gestures evolved over time. This provides us with a better understanding of touch-interactions that we use in day-to-day life and the reasons why designers assigned certain touch gestures to particular tasks, example: pinching for zooming, panning and flick for navigation, tapping for selection and so on. We then discuss the latest advances in touch interactions for common navigation tasks such as zooming and panning.

2.1.1 *History of Touch Interactions*

Touch Screens History

Touch screens have been around for more than 50 years. Currently, touch technology has matured to the point that most devices utilize touch as a standard method of interaction. The first touch screen was developed in 1965 at The Royal Radar Establishment in Malvern (Johnson 1965). Following a few years after this development, several new techniques for touch displays were introduced, which were progressive improvements to their previous works. In 1972, the PLATO IV computer (Bill Buxton 2007) introduced 16X16 touch-based plasma display for computer-based teaching, allowing students to answer questions by touching their screens. In 1982, the first multi-touch system called Flexible Machine Interface (Bill Buxton 2007) was developed using finger pressure and image processing on a frosted-glass panel. The first commercially available touchscreen was introduced by XEROX in 1980 (Nakatani and Rohrlich 1983), it was a black and white video display with a touch screen for operating the controls.

Touch Interactions History

In 1985, Krueger et al. (Krueger and Wilson Leonardo 1985) developed Video Place, a vision-based system that allows hand and multi-finger tracking to interact with computer-graphics using a rich gesture set. Interestingly, many hand gestures that we use today are adopted from Video Place, including pinch gestures for scaling and translating objects. In 1991, Wellner et al. (Wellner and Pierre 1991) introduced Digital Desk, a desk equipped with a computer-controlled camera and projector. The main purpose of Digital Desk was to add electronic features to physical paper, and add physical features to electronic documents. The projector projects the digital work environment on the desk and the mounted camera was used to capture the finger and hand gestures as input. The number of gestures we use today on smartphones and smartwatches are similar to those used by Digital Desk (drag, spread, and pinch gestures).

In 1999, a digital cork-board called Portfolio Wall was developed (Bill Buxton 2007). It demonstrated the richness of the flicking gesture, i.e. instead of simple left and right flicks, flicking in different directions can be used to invoke new behaviors. For example, a down flick on a video means stop, a right diagonal flick enables annotation and so on. However, this system was capable of only detecting single finger gestures.

Rekimoto et al. (Rekimoto and Jun 2002) introduced SmartSkin in 2002, a sensor architecture for making interactive surfaces sensitive to hand and finger gestures. The sensor architecture was capable of recognizing hand positions and shapes along with the distance between hands and a set of multi-finger gestures. For instance, multi-finger pinch gestures were used for map browsing, one finger for panning, two or more fingers for simultaneous panning and scaling.

In 2003, Wu et al. (Wu and Balakrishnan 2003) presented several multi-finger and hand gesture interaction techniques for tabletop. Apart from gestural input techniques, Wu et al. also explored interactions and visualizations for shared spaces, awareness, and privacy. They demonstrated all these techniques using a prototype for furniture layout called Room Planner. The input interaction techniques used for Room Planner were categorized into four main groups: single-finger, two-finger, single-handed, and double-handed interactions. The single-finger interactions included tap for selecting an object, double tap for popping a context-sensitive menu, drag for moving an object, flick for a throwing action and catch for copying an object; whereas, two-finger interactions included pinch, spread, and two-finger rotation for scaling and rotating objects. The hand gestures were mainly dependant upon the position and orientation of the hands. These include flat hand, horizontal hand, horizontal tilted hand, two vertical hands, and two corner-shaped hands. Apart from the whole hand gestures, all the gestures that we use today are the same as they were introduced for tabletops.

In 2007, when Apple Inc. brought iPhone to the consumer market, they employed the same multi-touch interactions, (Bill Buxton 2007) i.e. pinching as introduced by Krueger in 1985 (Krueger and Wilson Leonardo 1985) and flicking as demonstrated by Portfolio Wall in 1999. Soon after, all other mobile phone and smartwatch manufactures similarly adopted the same touch interactions.

2.2 touch interactions for navigation

Zooming and panning are currently the two standard interaction methods used for navigation on touch interfaces. Over time, researchers have proposed several different ways for navigating depending upon the use of cases and form-factors of interface design. In this section, we will briefly discuss some of the existing techniques for zooming and panning.

Besides pinch, the other commonly used method for zooming is double tap (Lai, Zhang, and Wang 2017). With each double tap, the zooming level increases by a discrete fixed amount. For zooming out, double tapping with two-fingers is required. This makes double tap less efficient for single-handed interactions or situations when precise zooming is required. In 2000, Bjork and Staffan introduced Flip Zooming (Bjork and Staffan 2000), a “focus + context” visualization technique in which the entirety of the information is split into a number of tiles. The focused tile is placed at the center of the screen whereas, other contextual tiles are placed around it in a sequential order. The tiles can be accessed by using a cursor or touch interface.

Robbins et al. (Robbins et al. 2004) introduced ZoneZoom in 2004, a method that divides the information view into nine segments and allows the user to zoom into the segment by pressing the corresponding number on the key-board and zooming out by pressing the same key again. This technique allows users to switch between contextual and focused views and easily compare information over different parts of the dataset. Similar to double-tap zoom, ZoneZoom also shares the limitation of changing scales by fixed discrete levels. AppLens is yet another "focus + context" visualization technique (Karlson, Bederson, and SanGiovanni 2005) that aims to solve navigation problems on PDA using single-handed thumb interaction. In general, AppLens uses the concept of DataLens (Bederson et al. 2004), a calendar interface for PDA, to organize and manage access to nine applications. Along with AppLens, they also examine LaunchTile, an interactive zoom space consisting of 36 application tiles divided into nine zones of four tiles each. It consists of three zoom levels: world level (36 tiles), zone level (four tiles) and application level (one tile).

In 2008, Olwal et al. described three techniques for zooming, using rubbing and tapping. Rub-Pointing is a one-handed zooming technique in which repetitive rubbing in a diagonal motion is used for zooming-in and zooming-out. Zoom-Tapping is a two-handed technique, where one finger points at the location and tapping with the other hand is used for zooming-in and zooming-out. Rub-Tapping is a hybrid of both, it uses Rub-Pointing for zooming-in and zooming-out and tapping to confirm the selection location.

GraspZoom (Miyaki and Rekimoto 2009) is a single handed technique that allows zooming and scrolling using thumb input and pressure sensing. For pressure sensing, a Force Sensitive Resistor (FSR) is attached to the backside of the mobile phone. CycloStar (Malacria, Lecolinet, and Guiard 2010a) are a set of techniques for clutch-free panning and zooming. Similar to Rub-Pointing. (Olwal, Feiner, and Heyman 2008), CycloPan includes to and fro oscillatory motion of the finger, but with more DoFs. The first motion of finger in Cyclopan has the same effect as that of the drag operation. The successive finger motions are used for continuous speeding control. In CycloZoom, the continuous circular gesture in clockwise and anti-clockwise direction are used for zooming in and zooming out.

In 2011, Hinckley et al. (Hinckley and Song 2011) explored hybrid "touch + motion" gestures to perform single-handed zooming. In their technique, users hold the tip of the thumb on the screen and tilt the device to perform zooming in and zooming out tasks. Boring et al. (Boring et al. 2012) have explored single-handed panning and zooming using the "Fat Thumb". In their work, they propose small contact sizes for thumbs for panning and large contact size for zooming. The movement of the thumb while in contact with the screen determines the zooming mode and panning direction. Avery et al. (Avery et al. 2014) suggested an enhancement to classic pinch gesture to reduce the number of clutches and the need for panning. This additionally brings the point-of-interest to the center of the screen before or during the zoom operation. They introduce zoom acceleration, which increases the zoom factor based on rapid spreading or pinching movements. To reduce the need of panning, they automated pan-to-center which automatically moves the zooming area to the center of the screen. In 2015, Bellino introduced two new gestures for zooming in i.e. Two-Finger-Tap for Tablets and TapTap for Smartphones. In Two-Finger-Tap, user tap the area to be zoomed with two fingers. The distance between the two fingers determines the zooming factor. They use classic pinching-in gestures for zooming out. Similarly, TapTap is a single handed gesture which allows users to zoom by two consecutive taps at two different points. The user can zoom-out by scrolling the thumb from the left edge of the screen.

Lai et al. (Lai, Zhang, and Wang 2017) have introduced ContextZoom, a single handed zooming technique that also provides switching between partial and whole viewports. In their technique, the user selects the zooming center by long presses with the thumb, followed by moving the thumb to perform the zooming. During zooming task, the panning is disabled and its resumed automatically after the completion of zooming. Aliakseyeu et al. (Aliakseyeu et al. 2008) have designed three multi-flick techniques (Multi-flick-standard (MFS), Multi- flick-friction (MFF) and Compound-multi-flick (CMF)) and compared their performance with standard scrollbar over three different devices- a PDA, a tabletPC, and a large table. In MFS, higher speed of scrolling can be achieved by one fast flick and one flick in opposite direction is sufficient to scroll in reverse direction. MFF is similar to MFS, though it includes an additional friction factor that decreases scrolling speeds with time. CMF provides the feedback to the user before lifting the pen, thus addressing the issue of under and overshoot. The results of their study demonstrate that all multi-flick techniques are as good as traditional scrollbar for short distances. CMF, however, is most preferred.

In this section, we have briefly discussed the history of touch displays and touch interactions. This has increased our understanding about current touch interactions that we use on a smartwatch. Pinch for zooming, flick, panning, and drag for navigation is not something new but has a very long history. Over the years, these gestures have transferred from one technology to another without any modification. Now, we are having the same gestures on smartwatch. It is still questionable whether these gestures are suitable for smartwatch use and if they require revision. This section proceeded to discuss zooming and panning techniques for touch-interfaces. This knowledge of new touch gesture is vital for our exploration of interactions for smartwatch use.

2.3 EFFECT OF MOBILITY ON TOUCH INTERACTIONS

Wearables are expected to provide users with an ability to interact at anytime and remain unaffected by different levels of mobility, e.g., sitting, walking, or running. In contrast, most current mobile interactions require the user to stand still and pay full attention to the display content. Such mobile interactions may not perform well when the user navigates through public spaces or performs any activity that demands visual attention. In this section, we present the literature discussing the effects of mobility on mobile device interactions.

Interacting with mobile devices while in motion is challenging. There is a good amount of research focusing on the effect of different mobility levels on user interactions and the design of new interactions that aspire to support these activity contexts. Mackay et al. (Mackay et al. 2005) presented a study to compare three different software-based navigation techniques (scrollbars, tap-and-drag, and touch-n-go) under different activity contexts: standing, sitting, and walking. Touch-n-go (Dearman, D., MacKay, B., Inkpen, K.M., Watters 2005) is a navigation technique in which direction is determined by the position of the touch relative to the center of the screen, whereas speed is determined by its proximity from the center. Results have shown that interactions and preferences of users change according to different mobility levels. Among different navigation techniques, tap-and-drag and touch-n-go outperformed traditional scrollbar techniques, however, participants preferred touch-n-go over tap-and-drag due to its ease of use and a better user experience.

Schedlbauer et al. (2007) have investigated the effect of mobility on target selection using stylus-based touch. The study showed an increase in error-rate with mobility. However, the task-completion time remained unaffected. A similar study was conducted by Schildbach and Rukzio (2010) to determine the effect of mobility on reading activity and one-handed target selection using the thumb. Results have shown a negative effect of mobility on target-selection accuracy, and reading speed. In order to compensate this negative effect, the authors increased the target and text size. The increase in target size resulted in better performance and decreased error-rates, though larger text did not yield any increase in reading performance due to increased scrolling need. Bergstrom-Lehtovirta et al. (Bergstrom-Lehtovirta, Oulasvirta, and Brewster 2011a) studied a quantitative relationship between walking speed and target selection on touch-interface using the dominant index finger. First, the speed of a treadmill was varied to determine the preferred walking speed (PWS) of each participant. Second, participant's new speed was measured while interacting with the touch interface. The results suggested a negative impact of mobility on target selection irrespective of walking speed.

A stable level of performance can be maintained when walking at 40-80% of PWS, indicating a non-linear relationship between walking speed and target acquisition on touch-interface. Lim and Feria (Lim and Feria 2012) have examined the perception process during visual search to determine the effect of object-size, contrast and target location under two different activity contexts: walking and standing. Results have shown that (1) there exists an increase in mobility, (2) bigger objects, and (3) targets in the inner area of the mobile device screen have a negative impact on visual search. However, performance remains unaffected when changing the contrast of shapes.

It is evident that mobility has a negative impact on interaction performances such as reaction time, completion time, and accuracy. To compensate for these negative effects, it is important to produce new interactions that seek to support all activity contexts. Kane et al. (Kane, Wobbrock, and Smith 2008) have developed the walking user interface (WUI) prototype that adapts user-interface based on user's movement to reduce the effect of mobility. The results of the study have shown that altering the size of the interface can be effective to reduce the negative effect(s) of walking. However, WUIs could not perform as well as simple-static interfaces. The authors have argued that this has mainly been due to the prototype design and the trade-off between screen and button sizes.

Bragdon et al. (Bragdon et al. 2011) have proposed various design-factors for touch-screen gestures to reduce attention load in mobile environments. A study was carried out to compare the performance of soft-buttons and gesture interactions in common mobile environments. Results have shown that gestures can significantly improve interaction performance and reduce attention loads in mobile conditions. Results further demonstrate that gestural interactions remain unaffected by environmental distractions and provide on-par performance as soft-buttons when the user's attention is focused on the screen. Vadas et al. (Vadas et al. 2006) have studied the impact of mobility on reading and have suggested audio as an acceptable modality for comprehension tasks in mobile conditions. The audio-display allowed participants to freely navigate in their environment, as it did not require any visual attention. Goel et al. (Goel, Findlater, and Wobbrock 2012) proposed WalkType, a text-entry system that uses accelerometer data to compensate the negative effect of mobility.

This section has provided an overview to demonstrate the effects of mobility on handheld mobile interactions and the effectiveness of new techniques devised to overcome performance issues. The knowledge of handheld mobile interactions gathered from this literature can be leveraged in our research to learn more about mobility issues while interacting with wearables. However, proposed solutions such as increasing target's size may not be transferable to wearables due to their limited display space, input space and resources.

2.4 effect of encumbrance on touch interactions

Besides different levels of mobility, another main aspect influencing wearable interactions is encumbrance. Since the beginning of mobile computing, most interaction techniques for mobile devices have used hands whether for touch or for gestural interactions while explicitly holding a device. But under several real-world scenarios, user's hands may get occupied in other tasks such as carrying bags or riding a bike. The encumbrance may vary based upon the user's current physical task. For some tasks, the user may still be able to use one or both hands or can use both hands with a burden or encumbrance such as carrying bags. For other tasks, the user may become totally incapable of using hands to interact with the mobile device, leading to complete situational impairment.

Ng et al. (Ng, Brewster, and Williamson 2013) have emphasized the need to study the impact of encumbrance on mobile device interactions. To understand the effect of encumbrance, they asked participants to perform a target-acquisition task on mobile devices while carrying bags and boxes in the dominant and non-dominant hand under two main activity contexts: walking and sitting. The results of the experiment have shown a negative effect on encumbrance and mobility on mobile device interactions leading to a decrease in selection accuracy. Results have also shown that encumbrance affects the dominant hand more than the non-dominant hand. Ng et al. conducted another study (Ng et al. 2014) to investigate the effect of encumbrance and mobility on one-handed and two-handed mobile interactions. The task consisted in performing target acquisitions, using three common mobile interaction postures: two-handed index finger, one-handed thumb, and two-handed thumb. Results have shown that, irrespective of the input method (single-handed or double-handed), encumbrance always has a significant negative effect on selection accuracy.

Ng et al. (Ng, Williamson, and Brewster 2015) examined the effects on encumbrance and mobility on four main touch-based gesture interactions: tapping, dragging, spreading pinching, and rotating. These touch gestures were evaluated under actual walking conditions in a controlled environment. Results have shown that encumbrance and walking had a negative impact on the performance of all these touch gestures, except the rotation gestures. Results further suggested that the use of two-finger gestures (spreading, pinching rotating) should be preferred for better accuracy than single finger-gestures (tapping dragging) at the expense of longer execution times. To improve the performance of single-finger gestures, the targets should be made larger to prevent occlusion.

This section has presented the importance of hands for mobile interactions. The effect of encumbrance and encumbrance on mobile interactions. We have learnt that the use of two-finger gestures and bigger targets could improve interaction performance under encumbrance conditions. Although not always possible with any wearable device due to size limitation, it is also not clear if such solutions could have the same benefits with wearables compared to handheld mobile devices.

2.5 interactions that support mobility and encumbrance

To deal with issues of mobility and encumbrance on mobile interactions, it is reasonable to consider other interaction methods that do not solely rely on eyes and hands. There has been substantial work that explores alternative interaction methods, which minimize the use of eyes and hands. Crossan et al. (Crossan et al. 2008) have studied wrist-rotation as an input technique to interact with mobile-devices eyes and hands-free. The performance of the input technique was evaluated in four different postures: resting, standing, sitting, and walking. Results have shown high success rates in static conditions. However, targeting performance decreased significantly under dynamic conditions due to a disturbance in accelerometer reading. Crossan et al. (Crossan et al. 2009) have discussed Head Tilting as a hands-free technique to interact with a mobile device. Head tilt angle was estimated using an accelerometer attached to a hat. Results have shown higher accuracy and shorter target acquisition times when the user was static in contrast to dynamic conditions. earPod (Zhao et al. 2007) is an eyes-free technique for menu navigation using touch reactive auditory feedback. By sliding the finger over the touchpad, the user can hear the menu item. The menu item is selected by lifting the finger. Results have shown that earPod outperformed the visual technique after a training of 30 minutes. Slide Rule (Kane, Bigham, and Wobbrock 2008) discussed how the touch screen could be made accessible to blind people using a set of audio-based multi-touch interaction techniques. Slide Rule is a completely eyes-free method for interacting with a touch interface. Results have shown that Slide Rule was preferred over familiar button-based systems.

