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Master's Thesis

EdgeGlass: Exploring Tapping Performance on Smart Glasses while Sitting and Walking

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Abstract

Currently, smart glasses allow only touch sensing area which supports front mounted touch pads. However, touches on top, front and bottom sides of glass mounted touchpad is not yet explored. We made a customized touch sensor (length: 5-6 cm, height: 1 cm, width: 0.5 cm) featuring the sensing on its top, front, and bottom surfaces. For doing that, we have used capacitive touch sensing technology (MPR121 chips) with an electrode size of ~4.5 mm square, which is typical in the modern touchscreens. We have created a hardware system which consists of a total of 48 separate touch sensors. We investigated the interaction technique by it for both the sitting and walking situation, using a single finger sequential tapping and a pair finger simultaneous tapping. We have divided each side into three equal target areas and this separation made a total of 36 combinations. Our quantitative result showed that pair finger simultaneous tapping touches were faster, less error-prone in walking condition, compared to single finger sequential tapping into walking condition. Whereas, single finger sequence tapping touches were slower, but less error-prone in sitting condition, compared to pair simultaneous tapping in sitting condition. However, single finger sequential tapping touches were slower, much less error-prone in sitting condition compared to walking. Interestingly, double finger tapping touches had similar performance result in terms of both, error rate and completion time, in both sitting and walking conditions. Mental, physical, performance, effort did not have any effect on any temporal tapping's and body poses experience of workload. In case of the parameter of temporal demand, for single finger sequential tapping mean temporal (time pressure) workload demand was higher than pair finger simultaneous tapping but body poses did not affect temporal (time pressure) workload for both of the sequential and simultaneous tapping type. In case of the parameter of frustration, the result suggested that mean frustration workload was higher for single finger sequential tapping experienced by the participants compared to pair finger simultaneous tapping and among body poses, walking experienced higher frustration mean workload than sitting. The subjective measure of overall workload during the performance study showed no significant difference between both independent variable: body pose (sitting and walking) and temporal tapping (single finger sequential tapping and pair finger simultaneous tapping).

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First and above all, I praise Allah, the Almighty to give me the opportunity and capability of graduation, in the field of Human-Computer Interaction (HCI). Without the assistance and guidance of several people, this thesis might not have been completed. I would, therefore, like to thank all the people for their contribution from the bottom of my heart. My very special thanks go to my supervisor Ian Oakley. He always tried to help me in every possible way he could help me during my entire master's period. He always wanted to raise me up whenever I was down to my academic life and as well as in my personal life. I was really lucky enough to get the great chance of being involved with your great research group during my master's degree. I also want to show my sincere gratitude to Professor Young-Woo Park and Professor Gyouhyung Kyung for reviewing/evaluating my thesis and both of you provided me some valuable comments and directions on my thesis defense in order to successfully finish it. I would like to acknowledge my friends and lab mates: DoYoung Lee, HyunJae Gil, Hongmin Km, Youngeun Song, Youryang Lee, Hyunmi-Oh, Mintra Ruensuk, Yonghwan Shin and Eunyong Cheon, you all made a fruitful impact on my life by encouraging and inspiring me all the way. Finally, I would like to give my very special thanks to my every family members and friends. Lastly, my spatial thanks go to my dear sweetheart beloved wife Suraiya Jahan Liza for being with me more than a decade in every up and down on my life. Every time you tried to encourage me in every possible way and always pushed me up for my betterment.

Research Attribution

In research collaborative work is common. No research can be done alone. This thesis also follows the same pattern. This thesis has a total of 5 chapters. In this preface, I (MD RASEL ISLAM) will explain the attribution of each individual in chapter wise. Among all five chapters, Chapter: 1 Introduction, Chapter 2: Literature Review, Chapter 4: (Experimental Design, Result, and Analysis) and Chapter 5: Overall Discussion and Conclusion, all the writings and framework were completed by MD RASEL ISLAM with the suggestion from his supervisor Ian Oakley and his lab mate DoYoung Lee. In Chapter 3: Hardware and Software System, these works had been extensively contributed by MD RASEL ISLAM supervisor. MD RASEL ISLAM is reporting Ian Oakley's extensive contribution to Chapter 3, on behalf of Ian Oakley, by asking and discussing with him. MD RASEL ISLAM always tried to seek the help of Ian Oakley to complete this chapter's work. MD RASEL ISLAM have discussed with his supervisor about his research concept, study design framework, and protocols. By following them, Ian Oakley implemented the system and hardware accordingly for the study of this thesis. Whereas, MD RASEL ISLAM have contributed by designing the housings and other prototypes for the hardware to mount it on the Epson Moverio BT200 glass securely. After generating the full study system, Ian Oakley gave the system to MD RASEL ISLAM for testing it if everything is working perfectly on both PC and Epson moverio Glass. After the system worked perfectly for PC, MD RASEL ISLAM tried to run the study to glass by the app. Initially, Ian Oakley, have made 2D temporal tapping interface and suggested MD RASEL ISLAM to try to convert them into 36 combinations for the performance study. From 2D to 3D temporal tapping visualization MD RASEL ISLAM have made simple mockup software to transform the 2D into a 3D design. We expected that the 3D transformation will help the participants to do a better performance. After the 3D design, minor software parameters needed to be adjusted. To wrap up the final study design and code the adjustment for proper final experimental conditions, combinations, repetition was contributed both by MD RASEL ISLAM and his lab mate DoYoung Lee.

Publications

Here are my published research works during the staying of Interactions Lab for approximately five years. The published works are listed below. I have been finished them during the five years of my journey in this lab with the supervisor of Ian Oakley and collaboration with other lab mates. I would like to highly acknowledge that, this thesis is my original work done during my two-year master's program, my master's thesis work is a non-published work and this thesis work does not conflict with my prior published projects.

International Conferences:

1. Ian Oakley, Jun Ho Huh, Junsung Cho, Geumhwan Cho, MD. Rasel Islam and Hyoungshick Kim (2018). "The Personal Identification Chord: A Four Button Authentication System for Smartwatches". In Proceedings of ASIACSS'18, Songdo, Incheon, Korea.

2. MD. Rasel Islam, DoYoung Lee, Liza Suraiya Jahan and Ian Oakley (2018). "GlassPass: Tapping Gestures to Unlock Smart Glasses." In Proceedings of Augmented Human 2018, Seoul, Korea.

3. Augusto Esteves, David Verweij, Liza Suraiya, MD. Rasel Islam, Youryang Lee and Ian Oakley (2017). "SmoothMoves: Smooth Pursuits Head Movements for Augmented Reality." In Proceedings of ACM UIST'17, Quebec City, Canada.

4. Ian Oakley, Carina Lindahl, Khanh Le, DoYoung Lee and MD. Rasel Islam (2016). "The Flat Finger: Exploring Area Touches on Smartwatches". In Proceedings of ACM CHI'16, San Jose, CA, USA.

5. Ian Oakley, DoYoung Lee, MD. Rasel Islam and Augusto Esteves [2015). "Beats: Tapping Gestures for Smart Watches". In Proceedings of ACM CHI'15, Seoul, Republic of Korea.

Korean Patents:

Ian Oakley, DoYoung Lee, Khanh Le, MD. Rasel Islam and, Carina Lindahl, Method and Apparatus for Multi-Touch Input, (10-1791132), 2017. 10. 27, Issued.

2. Ian Oakley, DoYoung Lee, MD. Rasel Islam and Augusto Esteves, Method for Providing User Interface According to Beats Touch Based on Mobile Terminal, (10-1695940), 2017.01.06, Issued.

Korean Conference Poster:

MD. Rasel Islam, DoYoung Lee, Suraiya Jahan Liza, and Ian Oakley. "Novel pattern based authentication input technique for unlocking smart eyewear." Ergonomics Society of Korea (2016): 182-182.

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Chapter 1:
Introduction

1.1 Background of head mounted display

Wearable smart glasses are a category of emerging devices that present many new interactive tasks [15, 27]. Which is equipped with high-resolution and closed-form graphic displays, users can display a variety of content and can have a quick access time to the information and it is also possible to deploy augmented reality applications on them. It is also a growing trend and taking more public attention [27]. The research on the head-mounted display has started since the late '80s [3, 8]. The concept of head-mounted displays has already appeared in 1968 [58], but never in the consumer market. "Google Glass Project" [12, 57] launched their product in 2012 in the market as Augmented Reality based glass and after that, it opened a new door and got high attention for the researchers, developers, critics, etc. Additionally, other products which include the Oculus Rift [11], head-mounted display have gotten the attention of large audiences and developers. "Oculus Rift is a lightweight headset that permits a user to step into virtual reality-based interactions.

1.2 Problem statement and scope

The fact that, user's personal content is only visible to users can be an ideal platform for displaying sensitive or personal information. However, as the touchpad is attached on the side of the devices so direct input is not possible, which makes the interaction process with the device harder and for that reason, it needs an eyes-free interaction [20, 48]. Subsequently, the input surfaces are also small as compared to the traditional controllers. For instance, the Google Glass, which has a feature touchpad of 76.2 mm by 10.4 mm [20]. The additional controllers might solve the small input space problem and also leverage the direct input as the screen of controllers can be seen visually. However, the problem of handheld/additional devices is, they always need to carry an extra device with the user which is bothersome, especially it restricts the movement of users [40], midair gesture- based input, which often require the unwanted gesture which raise the social attention and as well as repeated hand movement make the user fatigue [29], In voice recognition based input users need to pronounce the cue or parameter[1], therefore, it needs peer's free environment, which is not practical context of using any device and also arises social concern [39]. Google Glass can be also incorporated within built-in light sensor which can detect the winking of eyes for taking pictures which is fast and precise, but is also not socially acceptable, which often symbolize flirting of a person and could be an issue of trust, it is also a single input-based technique and not much interaction can be available with this technique [19]. Head and eye gaze movement-based input is also another dimension of input by using the inertial measurement unit (IMU) sensors. The gestures can be detected by the head and eye movement, which might also make unwanted social concern, and the user might become fatigued by repetitive head

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[1] OK Google, get directions to... opens Google Maps with a request for a navigation to a specific location.

movement [16, 17]. Gripping with multi-fingers interaction can have a much better firm grasping in different postures with one hand/two hand, which allow the user to rotate the phone or typing on the keyboard with different layout adaptability for tablets/phones [6, 7]. Furthermore, gripping around the edges-based interaction has also been investigated [59], it is a system in which the pattern of touches on an array of sensors spread all over a device is used to infer user intent. In InfiniTouch [35] they also used capacitive sensing, where the sensors are placed on the front, back and on three sides of a phone which allow the users to touch the whole device. In Pre-Touch [25] it allows sensing the user's capacitive touch on the above of the screen. It allows a special UI—appropriate to the context of different hand and finger approaching combinations. Temple of the glasses front side interaction has been investigated [36, 67] but the top and bottom side based interaction yet not been investigated for the glasses, four sides of edges surrounding the front screen of watches investigated, the mobility situation result of those researches is unknown. Rapid menu selection multi-touch was investigated [13] for the front of the watch screen to allow selection in a single action with two fingers simultaneously and multi-touch with single finger which means, two actions executed tapping has been investigated for the watches in static conditions and their result for 2*2 and 3*3 grid seems same for 2 steps is half slower than 1 step selection respectively, interestingly the error rate remains the same for both techniques. They did their experiment on wearable watches in static. Rzayev et al. [52] compared reading text with smart glasses while sitting and walking. They varied three text position as top-right, center, and bottom-center positions with Rapid Serial Visual Presentation (RSVP) and line-by-line scrolling. But selecting target input with side mounted touchpad did not investigate yet which needs to explore and we believe that this would give us interesting findings than other smart devices like phone or watches. Moreover, we know very little about target selection on the different input surface on the touchpad of glasses as top, front, and bottom surfaces. As well as from the mobility and other previous input research that mobility input reduces the performances and increased workload compare to sitting and standing conditions. There is very limited work on a similar level of performance level insight for various conditions like sitting, standing and walking conditions.