Pirhonen et al. (Pirhonen, Brewster, and Holguin 2002) have additionally demonstrated the use of touch gestures and audio interface to control mobile devices eyes-free. Oakley et al. (I. Oakley and O' Modhrain 2005) have discussed how a list can be navigated by tilting the device and using vibrotactile feedback. The study has shown that the use of vibrotactile feedback can significantly improve the accuracy performance in mobile conditions. Oakley et al. (Ian Oakley and Park 2007) presented the use of hand motions as an eyes-free interaction technique to control a marking menu system. The space between the horizontal and vertical orientation of the device is divided into three areas. The commands are issued by rotating the device in one of these areas. Williamson et al. (Wiliamson, Crossan, and Brewster 2011) presented a study to examine a mobile multimodal interface allowing the user to interact with the system using hands-free and eyes-free interactions while on the move. The system consisted of an RSS reader that can be accessed by two ways. The first, through eyes-free speech and audio, and the second, by hands-free using wearable sensors attached to the wrist. Results have shown that participants were successfully able to use the system while moving through public spaces. Participants were also more comfortable in using gestures on the street rather than in public areas.

Hooten et al. (Hooten, Hayes, and Adams 2013) evaluated and compared the performances of three communicative modalities: visual, audio, and redundant audio-visual modality while walking. Results of the study have shown that redundant audio-visual modality was not better than visual modality. However, both visual and audio-visual modalities have led to better performance than the audio modality. Results have also shown that these communicative modalities remain unaffected by the walking speed.

This section has reviewed several interaction techniques that use different modalities and in-built sensors to reduce the dependency on hands and eyes. We studied how researchers have used sensors in the past to deliver new interactions. This knowledge has inspired us to develop smartwatch interactions that use embedded sensors to interact under varying degrees of activity contexts.

2.6 MOBILITY AND ENCUMBRANCE EVALUATION METHODS

Researchers have explored various scenarios and methods for evaluating the qualitative and quantitative performances of mobile device interactions. Kjeldskov and Stage (Kjeldskov and Stage 2004) outlined the difficulties faced in performing field-based methods in contrast to controlled laboratory methods for the evaluation of mobile systems. Field-based evaluations make it hard to capture key situations, apply established evaluation techniques, and complicate data collection. Laboratory settings can provide a good representation of user-experience and performance, but to estimate the user workload, field-based evaluation methods can be more appropriate. Barnard et al. (Barnard et al. 2005) conducted an empirical study to compare the suitability of scenarios that can best represent mobile conditions for evaluating mobile device interactions. They use a treadmill to simulate the mobility and compare it with walking in a controlled environment. Participants were asked to perform two vision demanding tasks, comprehension reading, and word search. The results of the study have shown that the treadmill condition is an appropriate evaluation tool when performance measures (e.g., time and accuracy) are of primary interest, whereas controlled walking is useful to simulate the actual user experience and provide more accurate performance and subjective measures.

Lin et al. (2007) investigated the impact of mobility on stylus-based tapping under three different mobility conditions: sitting, treadmill-walking, and obstacle-course walking. Results have shown a significant difference in tapping performance between the treadmill and obstacle-course conditions. Compared to treadmill walking, the obstacle-course condition showed a dramatic decrease in accuracy even when the walking speed was reduced by 36%. The obstacle-course condition presented a more difficult and more challenging mobility situation than the treadmill-walking condition. Ng et al. (Ng, Williamson, and Brewster 2014) compared two mobile evaluation methods: treadmill walking and ground walking, in order to determine which method best represented encumbrance situations. To simulate the encumbrance, participants were asked to carry bags and hold boxes in their dominant and non-dominant hand while interacting with mobile touch-interfaces. Results suggest that the use of controlled walking should be preferred if the analysis of natural walking speed is important to the underlying study, otherwise, both methods are equally appropriate to examine mobile device interactions with their own specific limitations: treadmill-walking has very limited space due to safety sidebars which restrict new encumbrance scenarios, whereas controlled walking is difficult to setup and requires a human pacesetter to control the preferred walking speed of the participant.

This section has briefly explored the current evaluation scenarios for mobile device interactions. The knowledge of the mobile evaluation methods acquired from this section informs evaluation strategies to determine the performance of wearable interactions under different mobility and encumbrance contexts.

3

EFFECT OF MOBILITY AND ENCUMBRANCE ON SMARTWATCH INTERACTIONS

Interacting with a smartwatch while in motion is not just a desirable functionality, but a necessity for smartwatch use. This is what distinguishes smartwatches from traditional portable handheld devices. As touch is a standard input method on the smartwatch, touch interactions need to be modified to support all the activity conditions. In the past, researchers have examined the effect of encumbrance and mobility on portable handheld devices (Ng, Williamson, and Brewster 2015; Ng et al. 2014). Due to the always active nature of smartwatch, it is desired to have seamless interaction capabilities on smartwatch, irrespective of user's activity. Therefore, we study the effect of mobility and encumbrance on smartwatch to understand how well current interactions can handle these conditions.

In this chapter, we will discuss the setup of a first user experiment and analyze the results to investigate the effect of mobility and encumbrance on smartwatch touch interactions. We will first discuss different encumbrance and mobility scenarios for the user experiment, followed by experimental design, results, and discussion. This chapter answers our first research question, "what will be the effect of encumbrance and mobility contexts on smartwatch interactions?"

3.1 SCENARIOS

(a) both hands available (b) dominant hand busy (c) non-dominant hand busy (d) both hands busy

Figure 3.1: The four encumbrance conditions for the first user experiment.

In section 1.1, we discussed the two main axes of activity contexts i.e. mobility and encumbrance. We demonstrated in Table 1.1, how our daily tasks fit in these two axes. For first experiment, we examine the performance of smartwatch interactions under 12 different conditions determined by these two axes i.e. mobility and encumbrance. These 12 activity conditions consisted of the combinations of three mobility conditions (i.e. standing, walking, and running) and four encumbrance conditions (i.e. both hands available, dominant hand busy, non-dominant hand busy, and both hands available). The four encumbrance conditions are shown in Figure 3.1. Similar to Ng et al. (Ng et al. 2014), we simulate the encumbrance scenarios using commonly used grocery bags weighing 1.6 kg each. During the experiment, participants interacted with a smartwatch without bags, with bag in a dominant hand, non-dominant hand, and both the hands, under three different mobility conditions as shown below:

(a) Standing (b) Walking (c) Running

Figure 3.2: The three mobility conditions for the first user experiment.

The treadmill is used to simulate the mobility conditions. The walking speed is the "preferred or normal" walking speed of the participant. The running speed is taken as 1.5 times the PWS (preferred walking speed). The procedure for determining the PWS is discussed in Section 3.4. The following table lists all the 12 conditions for the first user experiment:

		Encumbrance Levels			
Mobility Levels		**Both hands Available**	**Dominant hand busy**	**Non-dominant hand busy**	**Both hands busy**
	Standing	Standing with both hands available	Standing with dominant hand busy	Standing with non-dominant hand busy	Standing with both hands busy
	Walking	Walking with both hands available	Walking with dominant hand busy	Walking with non-dominant hand busy	Walking with both hands busy
	Running	Running with both hands available	Running with dominant hand busy	Running with non-dominant hand busy	Running with both hands busy

Table 3.1: All activity conditions included in the first user experiment.

3.2 PARTICIPANT, EQUIPMENT AND PHYSICAL SETUP

(a) Precor 835 treadmill (b) Imacwear M7 smartwatch

Figure 3.3: Precor Treadmill and IMacWear M7 smartwatch used in the user experiment.

We recruited 12 participants from University of Manitoba (mean age 24.75, SD 2.6, 7 males, 5 females). To recruit the participants, we advertised widely through the bulletin boards across the campus. We paid $20.00 to each participant and the experiment took around 1.5 hours. All participants were having some previous experience with touch gestures using a smartwatch or smartphone. A Precor 835 treadmill with safety hand rails was used to simulate the mobility conditions. We used IMacWear M7 smartwatch running on Android 5.1 OS. The smartwatch measured 28.36 x 4.65 x 1.38 cm, weighed 118 g, had a glass capacitive multi-touch screen (39 mm diagonal, 240 x 240 px), 512MB RAM and 1GHz, Cortex-A7, Dual Core processor. All the built-in touch gestures for navigation were disabled to prevent disruption during the experiment. The interaction data was sent from the Android app running on a smartwatch to a laptop connected over a local network via a router. Commonly used grocery bags as provided by retailers such as Walmart or Superstore were used to simulate encumbrance. The dimensions (length x width x height) of the bags were 31.8 x 27.9 x 17 cm. Similar to (Ng, Brewster, and Williamson 2014; Ng, Williamson, and Brewster 2014), each bag weighed 1.6 kg to replicate the realistic experience, while at the same time ensuring that the participants do not get tired. NASA TLX (Hart and Staveland 1988) were used to measure the perceived workload in order to assess the performance of smartwatch interactions under different activity levels.

3.3 INTERACTION TASKS

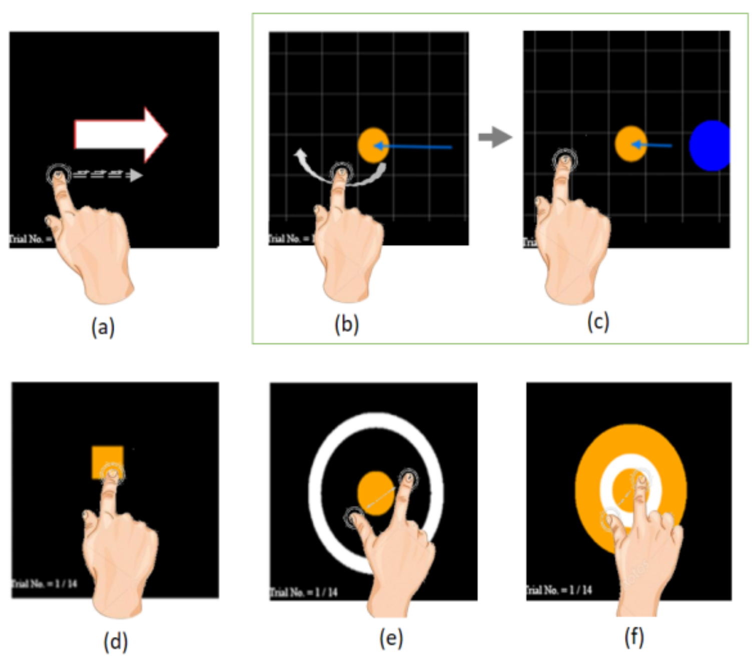


Figure 3.4: Touch Interaction Tasks (a) flicking (b) panning initial screen (c) panning reached close to the target (d) selection (e) pinching-out (f) pinching-in.

A number of studies have been performed earlier to examine the performance of flicking, tapping, panning, pinching and spreading touch gestures on smartphones and tabs (Nicolau and Jorge 2012; Findlater et al. 2013; Tran et al. 2013; Hoggan et al. 2013). However, it is still unknown whether these touch gestures can provide the same functionality on a smartwatch under various activity levels. To analyze the performance of these touch gestures on a smartwatch under different activity levels, we designed four experimental tasks as discussed below.

3.3.1 *Flicking Task*

To measure the performance of flicking touch interactions, an arrow is displayed on the screen presenting the direction of the flick. In this task, the participant has to flick in the direction of the arrow accurately and in the minimum possible time. The arrow can have four possible directions i.e. left, right, up and down, representing the commonly used navigation methods on smartphones and smartwatches. In a single trial, there are either two consecutive or three consecutive arrows with randomized, the number of trials for each condition are kept the same for uniformity reasons. In case of a wrong flick, an additional flick is added to the trial.

3.3.2 *Panning Task*

In a panning task, an orange colored circular object is shown at the center of screen with a vector indicating the pan direction. The length of the vector represents the distance of the circle from the target. As the circle moves closer to the target, the length of the vector becomes small. During each trial, the user has to perform consecutive pans to move the circle to the center of the target. The two different panning distances 240px and 480px are selected to determine the effect of the panning distance on the completion time and pan counts. Pan Counts are total number of pan events required to complete a single trial. The two distances present the panning navigation by one screen or two screens. During each trial, the panning distance (among 240px and 480px) and target direction are selected randomly, however, the number of trials with each panning distance are kept the same to retain uniformity.

3.3.3 *Selection Task*

Selection task consisted of a square shaped target of two different sizes 42px and 60px. We referred to the design guidelines for smartwatch interface given by Apple ("Icons and Images - watchOS Human Interface Guidelines" 2017), Android ("Interactive Watch Faces - Patterns - Android Wear Design Guidelines" 2017) and Sony ("Design Guidelines | Sony Developer World" 2017) and found that the sizes of icons and selectable images generally lies in the range of 38px to 96px. In each trial, a single square target is displayed on the screen at a random position. To complete a trial, the user has to tap the target. If a user touches any area other than the target, then it is considered as a wrong attempt. The two different target sizes are selected to analyze the effect of target size on accuracy and completion time under different activity conditions.

3.3.4 *Zooming Task*

To examine the performance of pinching-in and pinching-out gestures, we followed an approach similar to Tran et al. (Tran et al. 2013). For zooming-out tasks, a diminished circle of initial radius 20px is presented at the center of screen and the user has to perform pinch-out gestures to scale the circle to fit inside the white ring of radius 100px and width 5px. When the circle fits inside the white ring, the ring becomes green. If the circle stays in the ring for 100 milliseconds, it leads to a successful completion of the trial. In case of overshoots, the trial remains continued and the user still has the chance to bring the circle to the ring. The number of times a user overshoots the ring and the number of clutches are recorded as the measure of gesture accuracy. Similar to the zooming-out task, the performance of pinch-in gestures is examined by having a circle with an initial radius of 100px and ring of radius 40px and width 5px.

3.4 experimental design and procedure

We used a repeated-measures within-participants experimental design. At the beginning of the experiment, the "preferred walking speed" (PWS) of the participant is measured by incrementally increasing the speed of the treadmill by 0.1 miles/h. Similar to Barnard et al. 2005; Ng, Williamson, and Brewster (2014), we ask the participants to select the speed at which they normally walk in their daily life. Once we get the PWS of the participant, we give them the description of all the interaction tasks and ask them to perform the set of practice trials on the smartwatch until they get comfortable with the user-interface of the interaction tasks. There are three mobility conditions; standing, walking and running and four encumbrance conditions; both hands available, dominant hand busy, non-dominant hand busy and both hands available. Under the walking condition, the treadmill speed is set to PWS whereas in the running condition, the treadmill speed is set to 1.5 times the PWS (i.e. 1.5*PWS). In the encumbrance conditions, the participant is asked to carry no bags or one bag in their dominant-hand, non-dominant hand, or one bag in both hands. There are four interaction tasks- flicking, panning, selection and zooming, that the participant has to perform under 12 different activity conditions (combinations of three mobility and four encumbrance conditions), with 14 trials for each task. The activity conditions are selected using a Latin square design to control the undesired variation due to learning effects. The experiment is split into three sessions, each consisting of four activity conditions, a break of 10 minutes is given after each session so that the participant does not get exhausted by the physical workload. To summarize, the total number of trials performed during the experiment are:

12 participants

x 3 mobility conditions

x 4 encumbrance conditions

4 interaction tasks

x 14 trials each task

= 8064 trials

Depending upon the interaction task, a number of dependent variables such as completion time, accuracy, number of events, angle deviation, overshoots, etc. are recorded. The independent variables are task type, mobility condition, encumbrance condition, target size, target distance, target direction, etc. At the end of the experiment, participants are asked to fill the NASA TLX for two extreme activity condition: standing both hands available and running both hands busy, to determine the effect of mobility and encumbrance on participant's workload and performance.

3.5 RESULTS

We conducted a repeated measure two-way ANOVA (Type I)(Fujikoshi 1993) with two independent factors mobility and encumbrance to analyze the completion time, accuracy, and other dependant factors for each individual task. Before ANOVA analysis, we performed the Shapiro-Wilk normality test (Royston 1992) and Bartlett test (Chao and Glaser 1978) to check the homogeneity of variances.

3.5.1 *Panning*

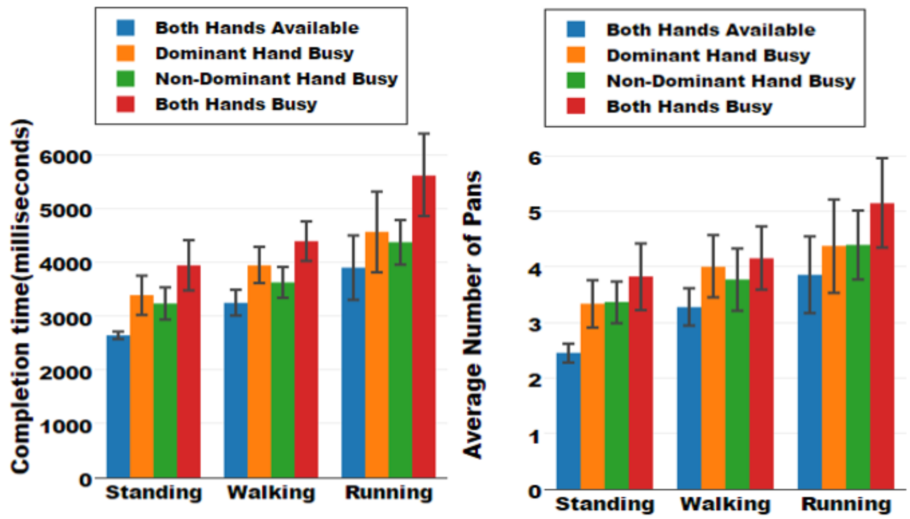


Figure 3.5: Completion time(milliseconds) and accuracy percentage for the panning task. Error bars represent 95% CI.

We report the mean completion time and average number of pans per trial in Figure 3.5. The graph shows that the participants took less time when their hands were available and standing still. The increase in mobility and encumbrance has led to the increase in completion time.

The ANOVA for completion time shows a significant main effect of encumbrance, ($F(3,121) = 25.26$, $p<0.001$). A significant main effect is observed for different mobility levels as well, ($F(2,121) = 29.52$, $p<0.001$). There is no significant mobility X encumbrance interaction ($p>0.05$) found. The posthoc pairwise comparison with Holm p-value adjustments shows that there is a significant main difference in all three mobility conditions i.e. with an increase in mobility levels from standing to walking to running, the panning performance declined by a significant factor. However, we could not find a significant difference between dominant hand busy and non-dominant hand busy conditions (p=0.195).

For the completion of a single panning trial, the participant has to perform a number of consecutive pans. We are interested in analyzing the effect of mobility and encumbrance on the number of pans per trial. In Figure 3.5, we report the effect of mobility and encumbrance on the average number of pans per trial. It can be seen that participants took more number of pans to complete a trial when their hands were encumbered and with an increase in mobility. The average number of pans doubled when participants were running with bags in both the hands. The increase in pan count can be seen as the major effect of bag vibrations and walking momentum on touch interaction, leading to inaccurate pans and overshooting. We also examined the relationship between panning distance and completion time (and pan counts). When the panning distance is doubled, the completion time and pan count did not increase by a factor of two. There is a 42.34% increase in average completion time (and 54.07% increase in average pancount) which clearly indicates that initializing the panning task and determining the panning direction takes more time than continuing the consecutive pans.

3.5.2 *Flicking*

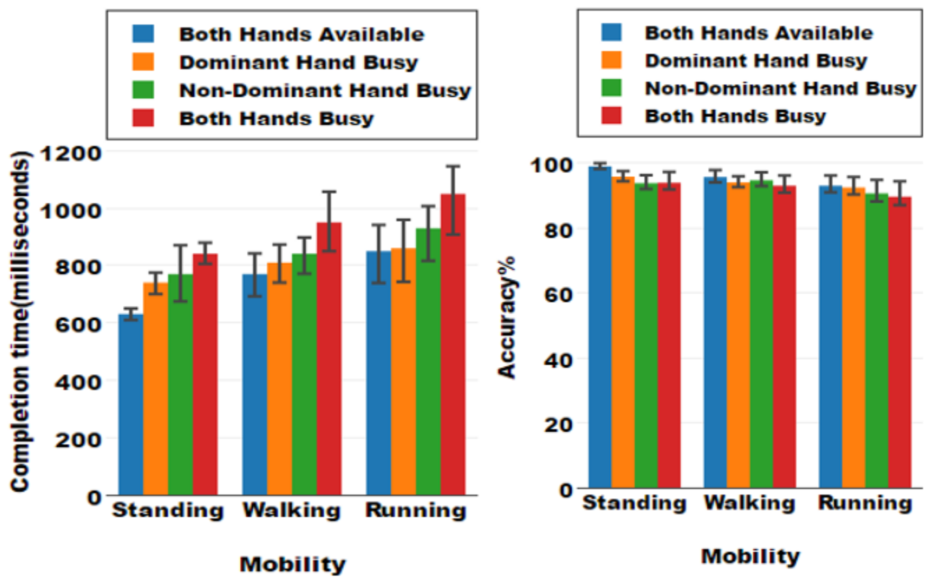


Figure 3.6: Completion time(milliseconds) and accuracy percentage for flicking task. Error bars represent 95% CI.

Interestingly, the accuracy of a flicking gesture remained above 90% under all the activity conditions, however, we still observed the negative effect of encumbrance and mobility on flicking performance. The ANOVA analysis for flicking accuracy shows a significant main effect of encumbrance ($F(3, 121) = 7.960$, $p < 0.001$) and mobility. ($F(2, 121) = 10.437$, $p<0.001$). However, there is no interaction for encumbrance and mobility ($p>0.05$). For flicking accuracy, there is no significant difference between non-dominant hand busy dominant hand busy ($p>0.05$) or non-dominant hand busy both hands busy ($p>0.05$). It indicates that the negative impact of encumbrance on flicking performance is independent of the hand carrying the bag. It suggests that the decline in performance is not merely due to a difficulty in performing flick gestures with bags in hand, but is rather due to the fatigue experienced by the participants on carrying the bags in one or both the hands.

The ANOVA for completion time of flicking shows a significant effect of encumbrance ($F(3, 121) = 13.140$, $p<0.001$) and mobility ($F(2, 121) = 13.330$, $p<0.001$). However, among all the interaction tasks, flicking is performed in the least amount of time with the mean value of 842 milliseconds. The high accuracy and lowered completion time under all the conditions have suggested that flicking requires less visual attention and can be performed in a carefree manner unaffected by vibrations and momentum due to walking. To further investigate the effect of mobility and encumbrance on flicking time, we performed a pairwise posthoc test with Holm p-value adjustments.The posthoc comparison shows significant differences between mobility levels on flicking time. No significant difference, moreover, between non-dominant hand busy and dominant hand busy was found.

3.5.3 *Selection*

The ANOVA for target selection accuracy shows a significant main effect of mobility ($F(2,121) = 45.536$, $p < 0.001$) and encumbrance ($F(3,121) = 12.998$, $p < 0.001$). The posthoc comparison for target accuracy shows a significant difference between all three different mobility conditions. However, no significant difference between non-dominant hand busy and dominant hand busy is found. The completion time and accuracy of selection task under all the mobility and encumbrance conditions are shown in Figure 3.7. It can easily be seen that the accuracy of the selection task dropped with an increase in encumbrance and mobility (48.81% for running with both hands).

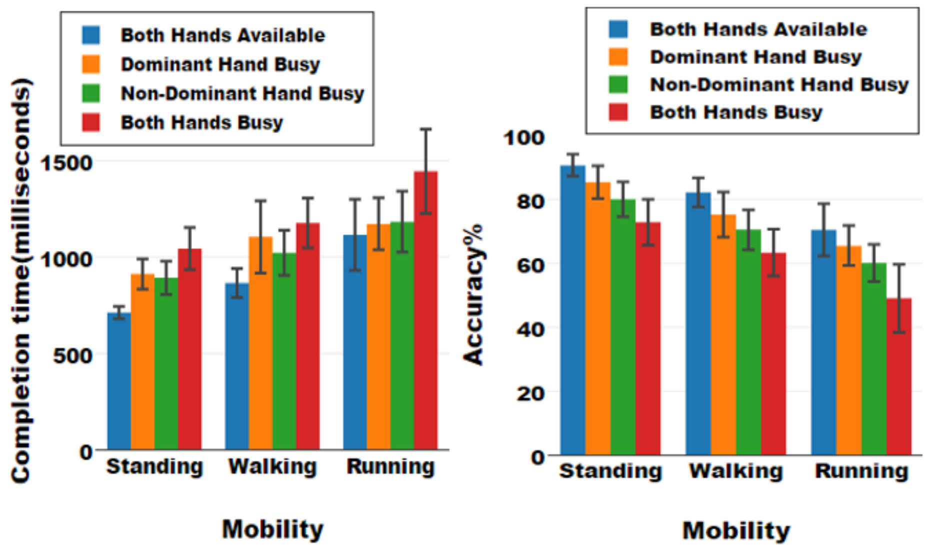


Figure 3.7: Completion time(milliseconds) and accuracy percentage for selection. Error bars present 95% CI.

It seems that, with an increase in bodily movement and bag vibrations, participants found it harder to tap the target accurately. A similar trend was seen for completion time. With the increase in mobility and encumbrance, participants took more time in selecting the targets. The ANOVA for completion time also shows a significant main effect of encumbrance ($F(3,121) = 10.297$, $p < 0.001$) and mobility ($F(2,121) = 20.020$, $p < 0.001$). We find significant differences between all the three mobility conditions for completion time, however, no significant difference between the non-dominant and dominant hand was found. The increase in completion time indicates that mobility delimits visual attention. We analyze the effect of selection target size in different mobility and encumbrance conditions as shown in Figure 3.8.

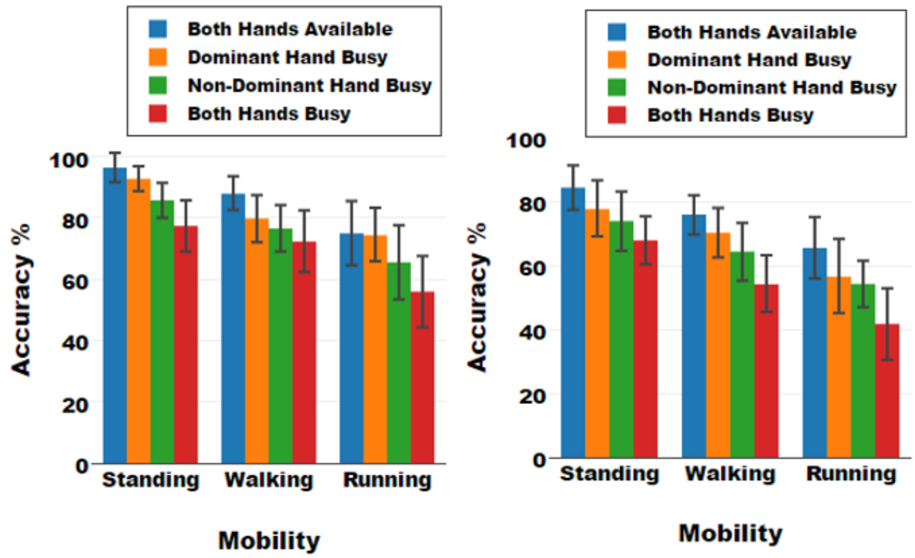


Figure 3.8: Accuracy percentage for bigger target size (60px) on left and smaller target size (42px) on right. Error bars present 95% CI.

The mean selection accuracy for bigger targets (60px) is found to be 12.68% more than the smaller targets (42px). It is backed by the fact that small targets are harder to select due to the increased visual attention and negative effect of the "fat" finger problem under mobile conditions.

3.5.4 *Pinching-in and Pinching-out*

The effect of mobility and encumbrance on pinching out and pinching in gestures are reported in Figure 3.9.

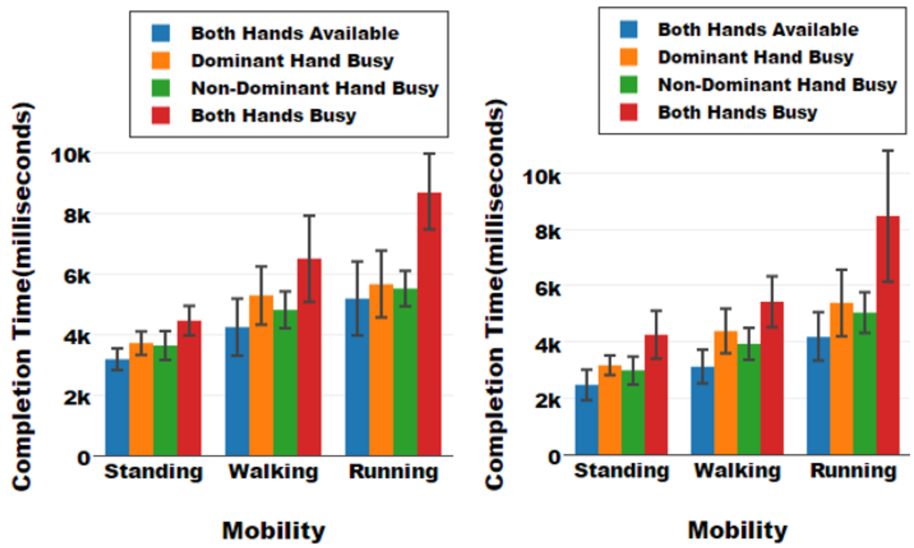


Figure 3.9: Completion time for pinching out (left) and pinching in (right) gestures for the zooming task. Error bars present 95% CI.

The ANOVA for completion time shows that the encumbrance ($F(3, 121) = 29.082$, $p<0.001$) and mobility ($F(2, 121) = 24.642$, $p<0.001$) has a significant main effect. A significant main difference is observed for all the different mobility levels, however, no significant difference between dominant hand and non-dominant hand is found. The result demonstrates that mobility and encumbrance have the worst negative effect on pinching touch gestures. As compared to standing still without bags, the participants took 3.05 times more time, no average, in completing the zooming task when they were running with bags in both hands. After inquiring, however, we found that participants found it hard to position and relatively move multiple fingers on the small touch screen to perform pinching gestures.

A thorough analysis of pinching gestures further informed this study that the increase in completion time was not merely due to the difficulty in positioning and moving multiple fingers. It was rather due to the diminished screen size, which forced participants to perform multiple clutches for completing a single zooming task. The average number of clutches under all mobility and encumbrance conditions are reported in Figure 3.10.

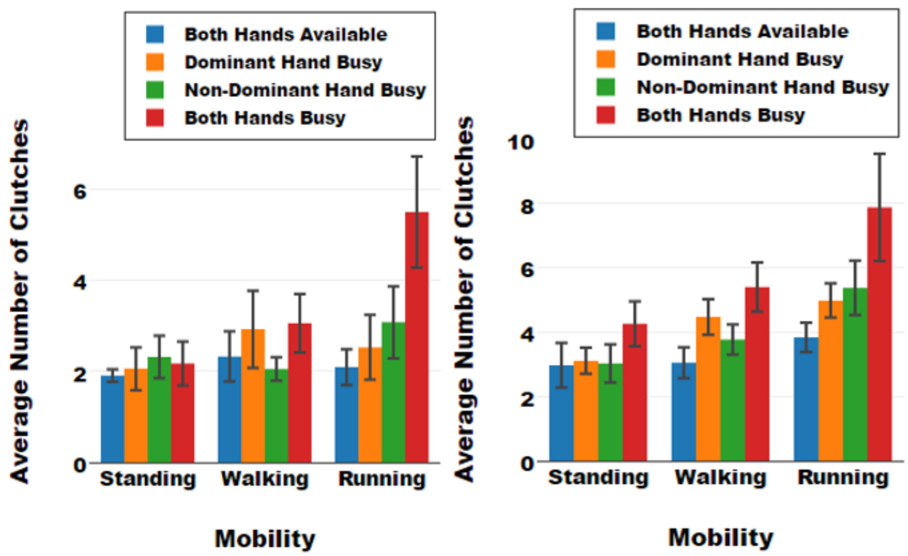


Figure 3.10: An average number of clutches for pinching out (on left) and pinching in (on right) gestures to complete a single zooming task. Error bars represent 95% CI.

On average, participants clutched 1.63 times more when pinching in than pinching out. The pinching in requires fingers to be positioned carefully initially at the boundary of the screen for maximum scaling whereas pinching out needs the fingers to be positioned at the center of the screen and then move outward smoothly. The small screen size complicates pinching in gestures because placing two fingers with maximum distance in between on small screen is challenging under activity contexts. Therefore, pinching in provides less scaling effect than pinching out and led to an increase in the number of clutches. Interestingly, the number of clutches did not remain the same under all the mobility and encumbrance conditions.

Participants overshot the target ring several times with an increase in mobility and encumbrance, due to performing additional clutches. The average number of overshoots for pinching in and pinching out gestures are reported in Figure 3.11.

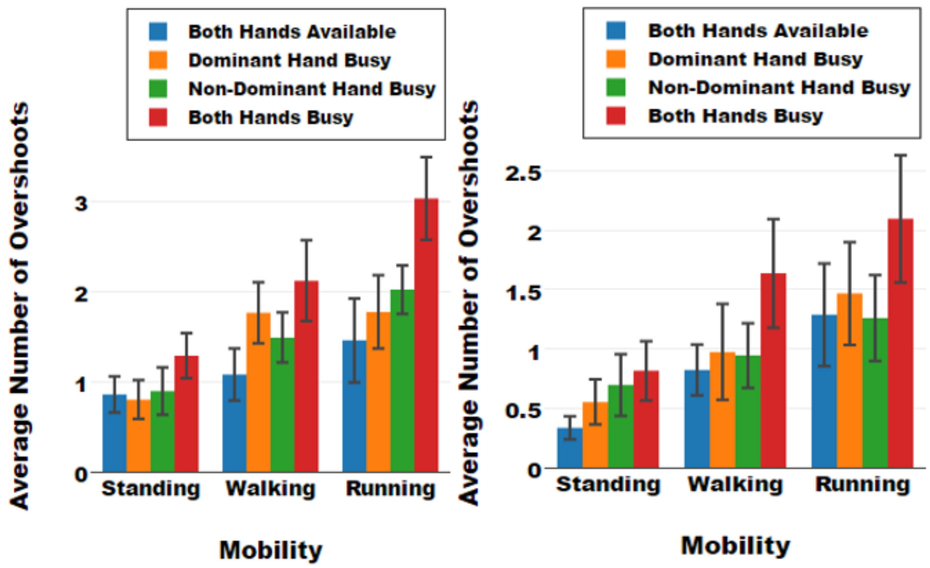


Figure 3.11: An average number of overshoots for pinching out (on left) and pinching in (on right) gestures to complete a single zooming task. Error bars represent 95% CI.

It seems, with an increase in mobility and encumbrance, participants lost their control over pinching gestures which led them to overshoot the target ring. Also, scaling the circular object to thin target ring requires visual attention which is delimited by the effect of mobility. On average, participants overshot the target 1.68 times more when pinching out than pinching in, despite the number of overshoots may have increased the number of clutches. The number of clutches and overshoots are not linearly dependent on each other. The relation between number of clutches and overshoots depends upon the ease of performing the pinching in or pinching out gesture and both these factors together are found to be responsible for the increase in completion time for pinching gestures. The reason why participants overshot more while pinching out than pinching in is surprisingly related to the number of clutches. As pinching out gestures can be performed more smoothly, it takes a smaller number of clutches to complete a single zooming trial. During each single clutch, the participant scales by a significant amount and mistakenly overshoots the target due to the effect of encumbrance and mobility. In contrast, pinching in gesture take a larger number of clutches, each with small scaling effects. Thus, the number of overshoots were less.

3.6 discussion

a) Which gesture performed well under all the conditions?

Among four commonly used gestures, the flicking gesture was the most efficient. For all conditions, the completion time of the flicking task remained well under 1.2 seconds and with an accuracy above 90%. The fact that it requires less visual attention and remains unaffected by the fat finger problem makes it the best gesture for smartwatch use. Although the use of particular gestures depends largely on the interaction task. From the results of this study, it is advised that flicking based gestures should be used whenever possible.

b) Which gesture is most affected by encumbrance and mobility?

Almost all the gestures are affected by encumbrance and mobility, though the extent to which they were affected varied significantly.

From the results shown, it is evident that encumbrance and mobility has the worst effect on pinching gestures. When participants were running with bags in both hands, the completion time reached the highest peek average of 8.8 seconds. Zooming no longer remained a single gesture task and a series of clutches were used to precisely change the scale of the circular object. Participants overshot the target ring several times due to the complexity of the gesture which was made even more worse by encumbrance and mobility. For panning tasks, the effect of encumbrance and mobility is in the form of increased number of pans which increased the completion time by a significant amount. For selection, encumbrance and mobility led to a decrease in accuracy and slightly longer completion time. However, from the results shown, it is advised that the negative effect of mobility and encumbrance on target selection can be accommodated by increasing the target size.

c) What is the response of participants and how did they feel while performing the interaction tasks?