1.3 Research contribution

To address these problems, we are proposing four conditions as the single finger two sequential taps, double finger one simultaneous tap, sitting and walking. There are total 9 first target and 4, the second target, which makes a total 36 combinations. We also contributed by building a customized prototype named “Edge Glass” which is 7.5 cm long and around 1.2 cm high, a hardware prototype instantiating this multi-touch functionality. The design also features sensing on its top and bottom surfaces (width 0.5cm). We used capacitive sensing technology (MPR121 chips) and an electrode size of ~4.5mm square, which is typical in the modern touchscreen. We created a system with 48 separate sensors; Each edge divided into 3 segments so, total 3 edges: top, front, and bottom have a total of 9 segments. We also contribute an assessment of the viability of this scheme through the results of a user study which characterized target selection performance task. There we set total four conditions as 1) single finger sequential tapping in sitting, 2) single finger sequential tapping in walking, 3) pair finger simultaneous tapping in sitting, 4) pair finger simultaneous tapping in walking. Google glass has 70.2mm height with 10.4mm of the width touchpad on the right side of their glass which only is able to sense the touches on the front side [1]. Google glass has the most limited input space, compared to other smart glasses. As our research goal is to facilitate interaction in limited input space and which also incorporate eye-free input. We believe, Top, front and bottom side input would help richer interaction possibility.

1.4 Research aim

We got motivation, from previous researches we have explored [34, 22]. For smartwatches and tables simultaneous tapping was faster than sequential two-step tapping, those temporal tapping for wearable glasses input are unknown. We argue that, as smart glasses have a larger screen display many possibilities of interesting applications can be possible for smart glasses. We also believe that, as simultaneous pairs tapping requires gripping of the touchpad sides which will increase the performance in walking situations compare sequential tapping in walking. We also want to emphasize that, smartphones target selection touch-based display size is larger than our customized touchpad and that’s why target distances for phones require more travel time around the touchpad and the screen occlusion problem for both phone and smartwatches, whereas our customized touch pad attached on the right side of a smart glass is able to do a comparable command selection performance in eyes-free situation. As we are facilitating both landOn and liftOff function which will improve the overall performance.

1.5 Research Hypothesis

Hypothesis 1: In terms of task completion time: Sitting will be faster than walking and Pair finger simultaneous tapping will be faster than single finger sequential tapping.

Hypothesis 2: In terms of error rate: Sitting will be less error-prone than walking and Pair finger simultaneous tapping will be less error-prone than single finger sequential tapping.

Hypothesis 3: In terms of subjective workload during the study: Sitting will have less workload rating than walking and Pair finger simultaneous tapping will have less overall workload rating than Single finger sequential tapping.

1.6 Thesis structure

In total, this thesis is consisting of total 5 chapters. In the first chapter, this thesis explained the introduction of a head-mounted display. In the second chapter describes the prior literature review. In the third chapter, it will describe the hardware and software implementation. In the fourth chapter, this thesis will describe the experimental design, result, and analysis. In the fifth chapter is the ending of this thesis, will have a discussion about the experimental result with expected future work and conclusions.

Chapter 2:

Literature Review

2.1 Overview

Wearable technologies are growing research interest in HCI because of its varieties of form factors, restricted and limited input areas, which makes them a ripe target for the development of new forms of interaction. Ranges of research have been done to support the new form of interactions. The work on this paper is mainly inspired by these prior studies and it got scope and seeks to leverage the benefits of the temporal tapping both simultaneous and sequential of interaction (in terms of its help for fast execution of interaction in both mobility situation and the reality it does observe this to the space-restrained smart glasses form aspect additionally facilitating two more input edges (top and bottom sides of touchpad mounted on the right side of the glasses) combined with traditional pad of glasses (front side). It explores how users produce those pairs of target selection in both single finger two sequential tapping consecutively and a pair of finger simultaneous tapping together in both sitting and walking.

2.2 Hands-free interaction

Voice input is one type of interaction technology facilitates hands-free input of smart glasses. Speech recognition is one of the already adopted and mature technology for smartphones and wearable glasses. However, it is inconspicuous in public places [13,37] and voice input is also undesirable compared to gesture and non-gesture input techniques [33]. Eye and face tracking is another trend of hands-free interaction. Eye movement [54, 60] and face gesture detection [18] have been further combined with the smart glass display. In this type of interaction, very light muscle movements are needed to interact, which can reduce extrusions, but these types of interactions require accurate and high calibrations and are prone to errors in performance and monitoring errors. Ishimaru et al. [26] also proposed a technique for understanding the user's excessive activity, such as discriminating speech and reading, by combining head movement and eye flicker frequency detection. This type of interaction requires a high degree of correction, and this type of gesture was not given preference by the users when there is hand type gestures are present. [33]. If we have the most accurate, more precise calibrated, and less error in the design interactions of head-mounted displays, then hand-input technology will not be needed. Zheng et al. [68] did an experiment, where the subjects were instructed to perform the specified conditions as follows: a participant can use smart glasses with a hands-free or handheld paper/tablet. The authors found that there was no difference in completion time, however, the subject was able to adapt well to his situation and the authors found the insight that the subject felt more comfortable to follow the task by hand.

2.3 On-body interaction

Various input techniques have developed such as body gesture-based interactions and it can be integrated with smart glasses [37, 63]. There are two types of detection in whole-body interactions. In one type it uses an external sensor and, in another type, it senses directly on the touch surface. In terms of gesture-based input, the user enters gestures physically on the body. Previous research has shown that location and gestures of the body have a distinct perception of social acceptability [49, 55]. Tung et al. [61], touching the palm is the preferred choice (51%). For example, PalmType [62] allows subjects/users to type with their fingers in the palm of the hand. Typing on the palm can reduce social concerns and can be tolerated in public and crowded spaces. However, this type of interaction not only restricts rich and diverse input interactions but also requires both hands to interact with palm-based inputs. Gugenheimer, J., et al. [21] explored the virtual reality head-mounted display and implemented the touch input for both fronts, left and right sides of the display. In this research work, we implemented a touchpad that uses both landOn and liftOff target selection techniques as used by Gugenheimer, J., et al. Their research work found that by combining landOn and liftOff, the error rate of the target selection was reduced by approximately 40%. Their touchscreen size was much larger than us: the front touchpad was (15.5cm x 9.8cm) and the left/right sides touchpads were (10.8cm x 6.8cm).

2.4 Mid-air interaction

Despite the fact that hand gestures have a greater social impact in a variety of contexts, they have the ability to allow for natural and rich interactions. Interactions composed of 2 dimensional or depth cameras were widely used for gesture recognition in wearable computer systems [4, 38]. However, this type of input requires a high level of setup into a real lab space that may not be suitable for wearable computing. Other researchers have developed gesture recognition technology to provide more reliable and accurate performance. For example, infrared (IR) based midair based gesture sensing [9, 32, 56, 64]. However, using vision-based input techniques is not the best way as it may have occlusion problems, and it needs to tie the gesture to the camera's viewing angle, so, gestures may need to be done in an unnatural way. In Microsoft HoloLens, the "Air Tap" action is recognized as pointing with index finger with "click on". Additionally, if the camera is set up inside the glasses, gestures ought to be executed in the front of the face, which proved to be much less ideal than in the front of the torso (63% vs. 37%) [24]. Researchers have proposed an included worn device with a camera at the torso, shoe or wrist [5, 31, 50], however, it can't resolve the hassle of the whole occlusion.

2.5 Hand-Worn interaction

Hand-worn devices use the hand-gesture input which solves the occlusion problem. As shown in Belt and ShoeSense [13, 50], separating the detection generation from the glasses can prevent noticeable types of motion. Past research has explored a variety of form factor artifacts worn on the other hand areas and fingers [30, 66], wrists [47], forearms [23, 41] and full hand [61]. Ideally, we can monitor hand gestures faster and accurately compare to visual monitoring, by holding the sensor in the user's hand. However, users need to wear extra devices with them which is a burden to carry separate devices. Minimizing the size of the detection tools will have a right away effect on permitting unobtrusive input. For instance, TIMMi [66] is a cloth-orientated interface and artifacts, have to be worn on index arms to interact upon pressure and bending. Lucero et al. intended to apply a rubbing pad-based finger-wear device that helped the wearer to focus their attention around. The authors implemented finger worn rub pad device which enables to interact with a minimal interface. Compared to small prototypes, head-mounted displays are likely to attract special attention. However, supporting a richer input system appears to be difficult.

2.6 Graspable interaction

Many researchers have investigated the use of touch sensors installed around mobile devices to aid context-sensitive interactions. For example, Graspables [59], a box-shaped element with a touch pattern spreads across the sensor array throughout the artifacts was used to infer user interest/desire. Cheng et al. [7] implemented a numbers of touch sensor along the two edges of the tablet computer, where capacitive sensors could sense the position of the user's hand and user could grasp the device by hand and adjust the position of the on-screen virtual keyboard so that it is always positioned properly under users finger. iRotateGrasp by Cheng et al. [6] investigated how to automatically rotate the screen of a mobile device depending on the user's screen viewing posture (how the user grasps the device). The custom prototype used 40 capacitive mpr121 touch sensors on using all the four sides and the back of the device. InfiniTouch [35] used capacitive sensing, where sensors were implemented on the front, back, and three-sided so that users could touch the entire device and they also used motion-sensing cameras to identify the finger motion of the users. Their result from the user-study showed that the system could identify the user's finger with an accuracy of 95.78%. Pre-Touch [25] enabled a touchscreen that could sense the user's capacitive touch above the screen and could detect the grips around the edges of the screen. It expanded input and interaction by allowing a special UI to fit in the context of a combination of one hand with the thumb, two hands with the index finger, and even a finger or thumb approaching with the other hand and fingers.

2.7 Around interaction

A typical problem with a small touch screen is occlusion. The problem prevents the user from seeing the list visually in order to manipulate it. As a result, many previous pieces of research had been done to solve this issue. Additional input space can leverage retrieving items from the list menu to make occlusion-free interface. For example, the back side of the small-sized display was proposed for the touch input [10]. As we know that, touch displays appear to permit for precise compactness, due to the fact they integrate input and display into the same bodily space. The opposite side could be a possible solution, but the problem is that for the back-screen accuracy from the input fingers of the person may degrade as they cannot see that back location to tap. That's why in this article [10] authors have customized the screen by making it transparent on both the front and back side, which allowed the user to touch on the back for interacting with the front screen contents, without occluding the front screen and therefore their performance did not decrease. Oakley et al. [43] proposed the idea to use the edge of the smartwatches as a solution of small front screen areas. This research focused on using the edges of a smartwatch for selecting the target. Other researchers have additionally proposed side tap [2], twist, including pressure sensing [65] for occlusion free interaction by using the edges of watches. Ahn et al. investigated the bottom side of the edge of the watch by separating the zones into three and as well as front screen were used for typing for the glasses which still required the watch and also occluded the screen someway.

2.8 Region interaction

Many researchers have investigated the region/area wise temporal tapping for wearable devices. For example, the Beats system [44] which is a pair of simultaneous touches for a watch with the index and middle finger. It allowed the users' eyes free rapid finger touches, as tapping followed the beating gesture in the same place by repeated touches which reduced the errors and times of tapping. Whereas, the flat finger [45] which customized the touch sensing based on 32 distinctive areas by using the index and middle finger. Another work by Oakley et al., have used the region based, password entry [46] for watches, where they have used both single and simultaneous tapping. GlassPass [28] which enabled to detect both the sequential and simultaneous temporal touches by dividing the touch sensing areas to the left and right regions. This customized system was also able to recognize both tapping and flat finger touches from the touchpad of the side mounted glasses. The front side of the google glass touchpad was used for 1-dimensional text entry, [67] where handwriting is a non-uniform gesture set that enabled text input in a one-dimensional side mounted front touchpad. Another researcher Grossman et al. [20] used the google glass front touchpad and divided that into three regions and they used swiping gestures on the Google Glass frame for text entry. In this way, several touch-based selection technologies have been considered. Mechanisms for spatial memory performance improvements have also been explored. For example, in FastTap for command selection, they have used sequential and simultaneous touches on tablet and watches [22, 34]. They allowed people to make choices by using multi-touch grid-based menu selection, where the structure of grid provided an external reference frame for the memory by commanding the location (for example, "top left").