At the end of the experiment, we asked participants to fill the NASA-TLX form to determine their perceived workload for performing the interactive tasks under two extreme mobility and encumbrance conditions: standing still without bags and running with bags in both hands. The response of the participants are reported in Figure 3.12. Most of the participants find pinching gestures frustrating and physically demanding. Particpants were asked: which gesture would they like to replace? Eleven out of twelve participants stated the need of modifying the pinching gestures for zooming tasks.

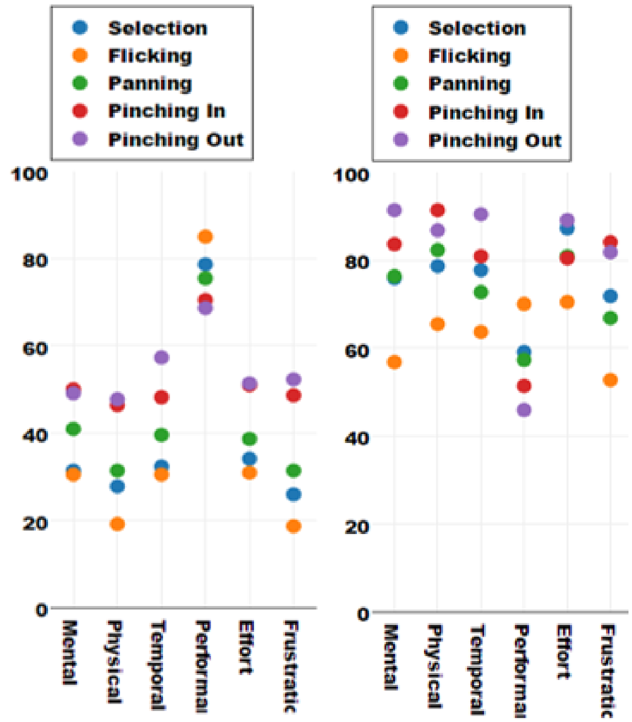


Figure 3.12: Mean perceived workload ratings of four interaction tasks across six NASA TLX dimensions when participants were standing still without bags (on left) and running with bags in both the hands (on right). Scores range from 1 to 100. The higher the number, the higher the perceived demand.

d) The comparison of our results with previous studies.

Although, our study is entirely different than the study conducted by Ng et al. (Ng, Williamson, and Brewster 2015), there are a few components on which broad comparisons can be made. Similar to their study, we studied the impact of encumbrance and mobility on touch gestures. Unlike their study, we used a smartwatch wearable device with a different set of interaction tasks that were relevant to the smartwatch use. Our study is more focused on exploring the challenges that mobile activities incorporate to the smartwatch touch gestures and find a suitable solution, in contrast to the study conducted by Ng et al. which was more focused on the effects of mobility and encumbrance. Ng et al. (Ng, Williamson, and Brewster 2015) reported that two-finger gestures can be performed more accurately than single-finger gestures with slightly more execution time. However, we did not find it to be the case for smartwatch interactions due to limited screen size and the complexity of gestures. Furthermore, we discovered a dramatic decrease in performance with an increase in mobility and encumbrance. Ng et al. (Ng, Williamson, and Brewster 2014) found a significant difference between the bag in dominant and non-dominant hand for target selection. However, in our case, there is no significant difference between the dominant and non-dominant hand. It suggests that the finger vibration from the bag in the dominant hand produces a similar effect as the vibration of the touch surface from the bag in the non-dominant hand.

In our study, we found that the flicking gesture remains less affected by mobility and encumbrance as compared to the target selection. This is in accordance to a study conducted by Bragdon et al. (Bragdon et al. 2011). However, our work is not limited to an analysis of touch-gesture design for reducing the attention load though it also focuses specifically on smartwatch interactions, i.e. the touch gestures that can be performed on a diminished screen that is worn on the wrist under different activity levels. It is evident that mark-based or flicking gestures can lead to performance gains for discrete events such as navigation (Kubo, Shizuki, and Takahashi 2016). It is still unknown, however, whether flicking based gestures can be used for complex continuous tasks such as zooming or panning.

3.7 SUMMARY

In summary, the user study presented in this chapter examined the performance of common touch interaction tasks on a smartwatch in different mobility and encumbrance conditions. We find that pinching gestures did not perform well under mobility conditions whereas flicking gestures were least affected by mobility and encumbrance. Two-finger gestures were hard to perform on smartwatches due to limited screen size whereas, single finger gestures are convenient and are less prone to occlusion. Also, pinching requires positioning and moving two fingers simultaneously on the small screen. The interactions on a smartwatch should not include accurate positioning of fingers which is delimited by mobility and encumbrance. The interactions should be simple with limited finger motion while in touch and should ideally be performed in an eye-free manner. In a panning task, navigating long distance led to an increase in completion time due to more number of clutches. The increased number of clutches is also noticed in pinching gestures under mobility and encumbrance conditions. The number of clutches is also another main cause for increased completion time. The interaction tasks should be designed to reduce the number of repetitions or clutches. For selection task, the accuracy decreased with small target size under mobility. It is advised to increase the size of clickable components to reduce wrongful selections.

This chapter has put forward important results and suggestions that can provide designers with insights for creating smartwatch interactions that support varied levels of mobility and encumbrance.

Based on the knowledge and conclusions from this study, in the next chapter, we will further investigate the design-space for new interaction techniques on smartwatch under activity conditions

4

INTERACTION DESIGN FOR ACTIVITY CONTEXTS

Results from the previous chapter confirm that mobility and encumbrance has a negative effect on current smartwatch interactions. We find that current zooming and panning methods on a smartwatch are not suitable under mobility and encumbrance conditions. In this chapter, we will explore the design factors for new smartwatch interactions that are robust to mobile activities users may be involved in. We encapsulate all the factors to propose a design-space for touch interactions on a smartwatch. Based on the design-space, the different interaction techniques for zooming and panning will be discussed.

4.1 DESIGN FACTORS FOR SMARTWATCH INTERACTIONS

From the results of our previous study and knowledge from the literature, we find that touch interactions for a smartwatch can be made more efficient if we consider the following simple rules:

(i) Avoiding double-finger interactions (Section 3.7).

(ii) Gestures should not require precise positioning of finger(s) (Section 3.7).

(iii) Gestures should limit the fat-finger user and occlusion (Ishii, Shizuki, and Tanaka 2016).

(iv) Ideally, gestures should be performable in an eyes-free manner (Kubo, Shizuki, and Tanaka 2016).

(v) Reduce the number of clutches or repetitions (Section 3.7).

(vi) If clutches are required, reduce the interval time between clutches (hypothesis based on 5.).

(vii) Reduce the motion while in contact with the screen (Section 3.7).

Considering the above rules, we introduce the concept of touch effort as discussed in the next section.

4.2 ON-TOUCH AND OFF-TOUCH INPUT

A touch gesture generally comprises of a sequence of events. We have broadly categorized a complete gesture into two main sequential events as discussed below:

(a) Off-Touch Efforts **(b) On-Touch Efforts**

Figure 4.1: On-Touch Efforts and Off-Touch Efforts.

While interacting with a touch screen, the finger(s) can either be in contact with screen or off the screen to prepare for the next touch event. For example, while performing pinching and/or panning gestures on a small screen, the finger switches between off-touch and on-touch sequentially. This sequence of off/on is referred to as clutching (Malacria, Lecolinet, and Guiard 2010a).

From our first study, one desirable characteristic for smartwatch interactions is to reduce the number of clutches. That is, touch gestures can be made better if we reduce the switching between off-touch and on-touch. The smartwatch interaction must be complete in a fewer number of events. Furthermore, we can improve interactions by reducing the efforts made by the user while having off-touch and on-touch input.

On Touch Efforts: On-touch efforts are the sub-tasks that a user performs while the finger(s) is in contact with the touch screen. These are:

1. Number of Fingers: From our previous results, we conclude that two-finger interactions are less desirable for smartwatch input as it augments the fat-finger problem and occlusion. Therefore, we consider the "number of fingers" as one of the design factors. On-touch efforts can be reduced by having few fingers or ideally just one finger in contact with the screen.

2. Degree of Contact: The degree of contact is defined in terms of duration and motion of the touch:

(i) Duration of touch: During a touch interaction, the duration of touch is the total time for which the finger remains in contact with the screen. To reduce the on-touch efforts, the interactions should aim at reducing the touch time

(ii) Motion of touch: The motion of touch is the number of pixels traversed by the finger while in contact with the screen. For less touch-efforts, interaction techniques should aim at reducing the touch motion.

Off Touch Efforts: Due to the small screen size, often the interaction task does not complete in a single event. To continue the interaction task, it requires users to go off-touch and prepare the finger for the next touch event. Off-touch efforts involve the thinking process and attention required to perform interaction tasks. The off-touch efforts are as follows:

1. Number of Events/Repetitions: From previous results, one of the conclusions is to reduce the number of clutches or events to complete the interaction task. It means that the interaction technique should ideally complete the task in a single sequence of events. After each event, the finger(s) repositions to prepare for the next touch event. By reducing events, touch efforts will be lowered with the elimination of overhead times with respect to the repositioning of fingers on the screen.

2. Visual Attention: Before going on-touch, the interaction task requires certain visual attention in determining the positioning and movement of the user's finger(s). From examining the relevant literature (Schildbach and Rukzio 2010), we have learnt that visual attention is delimited by mobility. Therefore, visual attention required for starting or performing touch events is one of the design factors for off-touch efforts. To reduce off-touch efforts, the interaction technique should ideally be performed in an eyes-free manner.

4.3 ABSTRACT VIEW OF DESIGN-SPACE

Based upon the concept of touch-effort, we posit the abstract view of our design-space in Figure 4.2. We have placed all major existing techniques from the literature in our design-space and have indicated the appropriate touch-effort required to perform these interactions. The following are some of the exceptions:

(i) The interaction technique must allow flexibility to change the zoom-level or navigate by a desirable amount. For example, we excluded "double tap", as it changes the zoom level by a fixed factor. Similarly, we did not include "zoom-tapping" (Olwal, Feiner, and Heyman 2008), "two-finger-tap" and "taptap" (Bellino 2015).

(ii) We excluded the techniques that were designed specifically for single handed interactions on smartphones, for example, "Fat Thumb" zooming and panning (Boring et al. 2012). These techniques are dependent on the contact surface of the thumb to distinguish between panning and zooming. This limits their usability in mobility and encumbrance conditions. Similarly, GraspZoom (Miyaki and Rekimoto 2009) uses external hardware attached to the backside of the mobile phone, which is not feasible with a smartwatch.

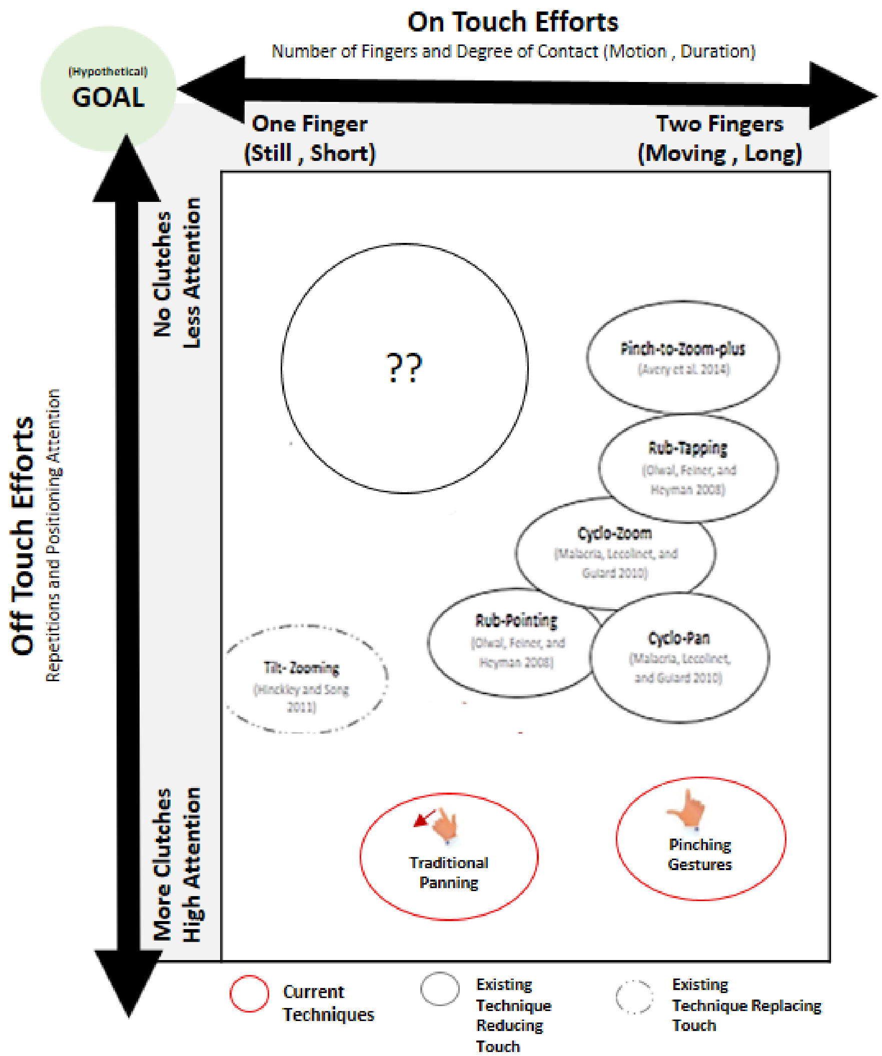


Figure 4.2: An abstract view of the Design-Space.

We started our exploration by implementing the techniques from the literature. The Cyclo Star (Malacria, Lecolinet, and Guiard 2010) and Rub-pointing. (Olwal, Feiner, and Heyman 2008) techniques require oscillatory motion of the finger on the screen. These techniques perform well in reducing the need of clutching in lieu of increasing attention. During our pre-study analysis, we found it hard to control the oscillatory motion of the finger(s) on the small screen under activity contexts. The to-and-fro motions of the finger led to overshooting the target which makes it unsuitable for smartwatch interactions. Similarly, the Tilt-Zoom technique that relies solely on sensor readings becomes impractical in mobility and encumbrance conditions, as it requires the controlled motion of the device.

There is an empty space in the top-left of our design-space. We could not find any technique from the literature to fill up that space. This directs our study to explore new techniques for ideal smartwatch interactions. To design new techniques, we employed a guessability study similar to Wobbrock, Morris, and Wilson (2009), as discussed in the next section.

4.4 USER-DEFINED SMARTWATCH TOUCH GESTURES

From the literature review, it is evident that most of the touch interactions that we use today are not defined by the user, but rather introduced by system designers (Bill Buxton 2007). The user-defined gestures are extensively studied in the literature (Wobbrock, Morris, and Wilson 2009; Mauney et al. 2010). In general, researchers study user-defined gestures to understand the mental-model of participants and design better gestures informed by user-behavior. But, in our case, we were interested in exploring new touch interactions on a smartwatch.

We recruited six participants (three males, three females) from the University of Manitoba. We asked participants to perform 12 trials each for flicking and zooming tasks (as discussed in section 3.3). We then displayed the zooming user interface and asked them to find the new touch gestures that we developed, provided it is as simple as flicking and as effective as pinching. In practice, there was new technique developed. The objective was to bring forward new creative ways for interacting with a smartwatch using easy new gestures. We recorded the touch gestures that participants performed. Each video lasted approximately 5 minutes. Interestingly, it allowed us to explore wide prospects of potential zooming gestures. The following figure lists some common gestures performed by participants:

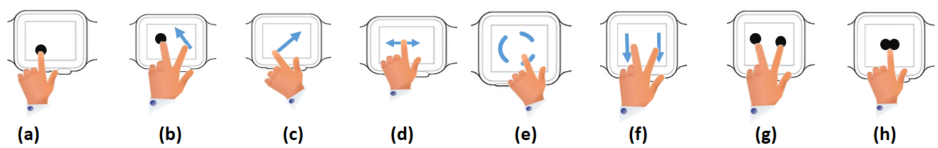


Figure 4.3: User-defined zooming gestures (a) tapping and long press at different parts of the screen especially at corners (b) hold one finger and move other finger (c) swiping diagonally from corners (d) to-and-fro finger motion (e) cyclic finger motion (f) two finger swipe (g) two finger tap (h) double tap at center.

As discussed in section 4.3, the cyclic and to-and-fro finger gestures require oscillatory motion which are hard to control under activity conditions. Therefore, we discarded these techniques immediately. Similarly, we rejected all the two finger gestures in line with the results from the previous user experiment. The gestures we were left with are double tap, tapping at different locations, long press, and diagonal swipes.

In the next section, we investigate the use of the aforementioned gestures to devise new zooming interactions for the smartwatch. We use the knowledge from the design-space to make the interactions that need minimum on-touch and off-touch efforts.

4.5 zooming techniques for smartwatch

To verify our hypothesis, we introduce two new zooming techniques, *SwipeZoom* and *TapZoom*. The design of these techniques has been formulated based on the design-space and the results from the previous user study. The following are two main requirements that we kept in mind while designing these techniques:

(i) Disambiguation: the techniques should be unambiguous i.e. our techniques must not conflict with any known smartwatch interactions. It should readily adapt to the current system without any modification.

(ii) Self-Contained: the techniques should not use any external hardware. It can only use the features and sensors that are embedded on the smartwatch.

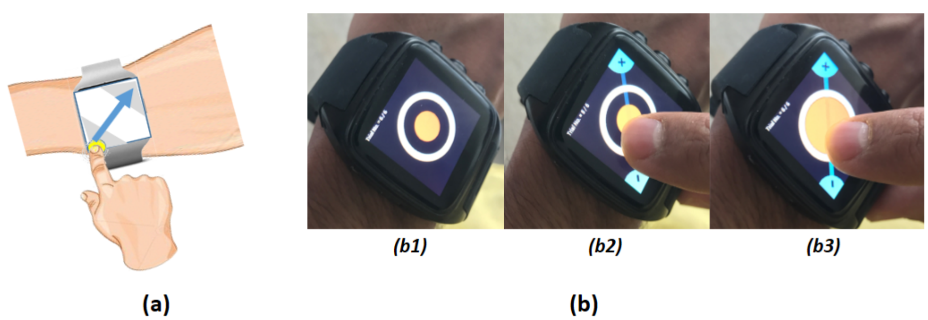


Figure 4.4: (a)*SwipeZoom* (b) Implementation of *SwipeZoom* demonstrating (b1) initial screen (b2)user press on left bottom-area of the screen and (b3)user perform diagonal swipe for continuous zooming in.

***SwipeZoom*:** In this technique, the user invokes the zoom mode by a single finger press (for 150 milliseconds), at either left-bottom or right-top area of the screen (shaded light-grey). The zoom mode exists when the user lifts the finger from the screen for more than one second. In zoom mode, a translucent diagonal line shows up on the screen indicating the finger path for zooming. The diagonal swipe from bottom-left to right-top leads to continuous zooming in, whereas the diagonal swipe in opposite direction switches to zooming out.

The diagonal is the maximum distance that can be spanned on the smartwatch. It therefore provides the maximum scaling effect in a single event. Thus, it reduces the need for additional clutching which is one of the main requirements of our design-space. It requires just one finger and can be performed with less precision as the width of the diagonal path is kept broad enough to avoid the fat-finger problem.

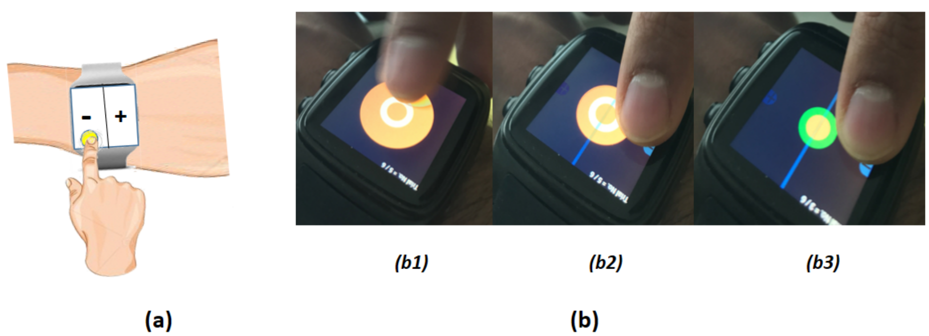


Figure 4.5: (a) *TapZoom* (b) Implementation of *TapZoom* demonstrating (b1) initial screen, (b2)user double tap and tap on left side screen for discrete zooming, (b3) user press screen for continuous zoom.

***TapZoom*:** In this technique, zooming mode is invoked with a double tap and exits when kept untouched for more than one second. The screen is divided into two equal halves, for zooming in and zooming out. The tap in the left half decreases the scale by a fixed zoom level, whereas, a tap in the right half of the screen increases the zoom level. The zoom effect of the first double tap for invocation is the same as that of the single tap. This technique provides the added functionality to perform continuous zooming by pressing either half of the screen for zoom-in or zoom-out. Ideally, this technique allows to change the zoom level by a big factor with a tap and in a continuous manner with a finger press. The integration of tap and press for zooming avails the benefits of both the discrete and continuous zooming.

This technique eliminates the need for clutching by allowing zooming using tap and press. Unlike *SwipeZoom*, it totally wipes out the need for moving the finger on the screen. It lowers down the attention requirement by providing two big areas on the screen dedicated to each zooming functionality. This technique provides all the desirable properties as proposed in our design-space.

4.6 Panning techniques for smartwatch

In the first user study, we find that current panning techniques on a smartwatch did not perform well due to the limited screen size. After devising the zooming techniques, we realized the need for developing parallel techniques for panning as well. Based on the same principles, we designed the new panning techniques, *PanPress* which is analogous to *SwipeZoom* and *FlickPan* which is analogous to *TapZoom*. Similar to zooming techniques, our panning techniques also follows the same set of requirements i.e. unambiguity and self-contained.

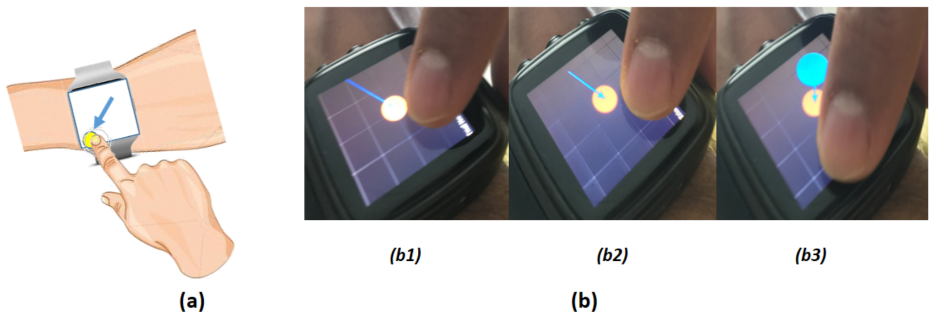


Figure 4.6: (a) *PanPress* (b) Implementation of *PanPress* demonstrating (b1) initial screen and user perform the first pan, (b2)user hold screen after the first pan for continuous panning motion and (b3) user change panning direction with minimal finger motion.

***PanPress*:** This technique is an enhanced version of the current panning technique on the smartwatch. In this technique, after a single panning event, the user can keep navigating by holding the finger on the screen. The pan distance during the first pan determines the speed of the panning i.e. the greater the distance, the greater the speed. The direction stays the same as the first panning direction, however, the user can adjust the direction with minimal finger motion. The panning motion can be stopped by lifting up the finger.

With this technique, the user still has the ability to perform the normal panning. However, it adds the extra functionality to traverse long panning distances without clutching, by holding the finger after the first panning event. Similar to *SwipeZoom*, this technique aims to reduce the need of clutching and the motion of the finger on the screen.

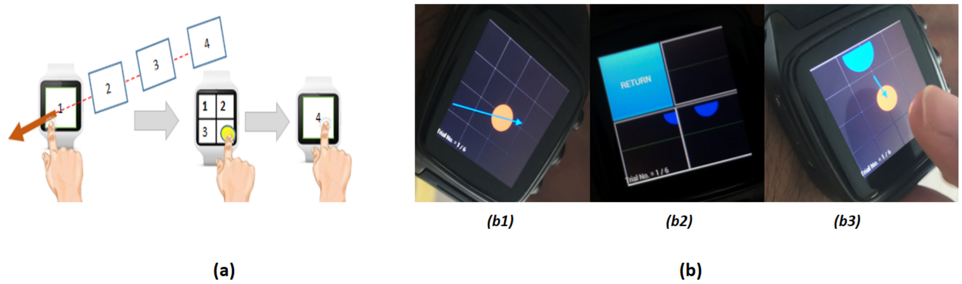


Figure 4.7: (a) *FlickPan* (b) Implementation of *FlickPan* demonstrating (b1) initial screen and user flick in pan direction, (b2) displaying thumbnails of next screens based on initial flick direction, (b3) the user selects the thumbnail and perform normal panning on selected screen.

***FlickPan*:** In this technique, the user flicks in the intended direction of the pan. Based upon the flick direction, the thumbnails of next screen is displayed. This technique displays the forecast or predicted next screens based on the initial flick. The user has the choice to return back to the initial screen by pressing "RETURN" or navigating to any other screen by tapping the corresponding thumbnail. After clicking the thumbnail, the user reaches to the center of the particular screen and may continue doing the normal panning or the *FlickPan*.

This technique allows for long distance navigation with a single flick. Thus, it eliminates the need for clutching. Similar to *TapZoom*, this technique reduces the motion and duration of the finger on the screen. It offers the benefits of both discrete and continuous panning. It allows discrete panning to traverse long distances with a single flick and small distances with continuous normal panning.

4.7 ADAPTIVE TOUCH INTERACTIONS

In the first experiment, we observe that mobility and encumbrance has a big negative effect on pinching and panning gestures. The increase in the number of pan counts and overshoots was the main cause of increase in the completion time. Based upon these findings, we propose the following hypothesis:

"due to encumbrance from vibrations of hand holding an object and body movement under activity conditions, it becomes hard to control finger and hand motion that lead to inaccurate touches. This, in turn, causes an increase in pan counts and an increase in overshoots."

To reduce such undesired events, one approach is to detect the activity of the user and adapt the interactions accordingly. The smartwatch has sensors such as a gyroscope and accelerometer which makes it possible to detect the hand orientation and activity of the user. For instance, when running with bags in hand, overshoots can be avoided by decreasing the scale rate *(scalefactor= scalerate x distance between two fingers, for pinching gestures)* for zooming. Thus, allowing more control over the touch interaction. Similarly, when standing still without bags, increase in the scale rate can result in minimum clutching and a reduced motion of touch. Similarly, for the panning task, the pan rate *(pandistance = panrate x touch pixels traversed)* can be adjusted based on user activity to provide a better interactional experience.

4.8 DESIGN-SPACE FOR SMART WATCH INTERACTIONS

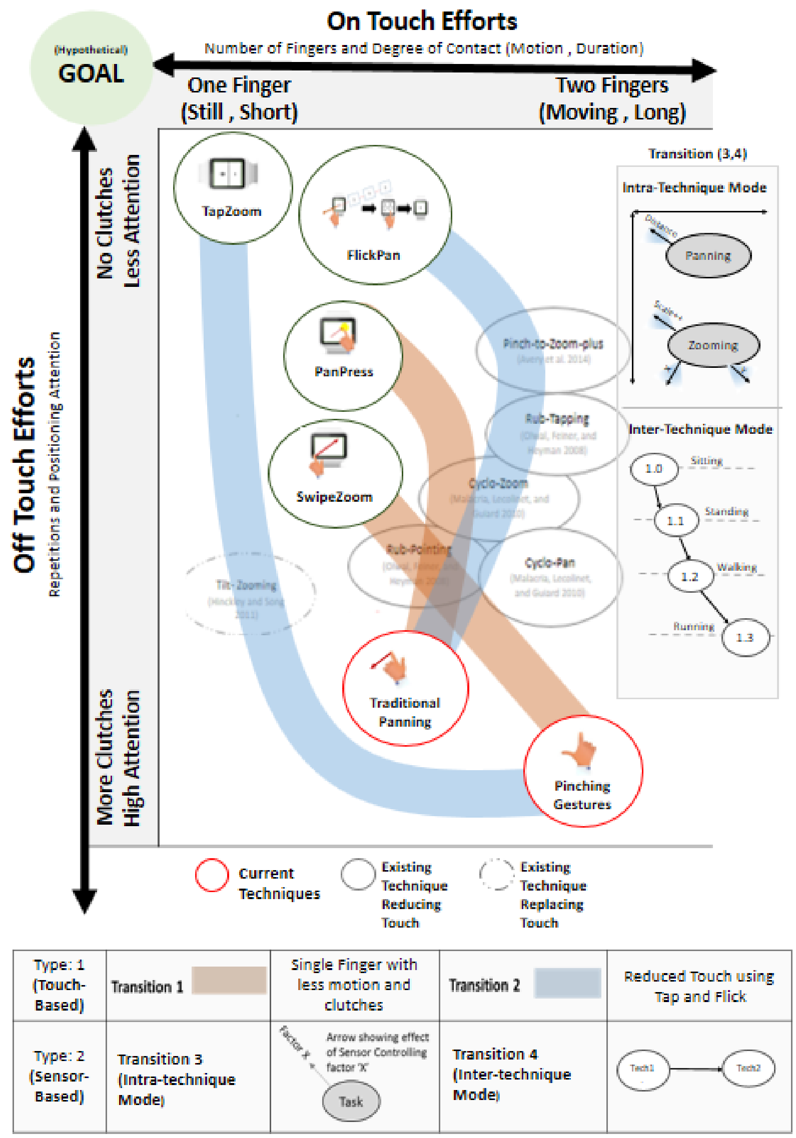


Figure 4.8: Design-space for smartwatch interactions.

The design-space represents the positioning of the techniques with respect to the two main axes as described by on-touch and off-touch efforts. It also describes the relationship between the techniques using transitions as follows:

Touch-Based Transitions: The touch-based transition allows classifying techniques based on the common characteristics shared by them. The touch transitions are of two types:

Transition 1 (Single finger, fewer clutches, and motion)- This transition demonstrates the relationship between current techniques and new interaction techniques with the aim to reduce touch efforts by a certain level. The use of a single finger, reduced number of clutches, less duration, and less motion are some of the common attributes shared by this family of techniques. *PanPress* for panning and *SwipeZoom* for zooming belong to this category.

Transition 2 (Discrete, Tap, and Flick)- This transition demonstrates the relationship between current techniques and new interaction techniques with the aim to develop the most optimized methods for zooming and panning. No clutches, less duration, less attention, and no motion are some of the common attributes shared by this family of techniques. The other main characteristic is the support of a discrete form of interaction. Both *TapZoom* and FlickZoom provides flexibility for continuous interactions but, at the same time, supports discrete ways for zooming and panning as well.

Sensors-Based Transitions: Sensor-based transitions harness the sensor capabilities of smartwatch along with touch to deliver adaptive interactions. These transitions are represented on the right side of the design-space. These are of two types:

Transition 3 (Intra-technique Mode) - Under this category of techniques, the inbuilt sensors of smartwatch such as gyroscope and accelerometer detect the activity of the user and changes the internal factor of the interaction accordingly. As discussed in section 4.7, to withstand the effect of mobility and handedness, the scale rate for zooming and the pan rate for panning adjusts with respect to the user activity.

Transition 4 (Inter-technique Mode) - Under this category of techniques, the inbuilt sensors of the smartwatch detect the activity of the user and changes the technique for the interaction task accordingly. For example, pinching under still conditions and *TapZoom* under activity contexts deliver a new way of interaction based upon the user's activity.

4.9 SUMMARY

In this chapter, we have discussed the idea of touch efforts based on the results from the previous study and the reviewed literature. We present a design-space with on-touch efforts and off-touch efforts as the two main axes. We positioned the previous techniques of our design-space and proposed the need for new interactions with desirable characteristics as governed by our design-space. We devised new techniques for panning and zooming, namely *PanPress*, *FlickPan*, *SwipeZoom*, and *TapZoom*. The idea of adaptive interactions based on user activity was discussed and included in our interaction design. The techniques were systematically categorized in the design-space under four main transitions and the significance of these transitions was discussed. In next chapter, we will validate our design-space by evaluating the new interaction techniques with a user study.

5

EVALUATION OF THE DESIGN-SPACE

In this chapter, we investigate the validation of our design-space with a user study. The goal of this chapter is to evaluate new touch interactions by comparing their performance with current pinching and panning gestures under varied levels of mobility and encumbrance. This chapter proceeds to first discuss the varying scenarios, hypothesis, experiential design, and interaction tasks that are included in the user study. In summary, we discuss the results and outline some of the main findings and conclusions of the user study.

5.1 SCENARIOS

We first begin by examining the performance of smartwatch interactions under different levels of mobility and encumbrance conditions. In our first study, we did not find any significant differences between non-dominant hand busy and dominant hand busy (as discussed in section 0). Thus, we only included the dominant hand busy condition in the second experiment. The study comprises of a total of nine activity conditions. These are combinations of three mobility conditions (standing, walking, and running) and three encumbrance conditions (both hands available, dominant hand busy and both hands busy). Similar to Section 3.1, we use grocery bags each weighing 1.6 kg to simulate encumbrance conditions along with the treadmill to duplicate different mobility levels (as shown in Figure 3.1 and Figure 3.2). Similar to the first study, we kept running speeds as 1.5 times, user's "preferred walking speed" (PWS).

The following table lists all nine conditions of the second study:

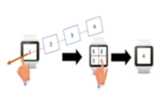
		Encumbrance Levels		
Mobility Levels		**Both hands Available**	**Dominant hand busy**	**Both hands busy**
	Standing	Standing with both hands available	Standing with dominant hand busy	Standing with both hands busy
	Walking	Walking with both hands available	Walking with dominant hand busy	Walking with both hands busy
	Running	Running with both hands available	Running with dominant hand busy	Running with both hands busy

Table 5.1: All activity conditions included in the second user experiment.

5.2 PARTICIPANT, EQUIPMENT AND PHYSICAL SETUP

We recruited 24 participants from the University of Manitoba (mean age 24.042, SD 7.17, 19 males, 5 females). To recruit the participants, we advertised widely through the bulletin boards across the campus. We paid $15.00 to each participant and the experiment took around 1.5 hours. Similar to the first study, we used a Precor 835 treadmill with safety hand rails and commonly used grocery bags (Walmart and Superstore) weighing 1.6 kg each, to simulate mobility and encumbrance conditions. All interaction tasks were performed on Imacwear M7 smartwatch (running Android 5.1 OS) and data from smartwatch was transmitted to the router wirelessly and stored in the MySQL databases. Besides the quantitative data, we asked participants to fill the NASA TLX forms at the end of the experiment to measure their perceived workload for each interaction technique under two extreme activity conditions i.e. standing without bags and running with both hands busy.

5.3 INTERACTION TECHNIQUES AND TASKS

Techniques	
	*1. Pinching* *2. Adaptive Pinching*
	*3. Swipe Zoom* *4. Adaptive Swipe Zoom*
	*5. Tap Zoom* *6. Adaptive Tap Zoom*
	*7. Normal Panning* *8. Adaptive Panning*
	*9. PanPress* *10. Adaptive PanPress*
	*11. Flick Pan* *12. Adaptive Flick Pan*

(a)

Activity Condition (Mobility, Encumbrance)	**Panning (*Pan Rate*)**	**Zooming (*Scale Rate*)**
Standing, Both Hands Available	1.3	1.207
Standing, Dominant Hand Busy	1.2	1.136
Standing, Both Hands Busy	1.1	1.065
Walking, Both Hands Available	1.1	1.065
Walking, Dominant Hand Busy	1	0.994
Walking, Both Hands Busy	0.9	0.923
Running, Both Hands Available	0.9	0.923
Running, Dominant Hand Busy	0.8	0.852
Running, Both Hands Busy	0.7	0.781

(b)

Table 5.2: (a) Twelve interaction techniques for the second user experiment, (b) pan rate and scale rate for adaptive interactions under different activity condition.