2.9 Mobility

Smart wearable devices are designed for short interactions in a variety of mobile contexts. However, there is little data on how the user's mobility situation influences to interact with these devices. Dobbelstein et al. [14] have done a study in mobility for encumbrance (carrying a bag filled with things on the hand) while walking and non-encumbrance situations (without carrying a bag) and as well as they have investigated the standing body pose. They investigated tapping, swiping and wrist-flicking techniques and found that swiping barely affected the performance of each condition (selection time and error rate). Whereas, in both tapping and wrists-flicking walking conditions there was a higher error rate and selection time compared to the standing conditions. Ng et al. [42] investigated walking and encumbrance condition for phone-based target acquisition task selection. In this paper, they investigated the encumbrance phenomenon with general objects such as shopping bag and the goal of the study was to find, how to achieve target acquisition through touchscreen mobile phone. Usually, people often pick up things and use mobile devices at the same time, and therefore in this study participants were instructed to use one hand and two hands to investigate the impact of the encumbrance. To evaluate the impact of carrying a bag on the performance in each hand during walking, they evaluated three common input positions: two-hand index finger, one-hand preferred thumb, and two-hand thumb target selection. Targeting performance was significantly reduced when users were in encumbrance situation compared to walking. Schildbach et al. [53] investigated both reading text and target selection for three different sizes of targets and text sizes on the phone and targets needed to be selected consecutively one after another. They found that as the target and text sizes increased the performance became faster and less workload was felt by the users.

From the related work, we have reviewed, around interaction were mainly focused on the use of the around surface of smartwatches. Touches to the around facilitate additional input space and confirm firm gripping. We have also reviewed wearable smart watches/glasses region based input techniques where, authors emphasized, dividing the regions to help eyes-free interactions. As researchers explored only the front side of the touchpad divided regions of the side mounted glass [1] yet they did not explore the top and bottom surfaces of the glass touchpad as well region based target selection around the edges of glasses in mobility situation.

Chapter 3:

Hardware and Software System

3.1 Overview of Hardware and software system

For tracking the finger touch, we used four MPR121 capacitive touch sensors. Each of the capacitive touch sensors had 12 electrodes. We have made our own version of the MPR121 boards with fully customized printed circuit board. We printed them from electronics PCB manufacturing companies named as Seeed studio and ICbanQ. The sensors PCB was connected with the Arduino mega board with 1-meter long wires and the touch sensor were mounted on the right side of the Epson BT200 Moverio glass with android IOS version of 4.0.4. The display of Epson BT200 Moverio glass was (960x540) x 3 pixels, with a field of view of 23° arm with attached clamp. The four touch sensors with 48 electrodes were then connected with the outer layer of the top, front and bottom sides of the touchpad. All the visual contents were shown on the glass from the MacBook Pro 13 inch by using Processing and OscP5 library and those were wirelessly connected by using specified Interactions lab Wi-Fi IP address. When the touch event has happened, sensors from the glass wirelessly send back them to the PC. The MPR121 touch sensor board electrodes which were connected to the Arduino Mega board. By this way, we have transferred all the touches data from Arduino (open-source electronics prototyping platform that allows users to create interactive electronic objects) to Processing (it is a Java-based graphical visualization software) of the MacBook Pro 13-inch laptop by the serial communication. To make Arduino Mega portable and wireless we have connected Xbee Arduino shield with an Xbee. To communicate with the PC another SparkFun XBee Explorer USB shield was attached to the XBee module which was connected via USB wire on PC. The following (figure1) diagram shows how the hardware and software communication had been done. For visualizing the contents, we have specified the screen size on processing as 960x540.

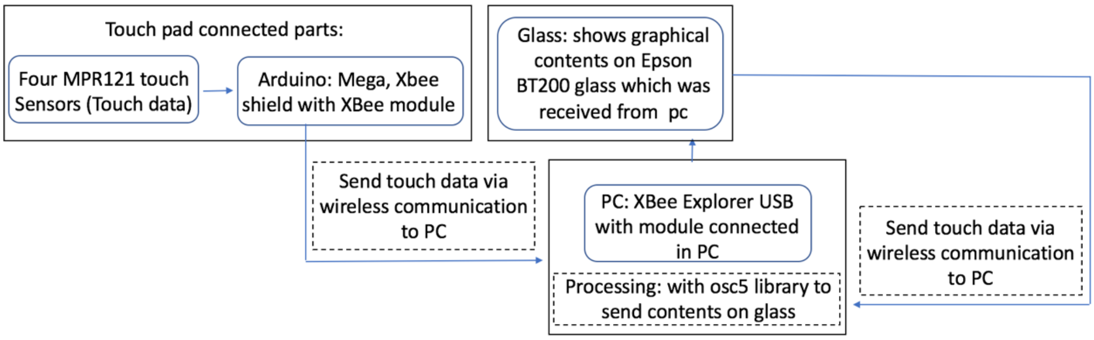


Figure 1: Diagram of hardware and software prototyping and implementation.

3.2 Hardware prototyping and Software Implementation

3.2.1 Touch sensor mounted on the right side of the glass

The total of 48 touch sensor electrodes from 4 MPR121 touch sensors boards was divided into three sides: top, front, and bottom. Topside was connected with the 12-touch sensor electrodes from 1 MPR121 capacitive touch sensor boards. Each of the pad of the Topside touchpad had an area of 4.5 mm square as touch sensing cells. On the other hand, the front side had total 24 touch sensors electrodes from 2 MPR121 boards in two rows, again each of the cells was 4.5 mm square as the touch sensing area. Lastly, the bottom touchpad had a total of 12 electrodes from another 1 MPR121 board as the Topside, with 4.5 mm square touch sensing area for each of them. Each side of the touchpad was 10mm in width and 60mm in height.

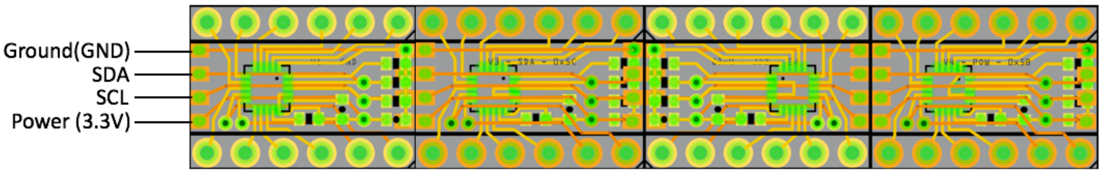
3.2.2 Briefing about MPR121 capacitive touch sensor board

For our hardware prototype, we have customized MPR121 sensor boards by ourselves, printed circuit board (PCB) design has done with Fritzing software. Each of our MPR121 boards was 10 mm in width and 15 mm in height so after four boards adjacent wire connections made 10 mm of width and 60 mm in height. But usually, the MPR121 capacitive boards which can be found in the market are 20mm in width and 30 mm in height, which is twice the dimension in both width and height than our customized sensor boards. As our primary goal was to reduce the touch input area as small as possible, that’s the reason we have customized the MPR121 capacitive sensor boards by ourselves. Capacitive sensor boards are very popular among the researchers and makers often use them as those boards can sense human capacitive touches quite precisely and robustly. Every electrically charged object has a capacitance that changes its value as it gets closer to other conductive objects. However, the MPR121 board can detect the human body's capacitance whenever it is close to the electrode. The board has 12 individual electrodes and can be connected via the i2C (Inter-integrated Circuit) communication protocol. The operating voltage of the MPR121 touch sensor board is 2.5V to 3.6VDC, which can be connected to a 3.3V DC power supply. All four MPR121 board’s thickness was 1.65 mm.

3.2.3 Wiring of the MPR121 sensor boards and wireless data transfer protocol

Four wires: Ground (GND), SDA, SCL, and 3.3 V Power, from all the boards were connected by soldering and the corresponding wires have been connected to the Arduino Mega. To make the hardware system portable we have used 9V DC battery, which supplied constant power to the Arduino mega board. Whenever the battery was dead after working for several hours (at least 5 hours) of a constant power supply. To run the experiment without any interruption, after every 3 subjects, we changed the previous battery with the new one. To use a multi-touch sensor board, each board must have a different address. We used the base address (ADD pin, connected to GND by default) on one of the four boards. To change the base address of the other three boards, first, we disconnect the connection between the ADD pin and GND, then connected the ADD pin of one board to the SCL pin and the ADD pin of the other boards to the SDA pin. To wirelessly send the touch data from the mega board to the PC by serial communication, on the top of the mega board, we have connected the Sparkfun XBee shield and at the top of that shield, the XBee Wi-Fi module was attached. On the other hand, a USB wire XBee explorer was connected to the 13 inches, MacBook Pro to receive and send the touch data from the Arduino mega board hooked up XBee shield. In (figure 2 A) fritzing PCB design of four boards has shown and as well as in (figure 2 B) connection with the mega board are shown.

(A)



(B)

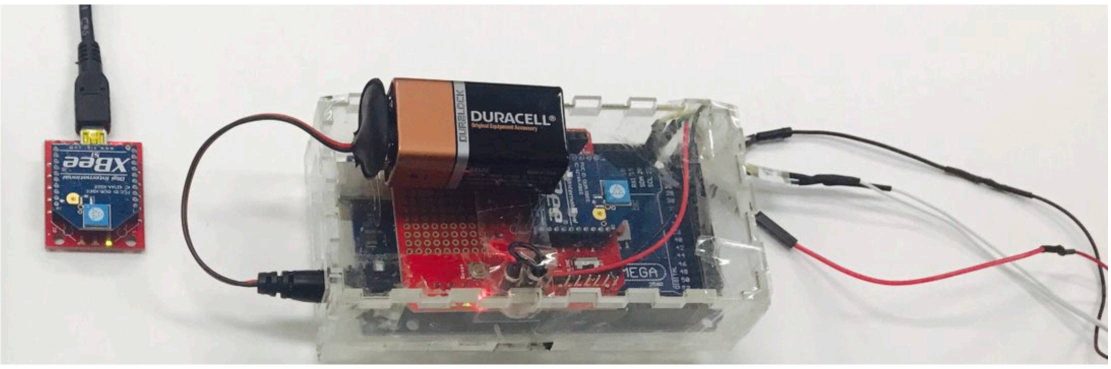


Figure 2: A) Four MPR121 boards have printed circuit boards design, B) connections with Arduino Mega board.

3.2.4 Wiring of the MPR121 sensor boards on Epson Moverio BT-200 glass

The top, front and bottom boards top layer view can be seen in figure 3 (A, B, C), each of the cells areas was 4.5 mm square with the hole size of 0.4mm. The top and bottom sides touchpad thickness was 0.6 mm, whereas the front side touchpad thickness was 1.65 mm. The top and the bottom touchpad were 10mm in width with 60 mm in height, but the front side touchpad was 11 mm wide with 60 mm in height. All the boards were 2 sided. The bottom layer of the front side pads showed in figure 3 (B) were connected with 24 more touch electrodes through the via to connect them by using 1.27 mm of 90 degree angled male headers. For top and bottom sides touchpad in figure 3 (A, C) each of the touch pads was connected with 12 more touch sensors through the via to connect them by using 1.27 mm of straight male headers. Figure 3 (D right image) shows the final prototype after all the boards were connected and soldered by using headers. The whole connected units needed to be securely attached to the Epson Moverio BT 200 glass on the right side of the glass. First of all, to attach the sensor unit we needed to make a flexible clamp to tightly attached it to the glass. It was 3D printed by using FabLab form 1 3D printer. The clamp had a lock type clip slot where the clamp of whole glass prototype was clipped perfectly. In order to firmly attach the back of the soldered unit, a supportive back clamp was 3D printed with Ultimaker 2, 3D printer. As well as the two-edge supported clamps were prototyped as 7.5 mm in height, 12 mm in width and depth each those are shown in figure 3(D left image). The four wires of Ground (GND), SDA (data), SCL (clock), Power 3.3 V has been taken out from the tiny hole of the left side of the clamp of edge. Then the soldered whole sensor, as well as touchpads, were clipped together with the clamp of edges and screwed them with 2mm diameter, by 12 mm long nuts. After that, a roughly textured rubber pad on both edges of the clamp was attached with 2-sided tape. This was attached in order to distinguish the areas better. In total after attaching the 3D printed back and both edges clamps, the total height of our prototype was 75 mm and each side was 12 mm in width which is shown in figure 3 (D right image). Our prototype is quite comparable to google glass touchpad size. Google glass has 70.2mm in height with 10.4mm in width touchpad on the right side of their glass which only is able to sense the touches on the front side [20]. Whereas, our customized prototype is able to sense top, front and bottom sides of the touchpad mounted on the side of the glasses.

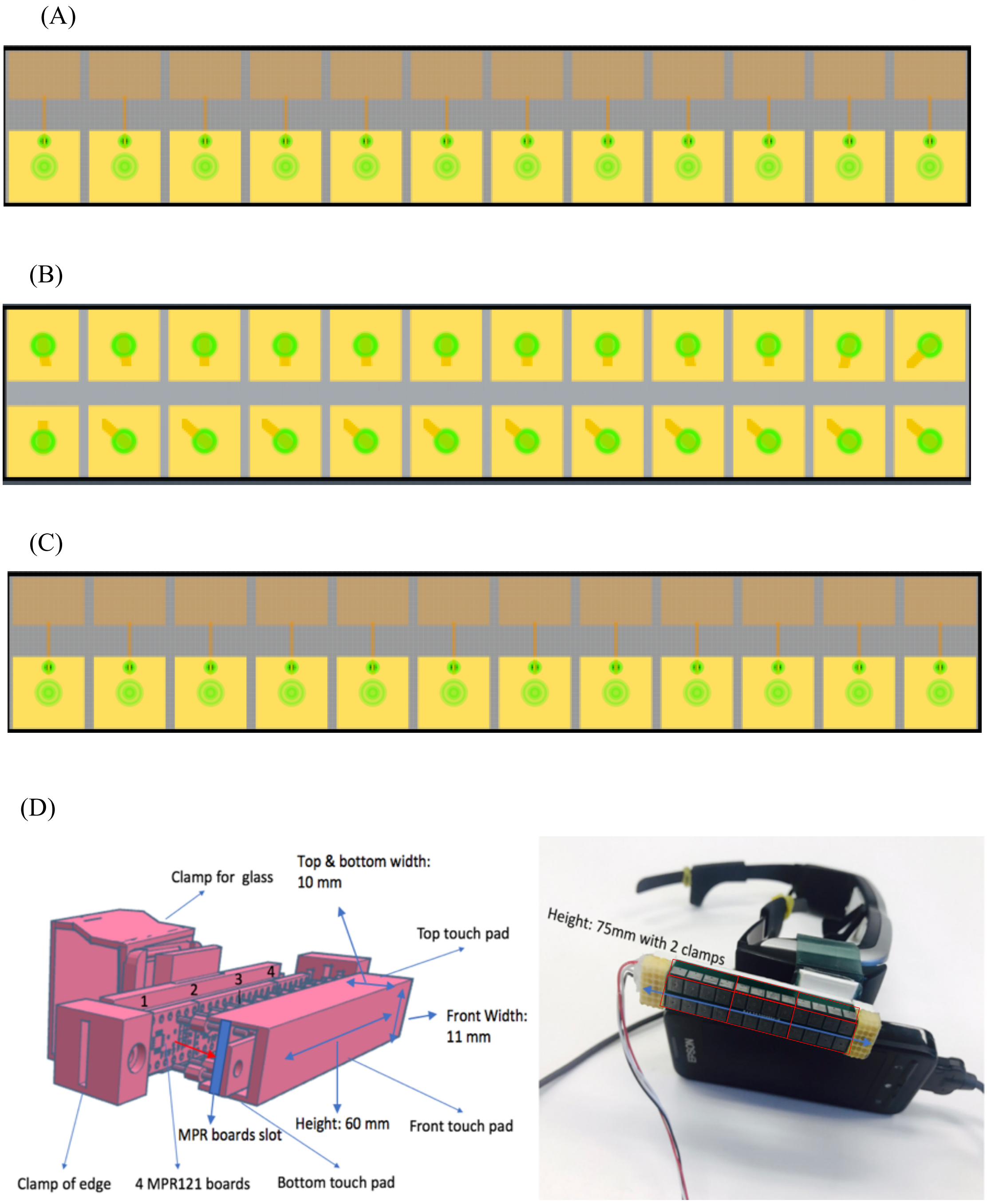


Figure 3: A) Top, B) Front, C) Bottom sides of the touch pad top layer PCB view, D) Left image: 3D view of MPR boards and touch pad with corresponding dimensions, Right image: Whole hardware unit mounted on glass.

3.2.5 Touch capacitance specification and demonstration

For sensing the capacitance of touches we have specified the threshold of minimum 10 to maximum 75. For our input system, we have used both single finger sequential tapping is shown in figure 4 (left image) and a pair of finger simultaneous tapping recognition demonstration is shown in figure 4 (right image). By using the serial communication, touch data sent from Arduino to the PC and by using osc5 processing library we could show the graphical contents of the glass. The user touch performance (touch time and error rate of those touches) data were transferred to the PC. Figure 5 (left image) shows the example and the protocol of both the single finger sequential tapping and the right image shows the pair finger simultaneous tapping.

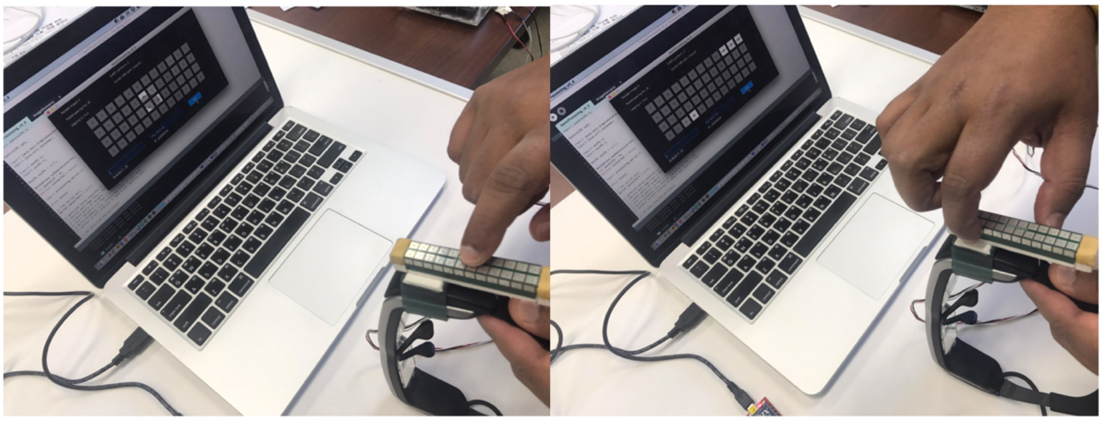


Figure 4: Left image: shows demonstration of single finger sequential touch, Right image: shows the demonstration of pair of finger simultaneous touch.

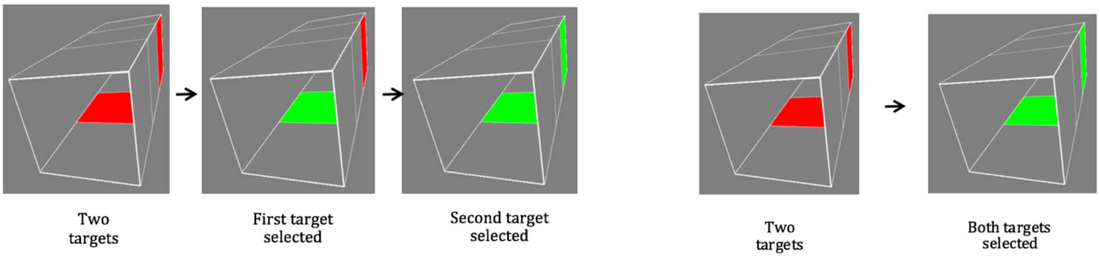


Figure 5: Both temporal tapping protocol and example Left image shows the single finger sequential tapping and right image shows the pair finger simultaneous tapping.

3.2.6 Novelty of the prototype

Currently, head-mounted displays are quite amazing, with a high-quality screen and high performance. Also, they are getting lighter and smaller. These displays can use additional touch-pad devices, or touchpad on the temple or the user can simply put an arm on the midair to make a command. Although they are working reasonably well, they have some problems like it can be cumbersome or can have a Limited input area or it can cause user fatigue. Touches to the around facilitate additional input space and firm gripping. For example, Gugenheimer et al. [21] used front and both sides of the head-mounted display. Whereas, Oakley et al. [43] and Ahn et al. [2], investigated watch edges for characterizing the performance. Moreover, many researchers have already worked in the region-based input. In GlassPass [28], the authors divided the side input space of the glass into two equidistance regions, for characterizing the tapping performance. Similarly, Grossman et al. [20] separated the side input space into 3 regions and Ahn et al. [1], dividing the bottom edge side of the watch into three zones for entering the text. Dividing the regions helps on eyes-free interactions more directly and our "GlassEdge", interaction system does not require any handheld devices as Ahn et al. [1], could use in mobility conditions. Our prototype was customized by the around edges touch sensing and had three sides (top, front, and bottom) of the touchpad. It had nine equidistance regions which leveraged the additional input space and firm gripping, as well as the divided regions facilitated rapid and direct eyes-free input. How gripping works for the mobility situation is also unknown for glasses. We believe that three sides with a flat surface will help users to grip firmly in pair finger simultaneous tapping scenarios, in both body pose and as well as they can interact with the device more rapidly and accurately compared to single finger sequential tapping's. From the pilot testing, we have found that in mobility situation single finger interaction was more error prone as single finger interaction slipped off from the touchpad.

3.2.7 Design rationales of the prototype

The height of the total prototype was 75 mm with 12 mm in width, our prototype is quite comparable to google glass touchpad size. Google glass has 70.2mm in height with 10.4mm in width touchpad on the right side of their glass which only is able to sense the touches on the front side [20]. Whereas, our customized prototype is able to sense top, front and bottom sides of the touchpad mounted on the side of the glasses. As far as we know google glass has the small-sized limited input space. As google glass is only capable of recognizing the touch on the front side of the touchpad (mounted on the right side of the glass) that's why we could not use it for our study. Google glass is really very light weight and it is comparable to regular glasses[2] whereas Epson moverio BT200 glass is about 90g we recorded and after mounting our prototypes on the top of it become approximately 130g. We could have used the normal glass

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[2] https://www.wired.com/story/google-glass-2-is-here/

and could have mount the touchpad on the side of the normal glass arm, which could give us a more robust platform like Google glass with the lightweight input device. We believe and agree that the study measures such as task completion time, errors, subjective workload and as well as post-experiment short interview result could give us different insight and outcomes if we would have used normal eyeglass or google glass. The reason for using Epson moverio BT200 glass was that it was an android enabled developer version and as well as we could wirelessly visualize the study related graphical contents during the entire study. For using the normal glass, we required to visualize the graphical contents in another external display like a personal computer, which could have been appropriate for the sitting condition, but not for the walking situation. Therefore, we did not have another option rather than showing the contents on the Epson moverio BT200 glass. Usually, for the input technique of the wearable glasses touchpad, many researchers used google glass for visualizing the contents according to their study task requirements. For example, Grossman et al. separated the side input space into 3 regions on the google glass touchpad for the swipe-based text entry system. In one-dimensional text entry [67], they used the front side of the Google glass for entering the text on the glasses. In order to facilitate the firm, grip we customized each side (top, front, and bottom) of the touchpad by making it flat, box-shaped and long, so, that user could easily grip the sides with a pair of fingers. Oakley et al. [43] used circular watch form prototype with enabling customized around touch sensing whereas Ahn et at. [2] used four edges of square/rectangle shape, those circular/rectangular shapes were well fitted for the watch. On the other hand, glass input requires eyes-free input that’s why usually touchpads are long, box-shaped and flat (as the arm of the glass is also long). Prior researchers also used long, straight, box-shaped touchpad on the side of the glasses, even though they did not intend to investigate “Graspable” feature [20,28, 67]. If we could explore other form shaped edges for touch pads, for example, triangular, round, pyramid, hexagonal etc., we might be able to find different performance measures result and the way of gripping the edges might give us valuable insights.

Chapter 4:
Experimental Design, Result and Analysis

4.1 Briefing of Experimental Design, Result and Analysis

With the customized prototype, we have done a user study. We wanted to know the impact of two different body poses (sitting and walking) and as well as two different temporal pattern tapping touches (single finger sequential tapping and pair of finger simultaneous tapping) on the input task completion time (in millisecond) and the error rate (in percentage). In terms of system or product usability both quantitative and subjective measures is an important aspect, that's why we have also recorded the subjective measure of NASA TLX including how mentally demanding the task was, physical level of demand of the task, temporal demand in terms of time pressure users went through, user's perception of their performance, accuracy level, effort users needed to give to accomplish the level of performance and what was the level of frustration they have gone through in all four different conditions [65]. The NASA TLX subjective measure form has attached in Appendix 4.