The main objective of this study was to evaluate new interaction techniques and compare their performance with current baseline pinching and panning techniques for zooming and panning. For each panning and zooming task, we have two new techniques, namely *PanPress*, *FlickPan*, *SwipeZoom* and *TapZoom* as discussed in section 4.5 and section 4.6. We develop an adaptive version for all these techniques (including baseline zooming and panning) using the principles of "Adaptive Touch Interactions" as discussed in section 4.7. We have 12 techniques in total, six each for panning and zooming as listed below in Table 5.2 (a):

For all the distinct zooming and panning techniques, we have an adaptive version that changes the scale rate and pan rate based on the activity of the user. As per the Apple documentation (Apple Inc. 2017), the zoom level of the content changes by a scalar. For pinch gestures, the scale factor is dependant on the distance between two fingers and it changes with a change in the distance between two fingers. Initially, the scale factor is set to 1.0 and after applying the scale factor to the content, the scale factor is again reset to 1.0.

i.e. Scale Factor = Scale Rate x Distance between two Fingers at given time

For normal pinching, the scale rate is 1. i.e. the scale factor and the distance between two fingers changes by the same proportion. However, we propose a change in the scale rate based on the user activity i.e. when the user is standing without bags, the content zooms by a larger proportion than the change in distance between the two fingers. It allows zooming on the small screen without the need of clutching. Similarly, when running with bags, content zooms in a smaller proportion with respect to the change in the distance between the fingers. It may lead to little more clutching but reduces the overshoots which are quite common in mobility and encumbrance conditions. In our implementation, for each activity condition, we changed the scale rate in a systematic order for all the zooming techniques as stated in Table 5.2(b). The definition of scale factor depends particularly on the interaction technique. The following table lists the scale factor for all the three zooming techniques:

Technique	**Scale Factor**
Pinching	*Scale factor = scale rate*(distance between two fingers)*
Swipe Zoom	*Scale factor = scale rate *(diagonal distance traversed by finger)*
Tap Zoom	*Scale factor = scale rate *(press time in milliseconds/100)*

Table 5.3: Scale Factor equations for zooming techniques.

Similarly, for the panning task, the pan distance depends on the particular panning task. For normal panning, the pan distance is proportional to the pixels traversed by the finger. The following table lists the pan rate for all the three panning techniques:

Technique	**Pan Distance**
Normal Panning	*Pan distance= pan rate*(distance traversed by finger)*
Pan Press	*Pan distance = pan rate *((distance traversed by finger during first pan/10) * (press time in milliseconds/100))*
Flick Pan	***During Flick:*** *Pan distance = screen width * (screen width/80)* ***After selecting frame:*** *Pan distance= pan rate*(distance traversed by finger)*

Table 5.4: Pan Distance equations for panning techniques.

For non-adaptive techniques, the pan rate and scale rate stays 1.0 under all the activity conditions. However, for adaptive techniques, the pan rate and scale rate changes in accordance with the activity conditions as stated in Table 5.2(b). The values for pan rate and scale rate were determined during the implementation in order to evaluate the efficacy of adaptive interaction by the user experiment.

In our study, we use the same zooming and panning task as discussed in section 3.3.4 and 3.3.2 to determine the performance of all these 12 interaction techniques under nine mobility and encumbrance conditions.

5.4 EXPERIMENTAL DESIGN AND PROCEDURE

We used a repeated-measures within-participants experimental design. Our experimental design is split into two main phases, out of total 24 participants, the first 12 participants performed the experiment for zooming interaction techniques while other 12 participants performed panning. At the beginning of the experiment, we measured the "preferred walking speed"(PWS) of the participant by incrementally increasing the speed of the treadmill by 0.1 miles/h. After recording the preferred walking speed, we gave each participant an overview of the interaction techniques. The participant has to perform six different interaction techniques for either zooming or panning in the experiment. The interaction techniques are ordered using a Latin square design to control the undesired variation due to the learning effect. Before starting the next interaction technique, participants performed practice trials until they become proficient with the technique. The participant performs ten trials under each activity's conditions for an interaction technique. There are a total of nine activity conditions, constituted of the combinations of three mobility (standing, walking and running) and three encumbrance levels (both hands available, dominant hand busy, and both hands busy). Under the walking condition, the treadmill speed is set to

PWS, whereas in the running condition, the treadmill speed is set to 1.5 times the PWS (i.e. 1.5*PWS). The activity condition changes after each ten trials. The sequence of activity conditions is randomized to prevent any undesired variation due to physical fatigue or tiredness. The experiment is split into three sessions, with each consisting of two interaction techniques. A break of 10 minutes is given after each session so that participants do not get exhausted by the physical workload.

To summarize, the total number of trials performed during the experiment:

Zooming	**Panning**
12 participants	12 participants
x 6 interaction techniques	x 6 interaction techniques
x 3 mobility conditions	x 3 mobility conditions
x 3 encumbrance conditions	x 3 encumbrance conditions
x 10 trials each activity condition	x 10 trials each activity condition
= 6480 trials	= 6480 trials
Total: **12960 trials**	

At the end of the experiment, the participants filled the NASA TLX for two extreme activity conditions: standing both hands available and running both hands busy, to determine the effect of mobility and encumbrance on participant's workload and performance.

5.5 HYPOTHESIS

The design-space that we have developed is based on the hypothesis that reducing on-touch and off-touch efforts can develop the smartwatch interactions and effectively prevent the negative impact of mobility and encumbrance. Following the principles of our design-space and corresponding techniques, we have come up with following main hypothesis:

H1: For zooming techniques, the average completion time will proceed with the following trend: *Adaptive Tap Zoom* < *Tap Zoom* < *Adaptive Swipe Zoom* < *Swipe Zoom* < *Adaptive Pinch* < *Pinch*

H2: For zooming techniques, the effect of mobility and encumbrance will decrease as we move towards the top-left (hypothetical goal) of our design-space: *Adaptive Tap Zoom* < *Tap Zoom* < *Adaptive Swipe Zoom* < *Swipe Zoom* < *Adaptive Pinching* < *Pinching*

H3: For panning techniques, the average completion time will follow the following trend:*Adaptive Flick Pan* < *Flick Pan* < *Adaptive Pan Press* < *Pan Press* < *Adaptive Panning* < *Panning*

H4: For panning techniques, the effect of mobility and encumbrance will decrease as we move towards the top-left (hypothetical goal) of our design-space:*Adaptive Flick Pan* < *Flick Pan* < *Adaptive Pan Press* < *Pan Press* < *Adaptive Panning* < *Panning*

H5: The effect and significance of adaptive behavior will decrease as we go towards the top-left of the design-space.

5.6 RESULTS

We conducted a repeated measure two-way ANOVA (Type I) with two independent factors: mobility and encumbrance, in order to analyze the completion time for each individual task. Before ANOVA analysis, we performed the Shapiro-Wilk normality test and the

Bartlett test to check the normality of data and the homogeneity of variances.

5.6.1 *Comparison Between Zooming Techniques*

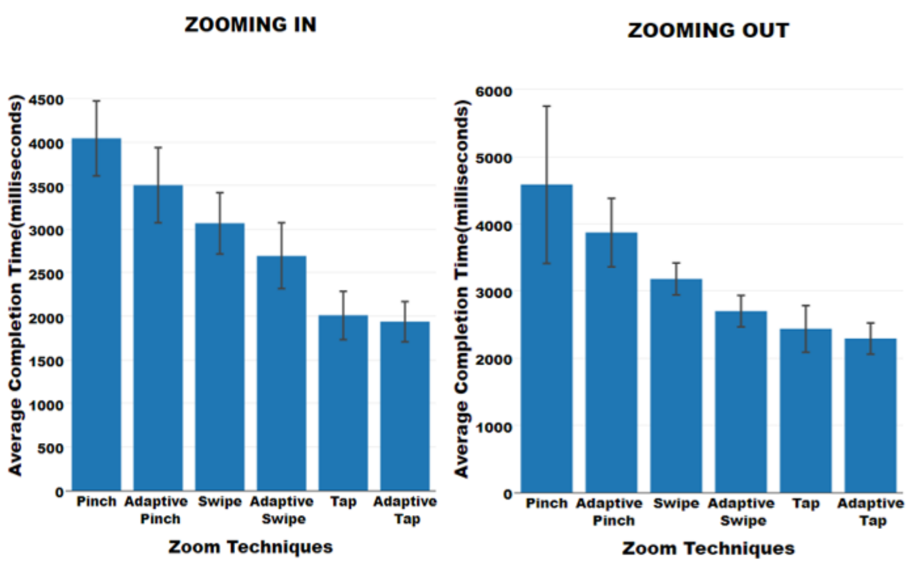


Figure 5.1: Average completion time for zooming techniques. Error bars represent 95% CI

We found a significant difference in completion times for all zooming interaction techniques ($F(5, 583) = 34.324$, $p < 0.001$) except *TapZoom* and *Adaptive Tap Zoom* ($p>0.05$, $p=0.47$). The average completion time for all interaction techniques is reported in Figure 5.1. In contrast to Pinch Zoom as the baseline technique, the *SwipeZoom* and *TapZoom* exhibited a 27.59% and 48.45% decrease in completion time. This satisfies our hypothesis H1:

Adaptive Tap Zoom $\approx TapZoom < AdaptiveSwipeZoom < SwipeZoom < AdaptivePinch < Pinch$

No significant difference between *Adaptive Tap Zoom* and *Tap Zoom* suggests that the significance of adaptive behavior decreases as we go towards the top-left of the design-space which satisfies our hypothesis H5. This also validates our design-space that by reducing the touch-efforts, we can develop new techniques that can be performed in timely manner.

We also record the clutches and overshoots for each zooming technique . As expected, there is a significant decrease in the number of overshoots as we go towards the hypothetical goal in the design-space (Figure 5.2), except *Adaptive Swipe Zoom* and *SwipeZoom* ($p>0.05$).

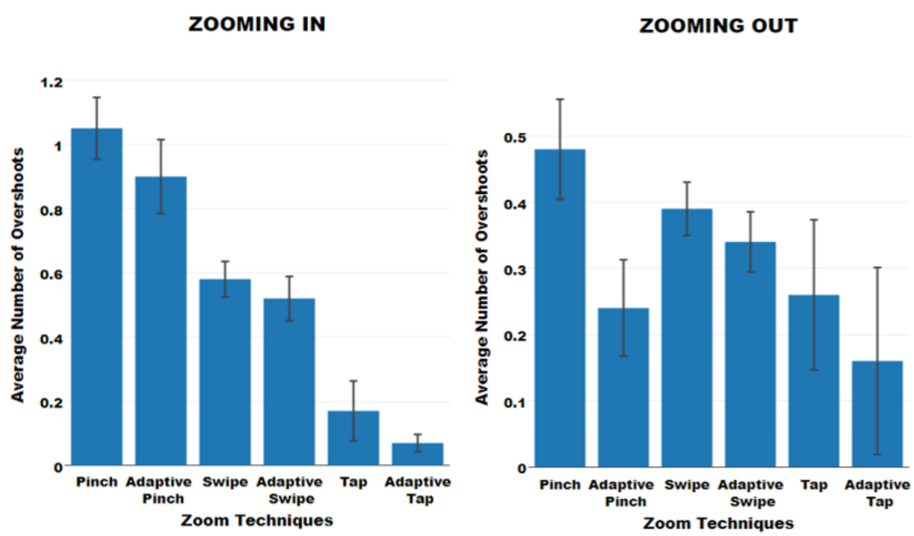


Figure 5.2: Average number of overshoots for zooming techniques. Error bars represent 95% CI.

Interestingly, the number of clutches for *TapZoom* is more than that of *SwipeZoom* (Figure 5.3). In the case of *TapZoom*, the clutches are simple taps which do not require any major repositioning or motion of the finger.

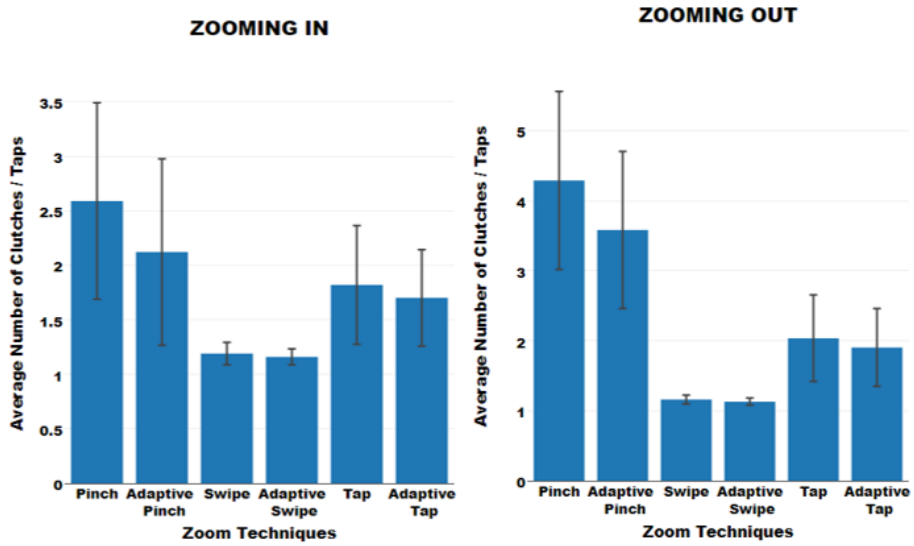


Figure 5.3: Average number of clutches for zooming techniques. Error bars represent 95% CI.

Despite having more clutches, the average completion time for *TapZoom* is less than that of *SwipeZoom*. The table 5.5 explains it with reference to the two main axes of our design-space.The attention required for *TapZoom* is less because the screen is divided into two big halves and does not need precise finger motion. This is validated by participant's response in *NASA TLX* (Figure 5.4).

	Factors	*SwipeZoom*	*TapZoom*
On-Touch Efforts	**Number of Fingers**	1	1
	Degree of Contact: (Duration, Motion)	(2694.3, Yes)	(823.7, No)
Off-Touch Efforts	**Number of Events**	1.17	1.92
	Visual Attention	More	Less

Table 5.5: Touch-Efforts comparison between *SwipeZoom* and *TapZoom* (Duration time in milliseconds).

At the end of the experiment, we asked participants to fill the NASA TLX forms to determine their perceived workload for all zooming interaction techniques. The response of 12 participants is illustrated in Figure 5.4.

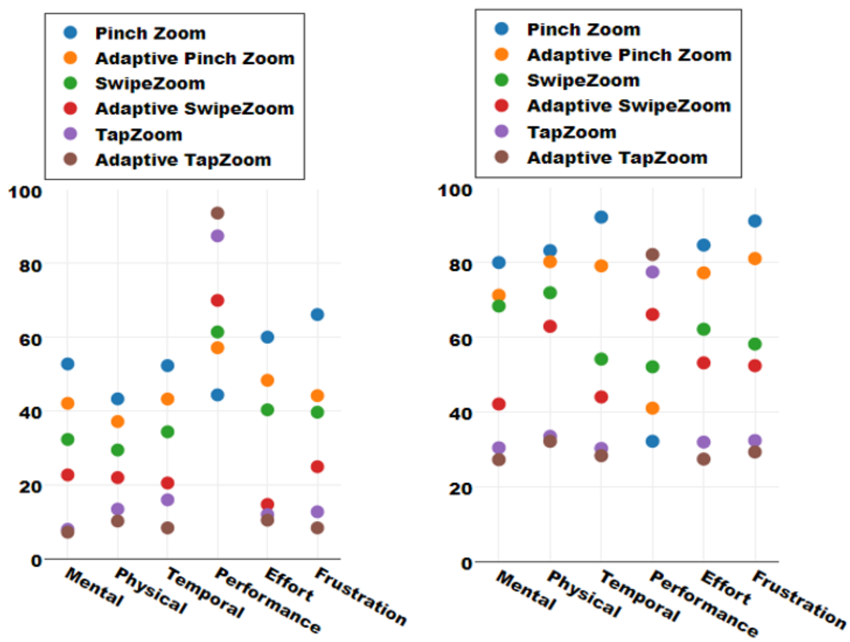


Figure 5.4: Mean perceived workload ratings of six zooming techniques across six NASA TLX dimensions when participants were standing still without bags (on left) and running with bags in both the hands (on right). Scores range from 1 to 100. The higher the number, the higher the perceived demand.

We found that participants favored *Adaptive TapZoom* and realized pinching gestures to be more frustrating and physically demanding. The participant's response also validates the concept of our design-space, whereby new techniques require fewer touch efforts and reduced perpetual activity.

5.6.2 *Effect of Mobility And Encumbrance on Zooming Techniques*

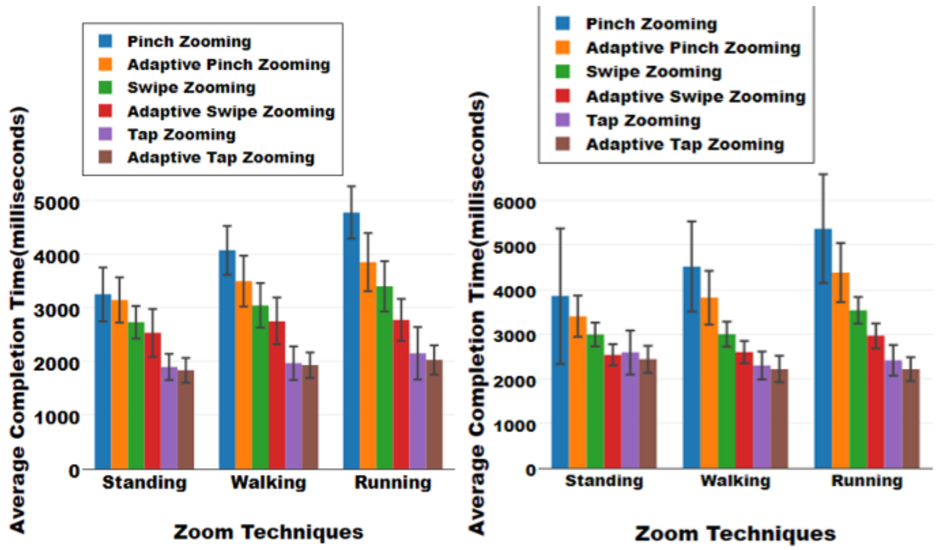


Figure 5.5: The effect of mobility on the zooming techniques (Zooming In on the left and Zooming Out on the Right). Error bars represent 95% CI.

There is an overall significant main effect of mobility on zooming technique's completion time ($F(10, 583) = 5.819$, $p<0.001$). With pairwise posthoc test with Holm p-value adjustments for completion time, we found a significant difference between all three mobility conditions for *Pinch Zooming* and *Adaptive Pinch Zooming* ($p < 0.001$). For Swipe Zooming, no significant difference between standing and walking conditions ($p=0.47$) was found. For *Adaptive Swipe Zooming*, there was a significant difference solely for standing and running conditions ($p=0.016$). For *Tap Zooming* and *Adaptive Tap Zooming*, we did not find any significant difference between any of the three mobility conditions. It seems that mobility has no effect on the completion time of *Tap Zooming* and *Adaptive Tap Zooming* ($p>0.9$). It validates our hypothesis H2 and verifies our design-space, whereby new interaction techniques are more tolerant to the effect of mobility.