4.2 Motivation

The motivation behind this study was to do a performance study for target selection and how much the thirty-six sequential and simultaneous single and a pair of a finger tapping are valid for the real-world use. All the experimental data from the users were recorded and analyzed to understand the user performance by quantitative and subjective measures for each of the conditions. The prototype also ensured a perfect and consistent operation during the whole study. This work explored the error rate in percentage of each individual tapping and the average time taken to input them in millisecond unit, easiness or hardness of the input and user's subjective measures by using NASA TLX.

4.3 Experimental Design

For the experiment, we have conducted a within-subject design and both quantitative and subjective data has been recorded. The independent variables in our experiment were body pose and temporal pattern tapping touches, as shown in (table 1). The body poses varied between sitting and walking. The temporal pattern tapping touches varied between single finger sequential tapping and, the pair of finger simultaneous tapping. Therefore, four different conditions have been made. All the conditions were counterbalanced by using the Latin square design. The dependent variable of this experiment was task completion time, error rate and workload. The four conditions are shown in (table 2).

Independent variables	Levels
Body pose	sitting, walking
Temporal tapping	single finger sequential, pair of finger simultaneous tapping

Table 1: Independent variable with level.

Conditions
Single finger sequential tapping in sitting
Single tapping sequential tapping in walking
Pair tapping simultaneous tapping in sitting
Pair tapping simultaneous tapping in walking

Table 2: Experimental conditions.

4.3.1 Participants

Sixteen right-handed participants (6 female, 10male) with a mean age of 25 years participated in this study. All the participants were either undergraduate or graduate student of UNIST, with a high smartphone and touchscreen experience, but low smart eyewear experience. The experiment took about 45-60 minutes. The participants were compensated with approximately 10,000 Korean Won. The experiment was conducted in the lab environment. The dimension for each finger from the knuckle was measured and the palm-size was also measured. The average dimension for the thumb on the first knuckle of thumb finger was a 16.5 mm, index finger 14.23 mm, middle finger was 15.47 mm, ring finger with 14.68 mm and lastly pinky finger with 12.89 mm. The average dimension for the palm was 79.89 mm.

4.3.2 Task design

We designed a total of 36 combinations for selecting two targets. Participants could choose those targets independently, which means they could have select any of those targets first by using any of their fingers from a right hand. On our customized prototype, we had a total of 12 sensor electrodes connected with 12 touchpads on both top and the bottom side. We have combined 4 touchpad areas as one target for both top and the bottom sides. So, there was a total of three equidistance target areas for both top and bottom sides, which was 20 mm in height and 5 mm in width. On the other hand, for the front side, we had a total of 24 touch sensors electrodes connected with 24 touch pads as shown in figure 3 (D). For this front touchpad, we have combined first 2 rows of 4*2=8 electrodes as one target location which was 20 mm in height and 11 mm in width. Therefore, for each side, there were three equidistance target locations. The temporal pattern tapping touches varied between single finger sequential tapping and a pair of finger simultaneous tapping. In our study design, we have facilitated both landOn and liftoff technique. Gugenheimer et al. [21] have implemented a customized touch for the virtual reality head-mounted display. In their study, for the front and both left and the right side of the touchpad, they have used incorporated both landOn and liftOff target selection techniques and in the eyes-free condition, it decreased errors for about 40%. The landOn technique as shown in figure 7 (left image) that triggered the selection event on the initial touch and liftOff technique as shown in figure 7 (right image) that triggered the final selection when the finger was removed. When initially user do landOn to the touchpad, a cursor will be initiated and by holding the touchpad the cursor can be placed in the right target place and then fingers can be lifted Off. Few examples of 36 combinations of a pair of targets for nine locations of the top, front and bottom sides are shown in (figure 6), all the combinations can be found in Appendix 1.

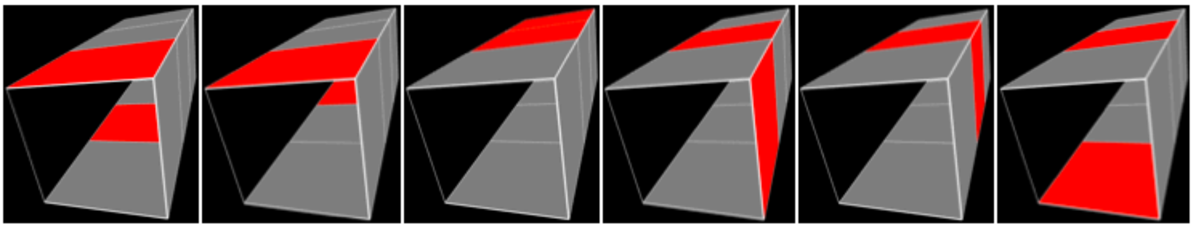


Figure 6: Examples from thirty-six combinations of pair of targets for nine locations of top, front and bottom sides.

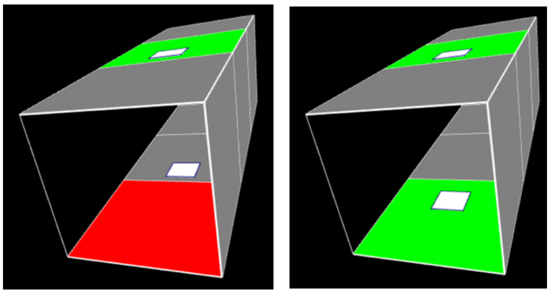


Figure 7: Example of landOn (left image) and liftOff (right image).

4.3.3 Experimental task

For conducting the experiment, we used the 36 combinations and participants completed each of the 4 conditions (Body poses: sitting, walking; Temporal tapping: single finger sequential tapping, pair finger simultaneous tapping, all conditions were fully balanced by the Latin square design) with 3 blocks of repetition. In total, each participant of the study generated 432 trials, 1st block of each condition was considered as practice trials so the remaining 288 trials for each participant were retained for the final analysis. All the trials were randomized for all participants. All the conditions were counterbalanced among the 16 participants. The experiment was a within-subject design, so each of the participants had to do all four conditions with a corresponding order of conditions as shown in (table 3). Between each condition, there was 3 mins break. During the break time, participants were instructed to fill out the NASA TLX form. In table 3, Latin square balancing for all the conditions is shown.

4.3.4 Procedure

Each trial began with the "Tap to begin the study" in the center of the glass display in 960 *540-pixel area. The participants were required to tap any place on the touchpad for "Tap to start". Afterward, a fixation spot as a circular shape could be seen in the center of the glass of screen with a diameter of 10*10 pixel and that remained on the screen for 500ms. In the next step, a random trial from the 36 combinations appeared (two target location) and participants needed to select those targets, according to the conditions they were assigned. Participants were given 5000ms time for tapping, within that time scale each trial needed to be accomplished. The feedback for the correct trial was given as a green colored circle and the wrong trial was given as a red colored circle, which was shown in the center of the screen for about 1000ms. After finishing each condition, a text “Study Finished” was shown on the screen. A single-trial from the study is shown in (figure 8). During the walking conditions, participants needed to walk with their usual walking speed. The experiment was conducted in the lab’s experiment room. The room size was 7-meter in height and 3-meter in width. In the center of the room, there was a large meeting table of 2.1 meters in height and 1.2 meters in width. The table was placed in the center of the room. Participants needed to walk around the table. A study was done by Dobbelstein et al. [14], for the walking and encumbrance situation they used a 5.3m long, 2.8m wide table, and around that table, the participant had to walk while doing the task. In our experiment, participants had to carry a lightweight backpack, which contained the electronic components required for the study. Prior to the walking condition, the study was started, each participant had to complete five laps around the table. Within those taps, how many steps and time was taken was collected by the experimenter for calculating normal walking speed. As well as the beginning of the walking condition study participants had to complete five laps as before while wearing glass in walking. This way of measuring walking speed is called PWS (preferred walking speed) and the PWS was followed by prior research [42]. After calculation, it turns out that average normal walking without wearing glass PWS for all participants was

5 km/hour. On the other hand, with wearing glass walking condition PWS for all participants was 4.5 km/hour. Each participant was required to walk in a clockwise direction. During the sitting condition, participants need to sit in an adjustable chair and placed their right arm elbow on the table. In both sitting and walking condition, participants need to align their hand with the glass touchpad. Sitting and walking condition is shown in the (figure 9). After coming to the experiment room, participants first filled out the demographics form (attached in Appendix 3), after that the experimenter gave the written instruction and demonstrated verbally all the experiment process. Then experimenter turns on the application in both glass and MacBook Pro 13-inch laptop. Written instructions for all four conditions can be found in Appendix 2.

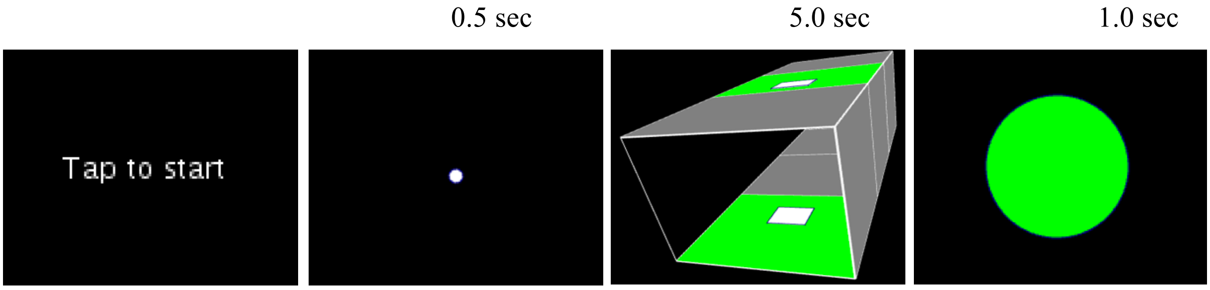


Figure 8: One full trial demonstration.

Figure 9: Both sitting and walking condition in the experiment.

Group 1	Group 2	Group 3	Group4
Single sequential tapping in Sitting	Single sequential tapping in walking	Pair simultaneous tapping in sitting	Pair simultaneous tapping in walking
Single sequential tapping in walking	Single sequential tapping in Sitting	Pair simultaneous tapping in walking	Pair simultaneous tapping in sitting
Pair simultaneous tapping in sitting	Pair simultaneous tapping in walking	Single sequential tapping in Sitting	Single sequential tapping in walking
Pair simultaneous tapping in walking	Pair simultaneous tapping in sitting	Single sequential tapping in walking	Single sequential tapping in Sitting

Table 3: Latin square counter balanced order among group.

4.3.5 Novelty of the study

We had two independent variables as temporal tapping and body pose. Temporal tapping had 2 levels (single finger sequential tapping, and pair finger simultaneous tapping), and body pose had 2 levels (sitting and walking). The target size was 20 mm by 5 mm from the top and bottom board, 20 mm by 10 mm for the front board. We had a total of 9 first targets and 4-second targets, which makes a total of 36 combinations. Each of the combinations had two targets around the three sides of the touchpad. Initially, the targets are highlighted in the red color and when the targets are selected then they became green color. In single finger sequential tapping, users could use any single fingers to select the target sequentially one after another. In terms of pair finger simultaneous tapping, the user could use any pair of fingers to select the target together. We have designed the combinations in a way that can be able to interpret single finger sequential tapping, and as well as pair finger simultaneous tapping. From the pilot test, we have confirmed that the single finger sequence is rapid and as well as can be able to interact with eyes free situation in sitting posture, whereas in walking posture single finger slipped off from the touchpad. On the other hand, pair finger simultaneous tapping needed to pair touches around the sides together which had firm gripping and grip helped accurate and rapid execution in the walking situation. No prior study, especially for glass-based input/target selection implemented these single finger sequential and pair finger simultaneous touches on three sides of the touchpad and it can benefit of both temporal tapping in different body pose situations. Especially, our study suggested that gripping based pair finger simultaneous tapping is an improved rapid and accurate selection while walking. To validate our expectations, we have recruited 16 participants. We were also not sure how the subjective fatigue will encounter during the study and that's why after each condition, we asked the participant to report their workload experience. For the workload subjective measure, we have used NASA TLX as it has six unique workload parameters: mental, physical, temporal (time pressure), performance, effort, frustration. The NASA TLX form is attached in Appendix 4.

4.4 Experimental Results

4.4.1 Quantitative analysis

We have analyzed the participants' quantitative performance in terms of task completion time (TCT) and task error rate (TER).

4.4.1.1 Mean Task completion time (MTCT)

MTCT is defined as the time difference between the task start time and task end time is shown in (figure 10). The average MTCT for all the conditions were: Single-Sitting (mean 1906.87ms, STD 94.70ms), Single-Walk (mean 1628.33ms, STD 43.77ms), Pair-Sitting (mean 1636.34ms, STD 38.26ms), Pair-Walking (mean 1523.81ms, STD 18.59ms). MTCT for Single-Sitting condition was the highest and the

MTCT difference between the Single-Sitting and Pair-Sitting was: 270.53ms whereas the MTCT difference between the Single-Walking and Pair-Walking was: 104.52ms. Moreover, the MTCT of Single-Walking was faster than MTCT of Single-Sitting and MTCT of Pair-Walking was faster than the MTCT of Pair-Sitting, which was very interestingly unexpected. Among the four conditions standard deviation of Single-Sitting condition was the highest indicating a larger variation among the participants (378.79ms).

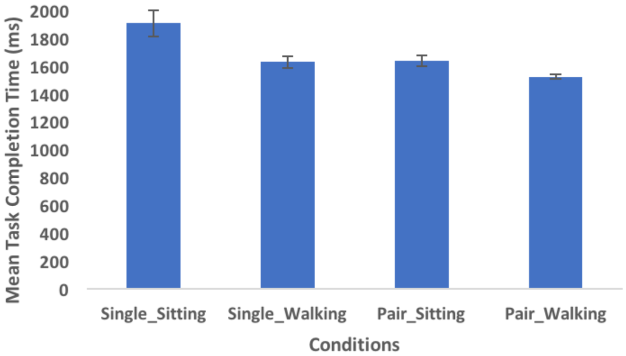


Figure 10: Mean Task Completion Time for the four conditions, bars show the standard error.

<u>ANOVA result of MTCT</u>

To compare the difference between the MTCT of the four conditions we did 2*2 two-way repeated measure ANOVA by taking the body pose (sitting and walking) and temporal taping (single finger sequential tapping and pair finger simultaneous tapping) as two independent variables to measure the dependent variable MTCT. We have found a significant difference between the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 11.365, p= 0.004, η2 = (0.431). Our data also showed the similar trend and indicating that, users took more time for sitting than walking, which means walking performance was faster than sitting in terms of task completion time. Significant effect for the body pose was also found (F (1, 15) = 9.484, p= 0.008, η2 = 0.387). We also checked the data which also showed the similar trend and significance, indicating that, among temporal tapping, single finger sequential tapping took longer time than sequential tapping which means pair finger simultaneous tapping was faster than pair finger sequential tapping. However, we didn't find any interaction effect between the body pose and temporal tapping (F (1, 15) = 2.389, p>0.05, η2 = 0.137). From (figure 11), it will be clearer, where we showed the mean task completion time for each variable with their levels.

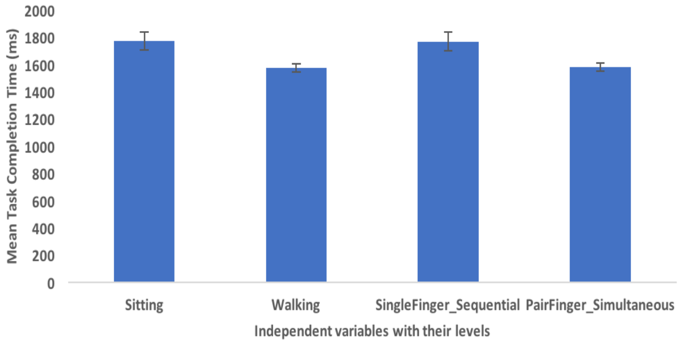


Figure 11: Mean Task Completion Time for independent variable body pose and temporal tapping variables with their levels, bars show the standard error.

4.4.1.2 Mean Task Error Rate (MTER)

MTER defines the mean error rate in terms of binary wrong and right target selection as converted in percentage shows in (figure 12). The MTER for all the conditions were: Single-Sitting (mean 10.94 %, STD 1.59%), Single-Walk (mean 21.44 %, 1.30 %)), Pair-Sitting (mean 14.81 %, STD 1.58%).), Pair-Walking (mean 15.13 %, STD 1.19%). MTER for Single-Walking condition was the highest and the MTCT difference between the Single-Sitting and Pair-Sitting was: 3.88 %, whereas the MTCT difference between the Single-Walking and Pair-Walking was: 6.31 % indicates that performance of Single-Sitting was better than the performance of Pair-Sitting and performance of Pair-Walking was better than the performance of Single-Walking. On the other hand, the MTCT difference between the Single-Sitting and Single-Walking was: 10.5% and the MTCT difference between the Pair-Sitting and Pair-Walking was: 0.31 % indicates that performance of Single-Sitting was better than the performance of Single-Walking which was expected and might be usual and performance of Pair-Sitting and performance of Pair-Walking was similar which was very interesting.

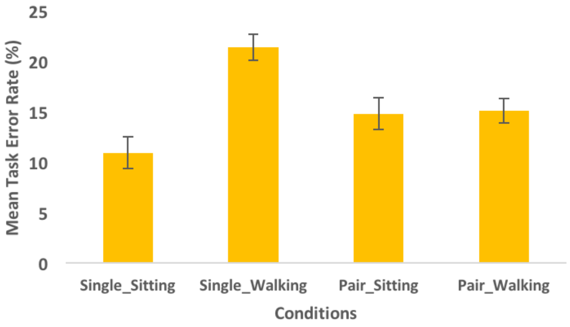


Figure 12: Mean Task Error Rate for the four conditions, bars show the standard error.

ANOVA result of MTER

To compare the difference between the MTER of the four conditions we did another 2*2 two-way repeated measure ANOVA by taking the temporal taping (single finger sequential tapping and pair finger simultaneous tapping) and body poses (sitting and walking) as two independent variables for measuring the dependent variable MTER. We didn't find any significant difference between the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 1.374, p > 0.05, η2 = 0.084). However, significant effect for the body pose was found (F (1, 15) = 13.657, p= 0.002, η2 = 0.477). Indicating that users made more error in the walking rather than sitting. Interaction effect was also found between the body pose and the temporal tapping (F (1, 15) = 16.045, p = 0.001, η2 = 0.517). Which indicating that, in temporal tapping with one finger sequential overall error rate was higher for the walking body pose and, in the temporal tapping with a pair of finger simultaneous tapping error rate was higher in walking condition. But the difference was very low. From (figure 13), it is clear and, where it is showing the mean task error rate for each variable with their levels and the interaction plot.

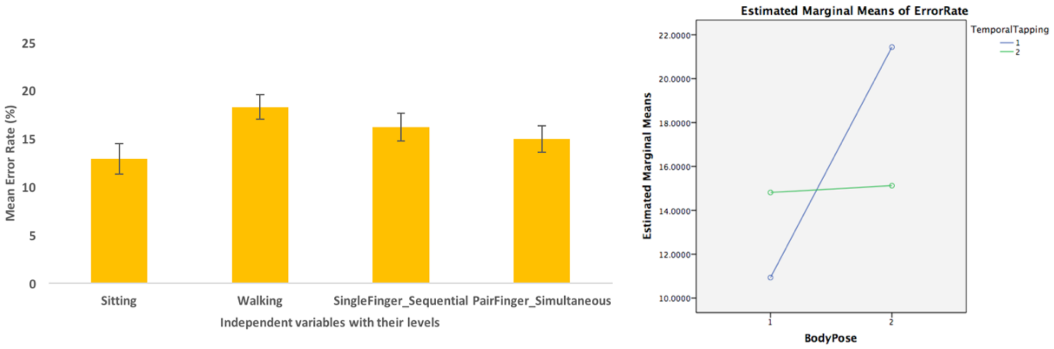


Figure 13: Mean Task Error Rate for independent variable body pose and temporal tapping variables with their levels, bars show the standard error and the interaction plot.

4.4.2 Subjective analysis

For subjective measure, we have used NASA TLX which has six categories of workload.

Mental Demand: How much demanding the task was, mentally and perceptually?

Physical Demand: How much demanding the task was, physically?

Temporal Demand: It evaluates the time pressure user felt in terms of task pace.

Performance: Satisfactory level of users.

Effort: Mentally and physically given effort to accomplish the done performance level.

Frustration: Level of frustration during the task.

4.4.2.1 Mean Rating of Workload (MRW):

In the (figure 14) each of the above categories Mean Rating data have shown. The x-axis is the six-workload category along with an aggregated mean of each category of workload measure, whereas Y-axis is the MRW for which scale ranges are from 0-6. In the below (figure 14), shows the TLX workload scores. Higher scores consistently indicate higher workload. As there are total six parameters in NASA TLX and those are mental demand, physical demand, temporal demand (time pressure), performance, effort, and frustration. The mean and standard deviation for each of the parameter are calculated for each condition. Moreover, we have also calculated overall workload by aggregating them for all the parameters. **First**, mental workload of all conditions was for single-sitting (mean 3.47, STD 1.50), single-walking (mean 2.94, STD 1.50), pair-sitting (mean 3.06, STD 0.96), pair-walking (mean 2.27, STD 1.32). **Second**, the mean physical workload of all conditions was single-sitting (mean 3.30, STD 1.45), single-walking (mean 3.13, STD 1.71), pair-sitting (mean 3.71, STD 1.51), pair-walking (mean 3.00, STD 1.69). **Third**, mean temporal (time pressure) workload of all conditions was single-sitting (mean 4.34, STD 0.68), single-walking (mean 3.70, STD 1.53), pair-sitting (mean 2.44, STD 1.51), pair-walking (mean 3.70, STD 1.65). **Fourth**, the mean performance workload of all conditions was single-sitting (mean 2.21, STD 1.58), single-walking (mean 3.78, STD 1.82), pair-sitting (mean 3.32, STD 1.80), pair-walking (mean 2.53, STD 1.55). **Fifth**, mean effort workload of all conditions was single-sitting (mean 2.06, STD 1.45), single-walking (mean 3.38, STD 1.87), pair-sitting (mean 3.70, STD 1.39), pair-walking (mean 3.32, STD 1.46). **Sixth**, mean frustration workload of all conditions was single-sitting (mean 2.03, STD 0.90), single-walking (mean 4.64, STD 0.78), pair-sitting (mean 2.93, STD 1.66), pair-walking (mean 2.42, STD 1.16). And the aggregated overall mean workload for all parameters of all conditions was single-sitting (mean 2.90, STD 0.51), single-walking (mean 3.53, STD 0.59), pair-sitting (mean 3.19, STD 0.66), pair-walking (mean 2.87, STD 0.32).

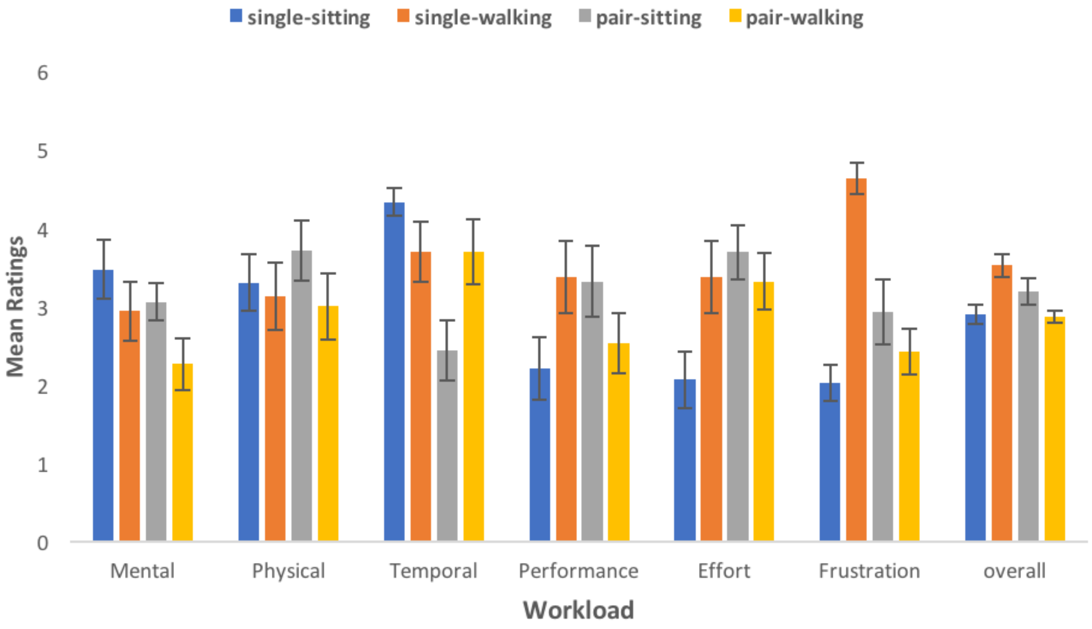


Figure 14: Mean ratings of subjective measure of NASA TLX of each condition, bars show the standard error.