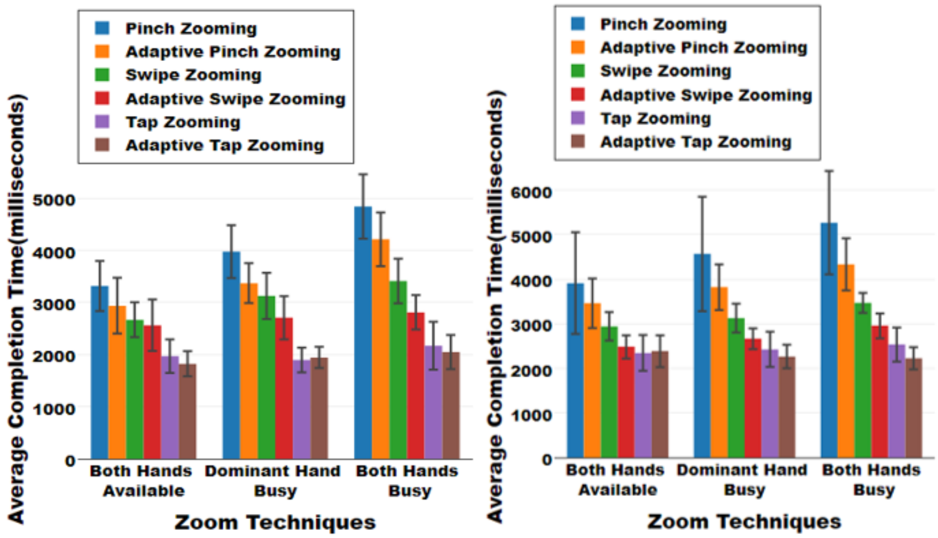


Figure 5.6: The effect of encumbrance on the zooming techniques (Zooming In on the left and Zooming Out on the right). Error bars represent 95% CI.

There is an overall significant main effect of encumbrance on all zooming technique's completion time ($F(10, 583) = 4.898$, $p<0.001$). With pairwise posthoc test for completion time, we found a significant difference between all three encumbrance conditions for *Normal Zooming* and *Adaptive Zooming* ($p < 0.001$). For *Swipe Zooming* and *Adaptive Swipe Zooming*, there was a significant difference only between both hands available and both hands busy conditions ($p < 0.001$). For *Tap Zooming* and *Adaptive Tap Zooming*, we did not find any significant difference between any of the three encumbrance conditions. The encumbrance had no effect on the completion time of *Tap Zooming* ($p>0.7$) and *Adaptive Tap Zooming* ($p=1$). It verifies our hypothesis H2 and supports our design-space that the effect of encumbrance reduces as we move towards the top-left in our design-space.

5.6.3 *Comparison Between Panning Techniques*

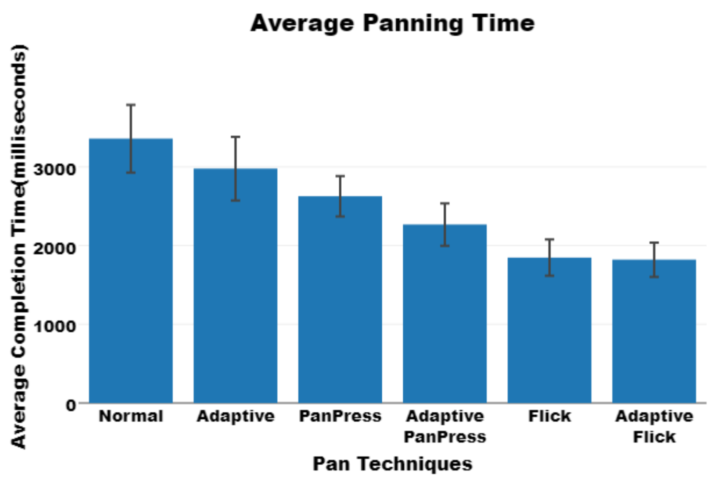


Figure 5.7: Average completion time for panning techniques. Error bars represent 95% CI.

We found a significant difference for the completion time for all panning interaction techniques technique ($F(5, 583) = 21.836$, $p < 0.001$) except *Flick Pan* and *Adaptive Flick Pan* ($p>0.05$, $p=0.78$). We report the average completion time for all interaction techniques in Figure 5.7. In comparison to *Normal Panning*, we found that there existed an increase of 21.79% and 45% improvements in the completion time for *PanPress* and *FlickPan* technique.

This satisfies our hypothesis H3:

Adaptive Flick Pan < *Flick Pan* < *Adaptive Pan Press* < *Pan Press* < *Adaptive Panning* < *Panning*

There is no significant difference in the completion time of *Adaptive Flick Pan* and *Flick Pan* (p=0.78). This suggests that as we move towards the top-left of the design-space, the significance of the adaptive behavior decreases. It satisfies our hypothesis H5 for panning techniques as well.

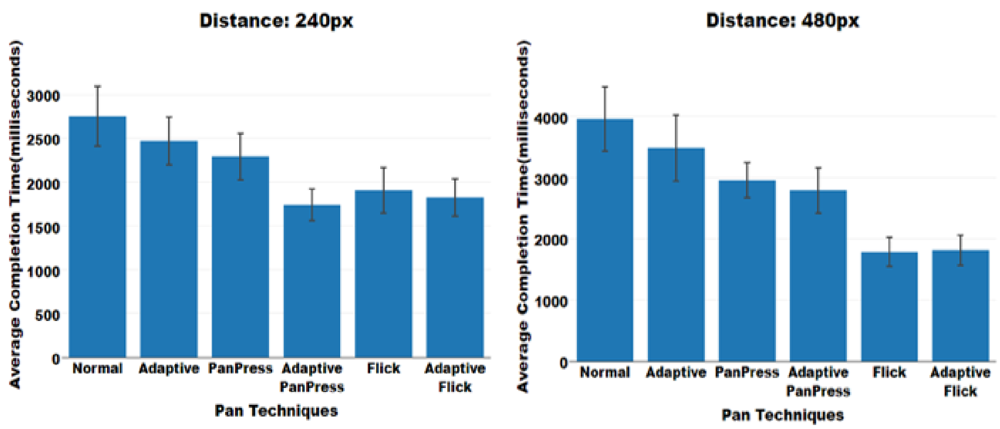


Figure 5.8: Average completion time for panning distances, 240px and 480px. Error bars represent 95% CI.

However, the *Adaptive PanPress* technique outperformed the *FlickPan* for short distances (Figure 5.8) because *FlickPan* is a three mode technique which requires the user to first flick and then select the appropriate frame for panning. In contrast, *Adaptive PanPress* is a single event technique. We concluded that *Adaptive PanPress* is appropriate for short distances, whereas *FlickPan* is more approprate for long distances.

The average pan counts for all panning techniques are reported in Figure 5.9. The new panning techniques have succeeded in reducing the number of pans or repetitions which is one of the desirable characteristics of our design-space.

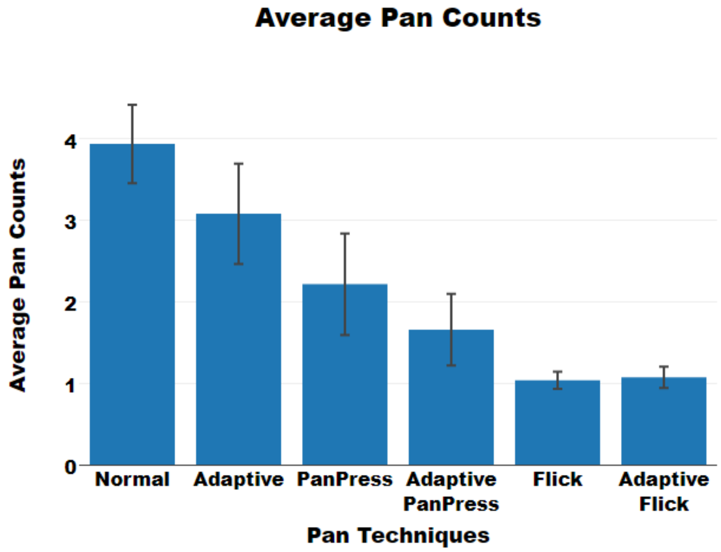


Figure 5.9: Average Pan Counts for panning techniques. Error bars represent 95% CI.

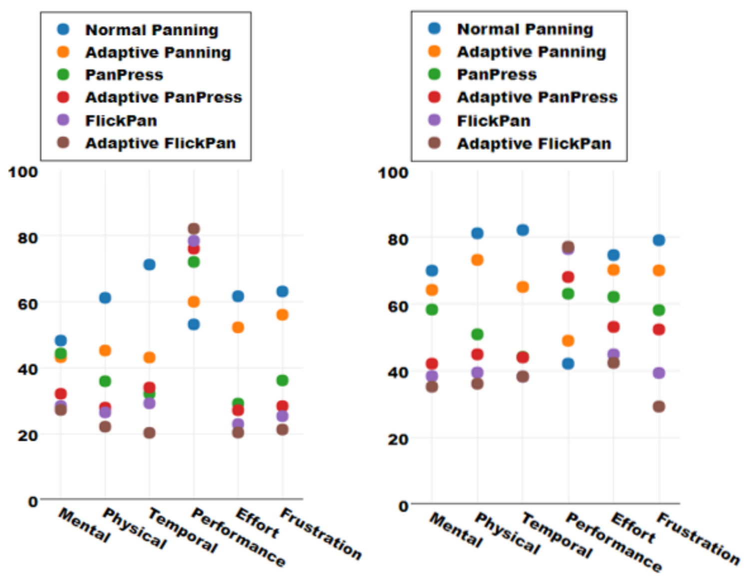


Figure 5.10: Mean perceived workload ratings of six panning techniques across six NASA TLX dimensions when participants were standing still without bags (on left) and running with bags in both the hands (on right). Scores range from 1 to 100. The higher the number, the higher the perceived demand.

Due to a reduced need of repetitions and less mental activity, the participants find the new techniques more superior than the normal panning technique. The analysis of *NASA TLX* shows that participants preferred new panning techniques over normal panning for navigation.

5.6.4 *Effect of Mobility and Encumbrance on Panning Techniques*

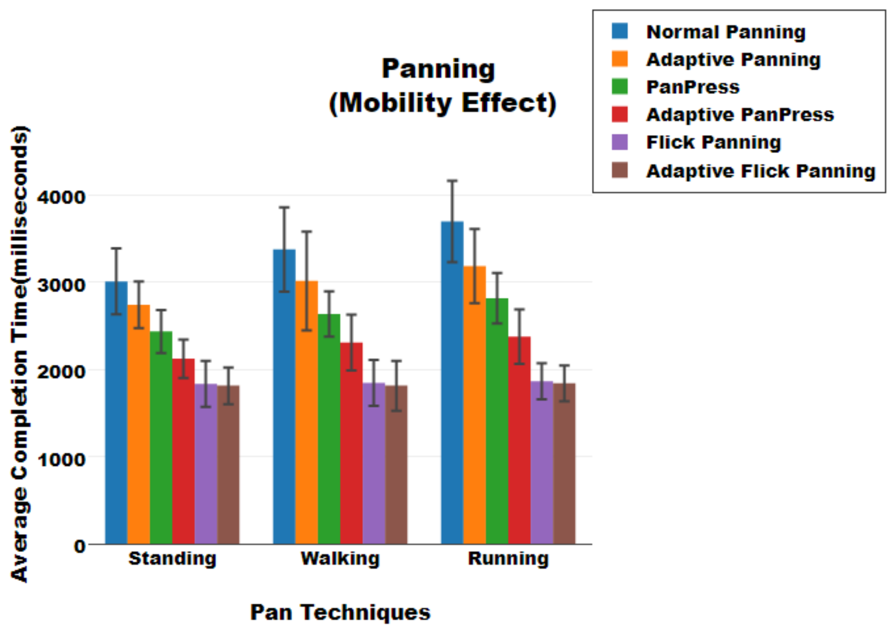


Figure 5.11: The effect of mobility on panning techniques. Error bars represent 95% CI.

There is an overall significant main effect of mobility on panning technique's completion time (F (10, 583) = 2.203, p<0.001). With pairwise posthoc test (with Holm p-value adjustments) for completion time, we find a significant difference between all the three mobility conditions for *Normal Panning* ($p < 0.001$). For *Adaptive Panning*, there is no significant difference between walking and standing conditions ($p = 0.110$).

There is a significant difference between all mobility conditions for *Pan Press* (p<0.02). For *Adaptive Pan Press*, there is a significant difference only between standing and running condition (p=0.04). We could not find any significant difference between mobility conditions for *FlickPan* and Adaptive *FlickPan* techniques (p=1). It is evident from our analysis that the effect of mobility decreases as we go towards our hypothetical goal in design-space. This is in accordance with hypothesis H4.

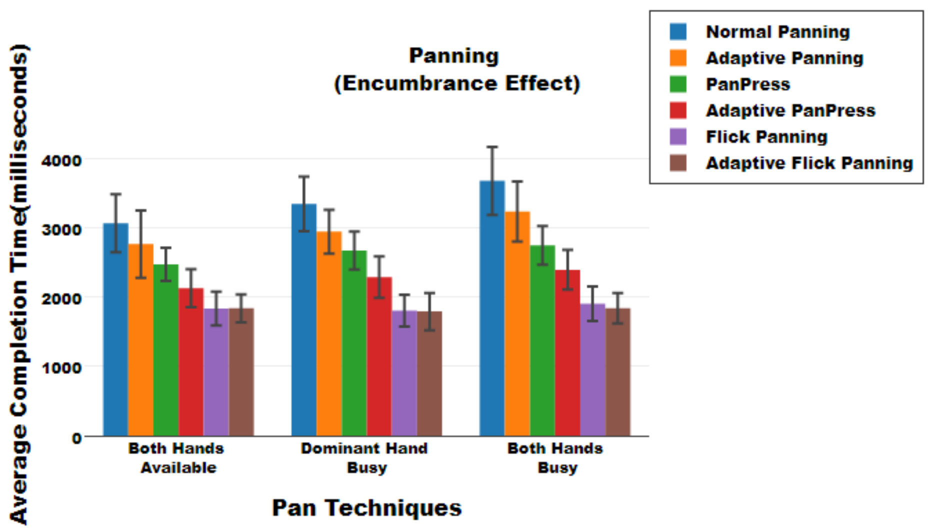


Figure 5.12: The effect of encumbrance on panning techniques. Error bars represent 95% CI.

The ANOVA for completion time showed a significant main effect of encumbrance on all the panning techniques (F (10, 583) = 3.733, p<0.01). With pairwise posthoc test (with Holm p-value adjustments) for completion time, we find a significant difference between all the encumbrance conditions for *Normal Panning* (p<0.001) and *Adaptive Panning* (p<0.02). For *Pan Press*, there is a significant difference between all encumbrance conditions (p<0.006) except dominant hand busy and both hands busy conditions (p=0.172). We find a significant difference only between the both hands available and both hands busy encumbrance conditions ($p=0.01$) for *Adaptive Pan Press*. We could not find any significant difference between any of the encumbrance conditions for *Flick Pan* and *Adaptive Flick Pan* ($p>0.9$). This verifies hypothesis H4, namely, that new techniques are impacted less by the encumbrance conditions.

5.7 DISCUSSION AND CONCLUSIONS

To conclude, the user study presented in this chapter validates the appropriateness of our design-space. We examined the performance of new zooming and panning techniques under varied level of mobility and encumbrance. We find that the new interaction techniques outperform the traditional panning and pinching gestures in terms of completion time and other dependent variables such as overshoots, pan counts etc. In contrast to traditional pinching for zooming, the *SwipeZoom* and *TapZoom* showed a 27.59% and 48.45% decrease in completion time. Similarly, *PanPress* and *FlickPan* outperformed traditional panning by 21.79% and 45% less completion time. The design-space is built on the concept of reducing on-touch and off-touch efforts. We observed a relationship between the touch-efforts and task completion time as shown in Figure 5.13. We also observed the relationship between touch-efforts and activity conditions in terms of completion time. The techniques that use fewer touch-efforts are not much affected by mobility and encumbrance. The techniques that are more optimized to reduce touch efforts namely, *TapZoom* and *FlickPan* showed more resistance to the effects of mobility and encumbrance.

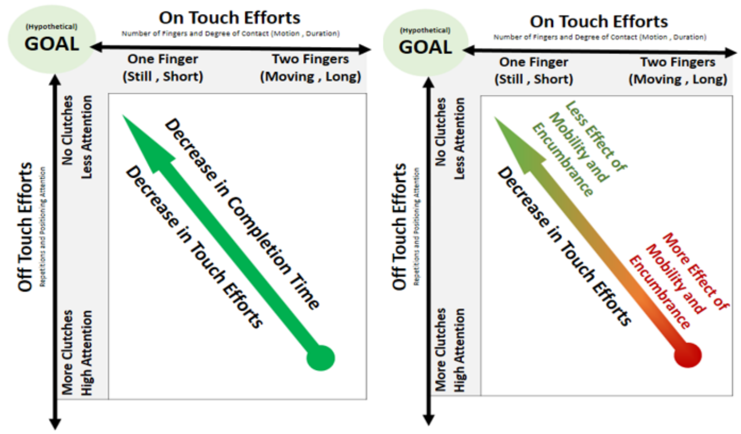


Figure 5.13: The relationship between the touch efforts and the completion time (on left) and relationship between the touch efforts and the effect of mobility and encumbrance (on right).

We also studied the usability of smartwatch sensors to employ adaptive interactions. We noticed a relationship between the touch efforts and the adaptive interactions as well:

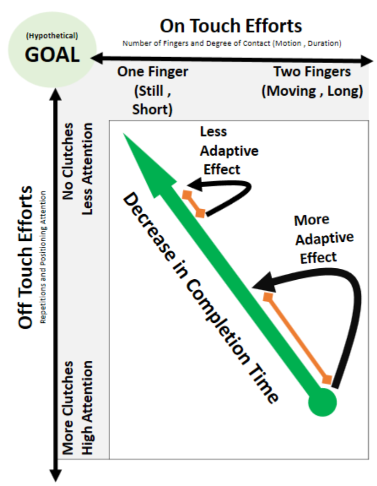


Figure 5.14: The relationship between touch-efforts and adaptability on the completion time.

We find that adaptability has a higher effect on the techniques that require more touch efforts such as pinching and normal panning.

The decrease in touch-efforts reduces the significance of the adaptability on the completion time. For pinching gestures, adaptability lead to a 13.27% decrease in completion time, however, for *TapZoom* adaptability just contributed to a 3.6% improvement in the completion time. Similarly, for panning techniques, adaptability decreased completion time for normal panning by 11.33% whereas, for *FlickPan* there is 1.3% decrease in completion time.