ANOVA result of Mental Workload (MWR):

To compare the difference between the, MWR of mental workload for all of the four conditions we did a 2*2 two-way repeated measure ANOVA by taking the temporal taping (single finger sequential tapping and pair finger simultaneous tapping) and body poses (sitting and walking) as two independent variables for measuring the dependent variable MWR. We didn't find any significant difference between the temporal tapping of the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 2.511, $p > 0.05$, η2 = 0.143). We also did not find any significant difference between the body pose: sitting and walking (F (1, 15) = 3.245, $p > 0.05$, η2 = 0.178). This suggests that neither the single finger sequence and pair finger simultaneous tapping nor the walking or sitting body pose, had a measurable impact on the mental workload demand experienced in the study. We also did not find the interaction effect between the temporal tapping and body pose (F (1, 15) = 0.173, $p > 0.05$, η2 = 0.011). From (figure 15), it will be clearer, where we showed the mental mean workload rate for each variable with their levels.

Figure 15: Mean mental workload rating for independent variable, body pose and temporal tapping variables with their levels, bars shows the standard error.

ANOVA result of Physical workload (MWR):

To compare the difference between the, MWR of physical workload, for all of the four conditions we did a 2*2 two-way repeated measure ANOVA by taking the temporal taping (single finger sequential tapping and pair finger simultaneous tapping) and body poses (sitting and walking) as two independent variables for measuring the dependent variable MWR. We didn't find any significant difference between the temporal tapping of the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 0.131, $p > 0.05$, η2 = 0.009). We also did not find any significant difference between the body pose sitting and walking (F (1, 15) = 1.353, $p > 0.05$, η2 = 0.083). This suggests that neither the single finger sequence and pair finger simultaneous tapping nor the walking or sitting body pose, had a measurable impact on the physical workload demand experienced in the study. We also did not find the interaction effect between the temporal tapping and body pose (F (1, 15) = 0.476, $p > 0.05$, η2 = 0.031). From (figure 16), it will be clearer, where we showed the physical mean workload rate for each variable with their levels.

Figure 16: Mean physical workload rating for independent variable, body pose and temporal tapping variables with their levels, bars shows the standard error.

<u>ANOVA result of Temporal workload [(Time Pressure) (MWR)]:</u>

To compare the difference between the MWR of temporal (time pressure) workload, for all of the four conditions we did a 2*2 two-way repeated measure ANOVA by taking the temporal taping (single finger sequential tapping and pair finger simultaneous tapping) and body poses (sitting and walking) as two independent variables for measuring the dependent variable MWR. We found a significant difference between the temporal tapping of the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 10.073, p = 0.006, η2 = 0.402). Which indicates that, between temporal tapping, single finger sequential tapping temporal (time pressure) mean workload demand was higher than pair finger simultaneous tapping. However, we did not find any significant difference between the body pose sitting and walking (F (1, 15) = 0.569, p > 0.05, η2 = 0.037). We found the interaction effect between the temporal tapping and body pose (F (1, 15) = 5.608, p = 0.032, η2 = 0.272). Which indicates that in temporal tapping with one finger sequential temporal (time pressure) workload rating was higher for sitting body pose, whereas in the temporal tapping with a pair of finger simultaneous temporal (time pressure) workload was higher in walking condition. From (figure 17), it will be clearer, where we showed the temporal (time pressure) mean workload rate for each variable with their levels and the interaction plot.

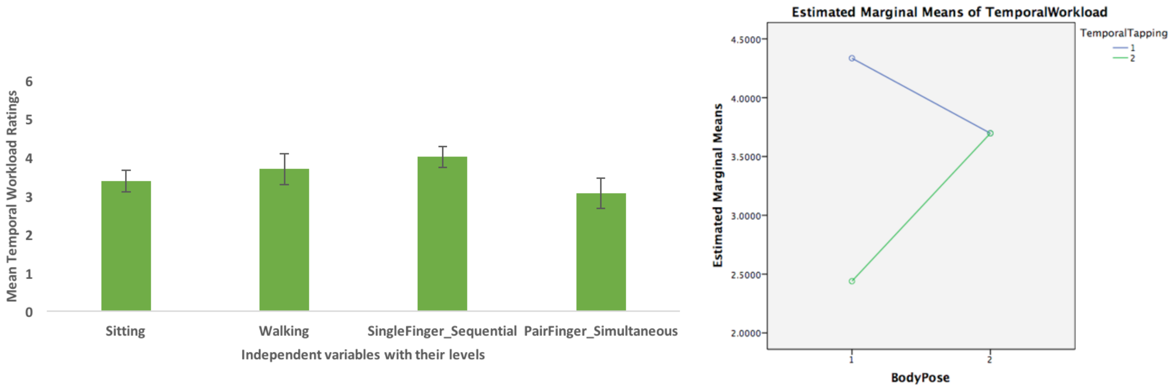


Figure 17: Mean temporal (time pressure) workload rating for independent variable, body pose and temporal tapping variables with their levels, bars shows the standard error and the interaction plot.

ANOVA result of Performance (MWR):

To compare the difference between the MWR of performance, for all of the four conditions we did a 2*2 two-way repeated measure ANOVA by taking the temporal taping (single finger sequential tapping and pair finger simultaneous tapping) and body poses (sitting and walking) as two independent variables for measuring the dependent variable MWR. We didn't find any significant difference between the temporal tapping of the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 0.125, p > 0.05, η2 = 0.008). We also did not find any significant difference between the body pose sitting and walking (F (1, 15) = 0.328, p > 0.05, η2 = 0.021). This suggests that neither the single finger sequence and pair finger simultaneous tapping nor the walking or sitting body pose, had a measurable impact on the participant performance workload experienced in the study. We also did not find the interaction effect between the temporal tapping and body pose (F (1, 15) = 3.637, p > 0.05, η2 = 0.195). From (figure 18), it will be clearer, where we showed the physical mean workload rate for each variable with their levels.

Figure 18: Mean performance workload rating for independent variable, body pose and temporal tapping variables with their levels, bars shows the standard error.

ANOVA result of Effort (MWR):

To compare the difference between the MWR of effort for all of the four conditions we did a 2*2 two-way repeated measure ANOVA by taking the temporal taping (single finger sequential tapping and pair finger simultaneous tapping) and body poses (sitting and walking) as two independent variables for measuring the dependent variable MWR. We didn't find any significant difference between the temporal tapping of the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 3.451, p > 0.05, η2 = 0.187). We also did not find any significant difference between the body pose sitting and walking (F (1, 15) = 1.565, p > 0.05, η2 = 0.094). This suggests that neither the single finger sequence and pair finger simultaneous tapping nor the walking or sitting body pose, had a measurable impact on the given effort workload experience by the participants in the study. We found the interaction effect between the temporal tapping and body pose (F (1, 15) = 6.165, p = 0.025, η2 = 0.291). Which indicates that in temporal tapping with one finger sequential given effort workload rating was higher for the walking body pose, whereas in the temporal tapping with a pair of finger simultaneous given effort workload rating was higher in sitting condition. From (figure 19), it will be clearer, where we showed the given effort mean workload rate for each variable with their levels and the interaction plot.

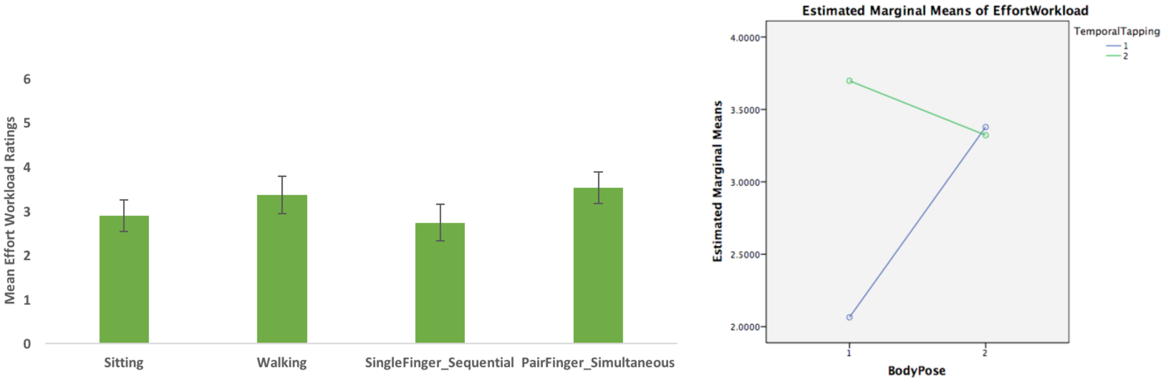


Figure 19: Mean given effort workload rating for independent variable, body pose and temporal tapping variables with their levels, bars shows the standard error and the interaction plot.

<u>ANOVA result of Frustration (MWR):</u>

To compare the difference between the MWR of frustration for the four conditions we did 2*2 two-way repeated measure ANOVA by taking the body pose (sitting and walking) and temporal taping (single finger sequential tapping and pair finger simultaneous tapping) as two independent variables to measure the dependent variable MWR. We have found a significant difference between the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 5.246, p= 0.037, η2 = 0.259). Our data also show the similar trend and indicating that, among temporal tapping, single finger sequential tapping experienced frustration mean workload was higher than pair finger simultaneous tapping. The significant effect for the body pose was also found (F (1, 15) = 11.200, p= 0.004, η2 = 0.427). We also checked the data which also show the similar trend and indicating that, among body pose, walking experienced frustration mean workload was higher than sitting. Moreover, we have found the interaction effect between the temporal tapping and body pose (F (1, 15) = 19.111, p = 0.001, η2 = 0.560). Which indicates that in temporal tapping with one finger sequential experienced frustration workload rating was higher for the walking body pose, whereas in the temporal tapping with a pair of finger simultaneous experienced frustration workload rating was higher in sitting condition. From (figure 20), it will be clearer, where we showed the experienced frustration mean workload rate for each variable with their levels and the interaction plot.

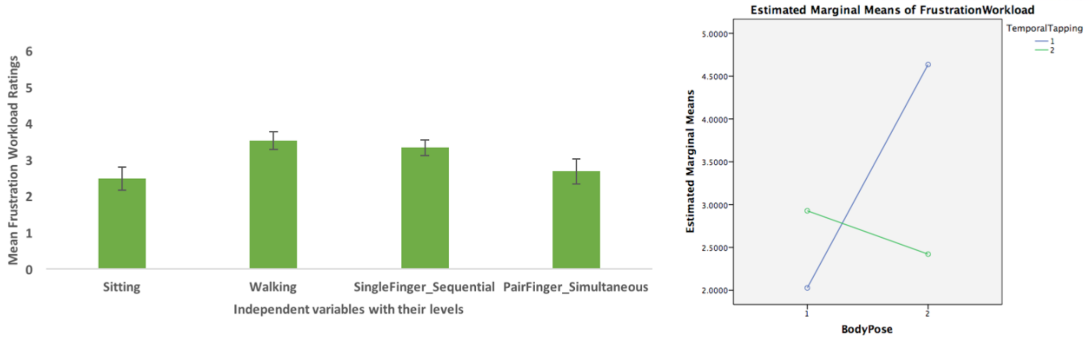


Figure 20: Mean experienced frustration workload rating for independent variable, body pose and temporal tapping variables with their levels, bars shows the standard error and the interaction plot.