This chapter has explored the significance of touch-efforts and, furthermore, validated the applicability of our design-space. We conducted a study to determine the effectiveness of our new interaction techniques that were built on top of our design-space. It has put forward many new results that can inspire designers to create new interactions for mobility and handedness conditions. We showed how optimizing the techniques with reduced touch-efforts can help built new interactions that use fewer repetitions and reduces the number of overshoots. We also demonstrated the usefulness of adaptive interactions under varied activity conditions. Ultimately, we hope our interaction techniques and design-space will prove helpful to interact with smartwatches unaffected by the activity conditions.

6

CONCLUSIONS AND FUTURE WORK

The smartwatch is the device that is meant to provide the fast access to information. Currently, the smartwatch is under-utilized as a platform. It does not support all the diverse range of activity contexts and the current interaction techniques are slow and laborious, requiring a sequence of clutches and precise finger motions. To highlight these issues, we determine the appropriateness of current interactions on smartwatch under different activity contexts, with a user experiment. To our knowledge, this dissertation is the first body of research to analyze the effects of mobility and encumbrance on smartwatch interactions.

The results of the first study indicated that mobility and encumbrance has a definite negative impact on the smartwatch interactions. The participants struggled to zoom the content using standard pinching gestures which led them to feel physically stressed and frustrated. This emphasized the need to explore the design factors for smartwatch use under activity contexts. In our study, we examined the different design factors that can potentially reduce the efforts needed to interact with a smartwatch. We classified these efforts into two broad categories namely, on-touch efforts and off-touch efforts. We proposed a novel design-space based on our hypothesis supported by the results of our first user experiment. We proposed a set of new zooming and panning gestures in line with our design-space and demonstrated the effectiveness and credibility of the design-space with another user experiment. The results of the second experiment provided the knowledge that we feel is vital for future smartwatch applicability.

In chapter 6, we first summarize all the main findings of our work and our approach to solving the study's research problems. We then propose some main design recommendations that can help designers to come up with new ideas for smartwatch interactions. This thesis provides an initial direction on developing smartwatch interactions to withstand activity contexts. A great deal of research is still required to develop better smartwatch interaction under specific activity conditions. We discuss these research opportunities and limitations of our work to shed lights on unexplored areas of the research. We then wrap up the thesis with some final words that we feel are inspiring for general readers and imminent researchers working with smartwatch interactions.

6.1 SUMMARY

In this thesis, we emphasized the need for developing new interaction techniques for a smartwatch that can consistently be used under all activity contexts without inducing any new unknown problems. We proposed mobility and encumbrance as two main activity axes that constitute an umbrella for many common activities that we perform in our day-to-day life. We conducted a user experiment to determine the performance of commonly used navigation methods on smartwatch under mobility and encumbrance conditions. We studied the performance of four commonly used navigation techniques namely, Selection, Flicking, Panning and Zooming under twelve different activity conditions. These activity conditions consisted of the combinations of three mobility (standing, walking and running) and four encumbrance conditions (both hands available, dominant hand busy, non-dominant hand busy and both hands busy). We find that mobility and encumbrance has a maximum negative impact on the pinching gestures whereas, flicking interaction is least affected. The increase in mobility and encumbrance has led to an increase in the number of clutches and overshoots. A similar trend is seen for the panning gesture as well. There is an increase in pan counts and completion time with an increase in mobility and encumbrance. The response of participants as recorded using *NASA TLX* form also suggests that participants find pinching gestures very frustrating and less likely to be used on a smartwatch. Participants favored the flicking gesture due to its simplicity and the fact that it requires less mental effort.

This motivated us to think about the new ways to perform zooming on the smartwatch with less efforts, ideally, similar to flicking. We identified the different factors that distinguishes flicking from zooming. Eventually, we posited the idea of reducing the touch efforts for interactions on a smartwatch. We classified the touch-efforts into two broad categories; on-touch efforts and off-touch efforts. As the name suggests, on-touch efforts constitute the measure of efforts that a user performs while in contact with touchscreen, such as the number of fingers placed, motion of fingers and the duration of the contact. In contrast, off-touch efforts measure the mental demand and behavioral aspects of the interaction needs. It involves the number of clutches and the attention required to precisely position or move finger on a diminished smartwatch screen.

We designed an abstract version of our design-space with on-touch and off-touch efforts as the two main axes. We gathered all the relevant zooming and panning interaction techniques from the literature and positioned them in our design view. We observed an empty area in our design-space in top-left corner emphasizing the need to develop new smartwatch interactions that aims to reduce the need of on-touch and off-touch efforts.

We began our exploration with a guessability study in order to receive new ideas for zooming on the smartwatch. We asked participants to find a new zooming gestures on smartwatch provided, it is as simple as flicking and allows full control similar to pinching. In fact, there was no such technique that we developed. The aim was to receive new and creative ideas from the participants. We video-tapped the hand and finger movements of participants while they were searching for new touch gestures. This experiment provided us with a diverse set of exhaustive ideas to develop zooming interactions on a smartwatch.

We pinpointed the gestures that were in line with our design-space and discarded the irrelevant interaction gestures. Summing up the ideas from guessability study, we proposed a set of new zooming techniques for smartwatch namely, *SwipeZoom* and *TapZoom*. In parallel to zooming techniques, we designed two new techniques for panning as well: *PanPress* and *FlickPan*. We analyzed the characteristics of these techniques and carefully positioned them in the design-space. Based on the proximity of these interaction techniques in design-space, we categorized them into a family of transactions. We realized that *SwipeZoom* and *PanPress* uses the same level of touch-efforts whereas *FlickPan* and *TapZoom* were more optimized to use the minimum touch efforts. We also explored the opportunity to exploit smartwatch sensors to allow better interactions that adapts in accordance with the user activity. We used smartwatch sensors to detect the activity of the user and deliver adaptive interaction that changes internal factor allowing more control to the user, even under activity contexts.

To validate our design-space, we evaluate the new interaction techniques with another user experiment. We assessed the performance of new touch interactions under nine activity conditions and compared their performances with baseline pinching and panning techniques. The new techniques outperformed the baseline techniques in terms of completion time and other dependent variables such as overshoots, clutches, and pan counts. We observed an interesting relationship between the touch-efforts and the task completion time. There is a decrease in the completion time with a decrease in the touch-efforts.

We also analyzed a trend between the touch efforts and the effects of mobility and encumbrance. The techniques that are more optimized are less effected by mobility and encumbrance. The adaptive interactions also led to decrease in the completion time. However, the techniques that uses more touch efforts such as pinching and panning are more benefitted by adaptability than *FlickPan* and *Tap-*

Zoom. The results of our study are also confirmed by the response of participants as reported by NASA TLX analysis. Overall, the study explored many interesting ideas for developing appropriate smartwatch interaction and leverage the potential of smartwatch sensors to allow adaptive interactions.

6.2 DESIGN RECOMMENDATIONS

The design-space is the most prominent piece in this dissertation. We included all the desirable characteristics to our design-space, which makes it a perfect graphical reference for the design recommendations. However, in this section we will explicitly list some important recommendations with reference to our design-space and the results from the user experiments:

(i) **Support Activity Conditions:** A smartwatch, being a wearable device, should support all activity conditions. We recommend that designers consider the activities under which the user might use their application.

(ii) **One-Finger Interactions:** It is unbefitting to put multiple fingers on a diminished smartwatch screen. Not just because it hides the content of the screen leading to occlusion, but also makes it harder for the user to simultaneously move multiple fingers over the small screen area, especially, under different activity contexts. It is evident from the first user experiment that two-finger gestures lead to more clutches and eventually, an increase in the completion time. Therefore, we recommend the use of a single finger for the smartwatch interactions.

(iii) **Appropriate Target Size:** In the first user experiment, the selection of small-sized targets led to an increase in the error-rates. Therefore, it is advised to avoid the small-sized targets.

(iv) **Reduce On-Touch Efforts:** The interactions should avoid intense movement of the fingers on the small screen. Under activity contexts, it is hard to keep the finger in constant contact with the screen. The interactions should also try to reduce the duration of the touch.

(v) **Reduce Off-Touch Efforts:** The smartwatch interactions should aim to complete in a minimum number of touch-events, ideally, the interactions should be made a single-event process without any need of clutches. The interactions should also avoid precise positioning or accurate pointing of the finger(s) which is delimited by the activity contexts.

(vi) **Adaptive Interactions:** The designers should look into new ways to use the inbuilt sensors of the smartwatch to make better and smarter smartwatch interactions. In this thesis, we demonstrated how the interactions can adapt according to the activity contexts in which users may be involved.

6.3 limitations and future work

While this thesis has extensively studied the smartwatch interactions under different activity contexts, there are still several limitations that can potentially be studied in the future.

(i) **Ground Walking vs Treadmill Walking:** In chapters 3 and 5, the user experiments were conducted in controlled laboratory environment because our focus was just to investigate the effects of mobility and encumbrance. However, it is valuable to study the smartwatch interactions in real-world scenarios. Instead of treadmill-walking, ground walking with bags in a shopping mall can provide a better presentation of the real-world environment.

(ii) **Transitions between Mobility Contexts:** In our experiments, we studied the effect of mobility under three independent different mobility contexts: standing, walking and running. However, it would be interesting to analyze the effect when the user continuously transitions from standing to walking, to running with varied speed that is not controlled by the treadmill.

(iii) **More Encumbrance Scenarios:** We used common grocery bags each weighing 1.6 kg to simulate the encumbrance conditions. But, it is worthy studying the effect of holding different sized objects, such as bags and boxes of different sizes and weights.

(iv) **Beyond Mobility and Encumbrance:** We grouped all the activities under two main axes of mobility and encumbrance, however, there can still be many other factors that can affect the smartwatch interactions such as lightning, the distance between hand and eyes etc.

(v) **Context Adaptive Interactions:** The smartwatch interactions can be developed to serve a specific context or activity such as bicycling, driving etc. Such interactions come under the category of context-adaptive interactions (Kane, Wobbrock, and Smith 2008; Goel, Findlater, and Wobbrock 2012; Manca et al. 2013). There is a huge amount of literature that discusses context-adaptive interactions however, a little work is done for the smartwatch interactions.

(vi) **More Tasks:** We evaluated the performance of four commonly used navigation tasks such as *Flicking*, *Selection*, *Panning* and *Zooming*. We excluded uncommon tasks such as Rotating, Dragging etc. The future work can investigate these interactions on the smartwatch as well.

(vii) **User-defined Gestures:** All the interactions proposed in this research are mostly influenced by the results of the user studies or the design-space. In midst of our research, we conducted a guessability study just to get the ideas for the zooming interactions. More of such studies are required to understand smartwatch interactions from the user point of view.

(viii) **Diverse Participants:** In our experiments, the participants were mostly hired from University of Manitoba with mean age 24 (min:19, max: 45). It would be interesting to examine the performance with older and young age groups.

(ix) **Inter-technique Mode:** We did not evaluate the inter-technique mode because it is a broad topic and beyond the scope of this thesis. A future research is required to study whether it is possible to change the interaction technique based upon user activity and what will be its effect on learning performance of the user.

(x) **Hand Orientation and Wrist Movement:** The adaptive interaction techniques that we discussed in section 4.7 were focused merely on changing the internal factors based on the mobility context of the user. However, we did not consider hand-orientation and wrist-movement for adaptive smartwatch interactions.

(xi) **Fixed Scale and Pan Rate:** In the second experiment, we used fixed scale rate and pan rate under each activity conditions to retain the consistency and uniformity for the experiment(as discussed in Table 5.2 (b)). It is interesting to analyze how the actual prototype will work under different activity contexts. During our research, we developed a prototype that can detect the mobility and hand orientation (Figure 6.1). To develop the prototype, we thoroughly studied the change in sensor readings and applied Kalman Filters (Kalman 1960) to detect user activities (Figure 6.2). However, still much work is needed to optimize the prototype.

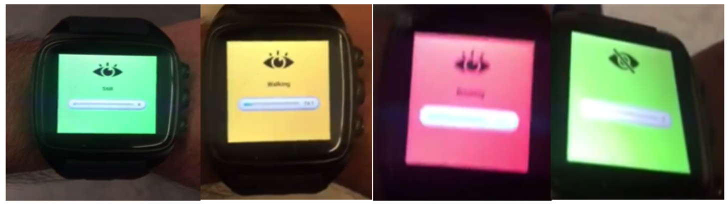


Figure 6.1: (a) user standing still (b) walking (c) running (d) hand wrist tilted away from the eyes.

Figure 6.2: The smartwatch sensor readings corresponding to the user activity.

6.4 CLOSING THOUGHTS

The ultimate motivation of this thesis was to bring forward the full potential of smartwatch as a wearable device. Due to its prominent position at the wrist, the smartwatch has an edge over the smartphone to provide easy and fast access to information under all the activity contexts. Our work studied the effect of mobility and encumbrance contexts on smartwatch interactions and changed the perception toward smartwatch interactions. Instead, focusing on the consequences of activity contexts, we took a forward step to explore and implement the ideas that can bring a revolutionary change in the future smartwatch interactions. We believe that the contributions of this thesis can bring about a paradigm shift on how users interact with the smartwatches. We hope that future smartwatch interactions will fully exploit the sensors and provide a customized experience to the user based on their needs. With the improvement in smartwatch interactions, it is now possible that smartwatches may replace the smartphones in the future.

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A

CONSENT FORM FOR USER EXPERIMENTS

Research Project Title: Mobility Based Context Transferable Wearable Interactions
Researchers: Dr. Pourang Irani (irani@cs.umanitoba.ca), Gaganpreet Singh (gagan@cs.umanitoba.ca), Dr. William Delamare (delamarw@cs.umanitoba.ca).

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Purpose of the research study: The purpose of this study is to bring to surface the full potential of wearable devices for accessing information, anytime and anywhere. To access the information, the user should be able to interact with the wearable, across various levels of activity. In recent years, a number of wearable devices have emerged in the consumer market. However, their interaction techniques have remained the same as those used on mobile handheld devices, such as smartphones. It is unclear whether such interaction techniques transfer well across the various mobility and handedness contexts that users may be involved with, as wearables become mainstream computing devices. The aim of this work is threefold:

(i) to investigate how well current interaction techniques support common tasks on wearables, across activity levels.

(ii) to design and implement novel interaction techniques for the common wearable devices that operate across mobility contexts.

(iii) to study whether techniques should change or remain the same when supporting different mobility contexts.

For this study, you will participate in a user experiment that will be conducted in the laboratory environment. In the experiment, you will be asked to perform basic tasks such as selection, zooming and flicking (swiping) on a smartwatch in mobile conditions. To simulate different mobility contexts, a treadmill will be used. Before the start of the experiment, you will be informed about the features and safe usage of the treadmill. During the information session, you are encouraged to ask questions regarding the experiment and the safe use of the treadmill. At the beginning of the experiment, you will be asked to walk naturally on the treadmill to measure your "Preferred Walking Speed (PWS)". Once your PWS is measured, you will be asked to perform basic interactions on smart wearables under different mobility and handedness contexts. The degree of mobility ranges from being inactive (standing), active (walking: PWS) to highly active (running: 1.3 Ã PWS). Usage handedness includes having both hands available for interaction or having only one-hand or even no-hands, such as when holding items using two hands. To simulate the busy hand scenario, the on-site researcher will ask you to carry commonly used shopping bags in one hand (dominant or non-dominant hand) or both the hands with each bag weighing less than 1.7 kg. Once the experiment is over, feel free to approach the on-site researchers who will provide additional feedback on the research project and give you the opportunity to ask any other questions you might have. If you are interested to follow up on the outcome of this study, you can provide your email in consent form or can alternatively send an email to Gaganpreet (gagan@cs.umanitoba.ca).

Participation in this study is voluntary and will take approximately 1.5 hours with a 5 minutes break in between every task. You will receive $20 for your participation. The failure to take part in experiment due to any reason (whether PARQ+ "fail" or any other) after signing the consent form will not prevent you from getting the compensation. Aside from this incentive, you will get a chance to explore new advancements in smart wearables by interacting in new ingenious ways. Also, there are no extra known risks associated with your participation. All information you provide is considered completely confidential. Data collected during this study will be used for academic research and publication purposes in an anonymous form. All consent forms and names and numbers linking data with consent forms will be stored separately from the data in a locked file cabinet in Dr. Irani's office (E2-580 EITC) with a lockable door. The identity information and the consent forms will be destroyed two weeks after the user experiment. The data collected through experiment will be retained for a period of a maximum 1 year after the submission for the publication i.e. until September 2018. Only researchers associated with this study will have access to the data. If for any reason, you require the withdrawal of your data collected during the study, please feel free to contact any of the researchers listed in this form at any time during your participation or within the first two weeks after your participation. As a result of a request for withdrawal of your data, we will destroy your data and it will no longer be used in any future reports or publications.

For purposes of research analysis, the quantitative data (i.e. reaction time, interaction time and accuracy) will be collected during the experiment. We will also ask you to fill up questionnaires for qualitative data to get an overview of the difficulties faced while performing the interaction tasks. The questionnaire will include NASA TLX and self-assessment questions regarding your performance under different mobility and handedness conditions. The NASA Task Load Index (NASA-TLX) is a widely used assessment tool that rates perceived workload in order to assess the performance of tasks. You are required to fill the NASA TLX form indicating your experience while interacting with smartwatch under different mobility and handedness conditions. Neither your name nor any other identifying information will be used in presentations or in written products resulting from the study. You are also required to fill up the PARQ+ questionnaire before taking part in the user experiment. The main purpose of PARQ+ questionnaire is to ensure that whether it's safe for you to use the treadmill and perform any physical activity. The information collected using PARQ+ questionnaire will not be used for any other research purpose. The PARQ+ forms will be administered and stored/destroyed by the members of Activity Center in accordance with their existing procedures. By signing this consent form, you agree that you understand this and that we may use the qualitative and quantitative data collected from the experiment. We will not use any names in our reports and the reports will only be used by the researchers listed on this form.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence and you will still receive the $20. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at your research records to see that the research is being done in a safe and proper way. This research has been approved by the Joint-Faculty Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Coordinator (HEC) at 474-7122 or email: humanethics@umanitoba.ca. A copy of this consent form has been given to you to keep for your records and reference.

I would like to receive a summary of the findings:
No _____ Yes_____ Email or ground mail: _____
Participant's Signature _____ Date _____
Researcher's Signature_____