ANOVA result of Overall (MWR):

To compare the difference between the overall MWR for all of the four conditions we did a 2*2 two-way repeated measure ANOVA by taking the temporal taping (single finger sequential tapping and pair finger simultaneous tapping) and body poses (sitting and walking) as two independent variables for measuring the dependent variable MWR. We didn't find any significant difference between the temporal tapping of the single finger sequential tapping and the pair finger simultaneous tapping (F (1, 15) = 1.698, p > 0.05, η2 = 0.102). We also did not find any significant difference between the body pose sitting and walking (F (1, 15) = 1.695, p > 0.05, η2 = 0.102). This suggests that neither the single finger sequence and pair finger simultaneous tapping nor the walking or sitting body pose, had a measurable impact on the participants overall workload experienced in the study. However, we have found the interaction effect between the temporal tapping and body pose (F (1, 15) = 9.788, p = 0.007, η2 = 0.395). Which indicates that in temporal tapping with one finger sequential overall workload rating was higher for the walking body pose, whereas in the temporal tapping with a pair of finger simultaneous overall workload rating was higher in sitting condition. From (figure 21), it will be clearer, where we showed the overall mean workload rate for each variable with their levels and the interaction plot.

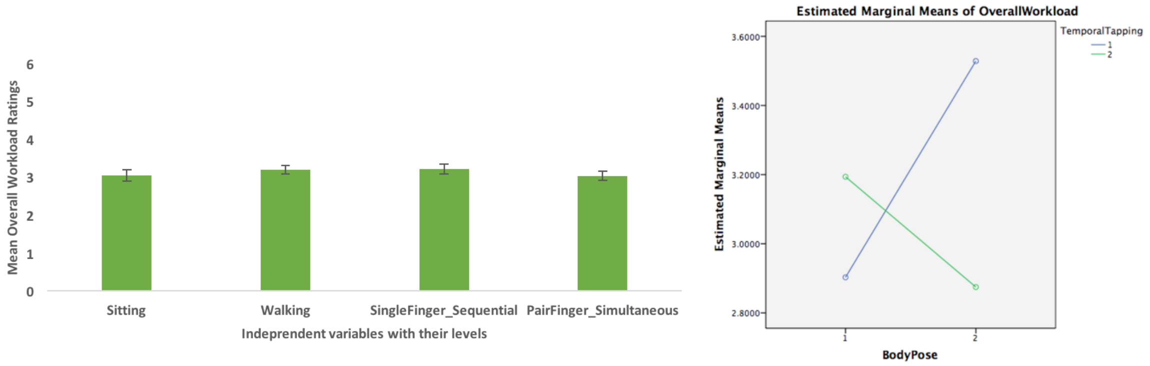


Figure 21: Mean overall workload rating for independent variable, body pose and temporal tapping variables with their levels, bars shows the standard error and the interaction plot.

Significant ANOVA result of quantitative (task completion time, error rate) and subjective measure (NASA TLX Workload) has tabulated as below (table 4).

Measure	Comparison		Outcome	
Task completion time	Temporal Tapping	F (1,15) = 11.365	p = 0.004	η2 = 0.431
	Body pose	F (1,15) = 9.484	p = 0.008	η2 = 0.387
Error rate	Body pose	F (1,15) = 13.657	p = 0.002	η2 = 0.477
	Temporal Tapping* Body pose	F (1,15) = 16.045	p = 0.001	η2 = 0.517
Temporal workload	Temporal Tapping	F (1,15) = 10.073	p = 0.006	η2 = 0.402
	Temporal Tapping* Body pose	F (1,15) = 5.608	p = 0.032	η2 = 0.272
Effort workload	Temporal Tapping* Body pose	F (1,15) = 6.165	p = 0.025	η2 = 0.291
Frustration workload	Temporal Tapping	F (1,15) = 5.246	p = 0.037	η2 = 0.259
	Body pose	F (1,15) = 11.200	p = 0.004	η2 = 0.427
	Temporal Tapping* Body pose	F (1,15) = 19.111	p = 0.001	η2 = 0.560
Overall workload	Temporal Tapping* Body pose	F (1,15) = 9.788	p = 0.007	η2 = 0.395

Table 4: Significant ANOVA results from the study.

4.4.3 Descriptive analysis

From the performance analysis, we found that, for the pair finger simultaneous temporal tapping case, as the furthest distance eight combinations and as well as all three combinations in bottom side touchpad targets have a higher error rate and slower task completion time. Here are a few examples of them in (figure 22). These types of combinations are in total 11 combinations among 36 those furthest distance, as well as bottom side touchpad combinations, are highlighted in yellow color rectangular stroke in Appendix 1. After the experiment, we asked every participant by asking, please explain your ranking- what is good about your favorite condition and combinations? And what is bad about your least favorite condition and combinations? Most of the participants reported that furthest distance and as well as any combination of bottom side oriented pair finger simultaneous tapping have a higher error rate and task completion time took longer than other combinations in both walking and sitting situations. They also reported, in the case of single finger sequential tapping case all the combinations were better at the sitting condition. Difficulties for all combinations of single finger sequential tapping increases in walking condition. Most of the participants preferred walking condition simultaneous touches rather than sequential ones. They mentioned that, as simultaneous touches are graspable that's why it was easy to perform during walking and sitting situation. Whereas in walking single finger sequential tapping, often fingers slipped off from the touch. As the fingers slipped from the touchpad because of that, target selections were difficult in single finger sequential tapping in walking condition. Overall 36 combinations v's furthest edges and bottom side 11 combinations quantitative (task completion time, error rate) characterized performance are shown in (table 5).

Conditions	Mean task time overall (36 taps)	Mean task time furthest &bottom side (11 taps)	Mean error rate overall (36 taps)	Mean errors furthest &bottom side (11 taps)
Pair sitting	1629.66ms	1795.21ms	14.25%	18.19%
Pair walking	1516.99ms	1642.18ms	14.08%	21.45%
Single-sitting	1920.67ms	1933.41ms	10.63%	11.18%
Single-walking	1629.45ms	1620.11ms	20.27%	23.36%

Table 5: Overall combinations vs furthest edges & bottom side task completion time and errors.

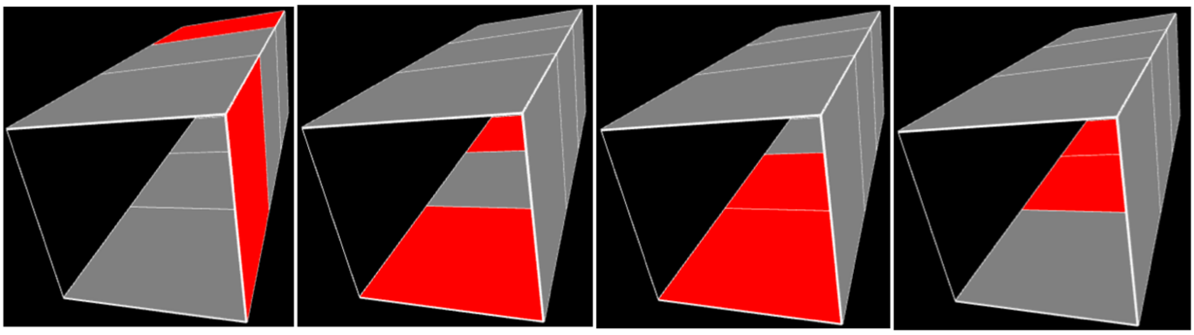


Figure 22: Examples of high error prone pair of finger simultaneous tapping.

Chapter 5:

Overall Discussion and Conclusion

5.1 Overall discussion

In terms of task completion time, our expectation was, sitting will be faster than walking and Pair finger simultaneous tapping will be faster than single finger sequential tapping. However, from the result, it seems in terms of task completion time walking was significantly faster than the sitting which did not match with our expectation, but it was an interesting finding, to support that evidence we checked the participants answer from the follow up informal questions after the study, where we asked them which conditions and combinations were more favorites/least favorite to them. They said that for walking they felt that walking has a symbolic meaning with faster action and that might help them faster task completion time in walking. On the other hand, pair finger simultaneous tapping was significantly faster than single finger sequential tapping, which matches our expectations, we thought that simultaneous tapping is graspable which will help the participants to select faster whereas single finger sequence tapping's does not support this grasping feature. In terms of error rate, we expected that, sitting will be less error-prone than walking which matches our expectations, as sitting is normally static and direct, accurate entry is therefore possible and participants will be more aware of surrounding edges of the glass, and our hypothesis was, pair finger simultaneous tapping will be less error-prone than single finger sequential tapping that also matches with our expectation but from an ANOVA analysis we found that they were not significantly different. After analyzing individual parameters of NASA TLX workload, we have found that mental, physical, performance, the effort did not have any effect on any temporal tapping's and body poses experience. In case of the parameter of temporal demand, for single finger sequential tapping mean temporal (time pressure) workload demand was higher than pair finger simultaneous tapping but body poses did not affect temporal (time pressure) workload for both of the sequential and simultaneous tapping type. In case of the parameter of frustration, the result suggests that, among temporal tapping, single finger sequential tapping experienced higher frustration mean workload than pair finger simultaneous tapping and among body pose, walking experienced higher frustration mean workload than sitting. Moreover, the overall workload had no significant difference between both independent variables body pose as (sitting, walking) and temporal tapping as (single finger sequential tapping, pair finger simultaneous tapping), which indicates that both independent variables, equally impacted the experienced workload to the participants during the study. But our expectation was, during walking for both single finger sequential and pair finger simultaneous tapping will have higher workload ratings.

5.2 Conclusion

From the result and analysis, we observed that the task completion time for the simultaneous pair taping was faster than the single tapping for both walking and sitting conditions. As the single sequential tapping always requires tapping one after another target so requires much more time. On the other hand, pair finger simultaneous tapping requires the user to tap two targets together, which reduces the movement time and make the task completion time faster. Overall in our study single finger, sequential tapping took overall 1.75 seconds whereas, pair finger simultaneous tapping took overall 1.60 seconds. Lafreniere et al. [34] did a study with smartwatch with 3by3 grid-based menu selection and their result showed one-step selection is much faster than (0.70 seconds) two-step selection (1.15 second) in sitting situation. Moreover, in GlassPass [28] authors used, sequential and simultaneous tapping on the front touchpad mounted on glass and divided the front regions into two regions and they found that pair finger sequential tapping took about 0.35 second whereas, two fingers simultaneous tapping took about 0.18 second in sitting situation, those completion times were the average of both tapping and flat fingers touch-based input. As our prototype had nine equidistance location and also it had a different finger orientation and movement especially of pair finger simultaneous tapping's which requires a longer time for target selections in eyes-free input in three sides of the touchpad. But our result follows the prior research trend that simultaneous touches were faster than sequential touches. Interestingly, the walking condition was faster compared to the sitting condition. P9 mentioned that "in the sitting body become rigid and less flexible but in the case of walking I can have much more flexibility and I know my walking rhythm and movement which makes my task completion time faster". The other reason P4 reported that "walking always makes my action quick or urgent, which also helps to finish my action faster, I think it's symbolic". The error rate for simultaneous pair taping for the sitting condition was higher than the single finger sequential tapping in sitting condition because, in sitting condition P15 reported that, "I can feel better areas for single finger tapping as it has a rhythm" but for the case of simultaneous tapping participant reported the previous same reason as the body has less flexibility and requires different combinations of finger orientation which is the reason for their higher error rate in sitting condition. Whereas, in single finger sequential tapping error rate was higher in walking than the pair finger simultaneous tapping in walking. The reason behind this is most of the participants mentioned that, as simultaneous touches are graspable, that's why it was easy to do during walking, previous research also proves the evidence [6, 7, 25, 35, 59]. Whereas, in walking a single sequential tapping slipped off the finger and target selection was difficult. Interestingly, regardless of body pose, pair finger simultaneous tapping (14.96%) was less error-prone compared to single finger sequential tapping (16.18%) even though they were not significantly different among each other. Which also follows the trend of GlassPass [28], they reported error rate for pair finger sequential tapping (about 10%) was higher than the simultaneous tapping (about 7%), those errors were the average of both finger-tip tapping and flat fingers touch-based input and sequential and simultaneous tapping were done by a pair of fingers (index and middle finger). We also want to mention that, 11 combinations (the furthest 8 and bottom side touchpad 3 adjacent combination) of pair finger-simultaneous tapping was more error-prone and longer time was taken for task completion. Which is about 5 % more different compared to overall 36 combinations characterized quantitative performance result (error rate, task completion time). As we facilitated both landOn and liftOff technique for target selection, which allows the participants in the eyes-free situation. Participants also mentioned that "I feel my performance could be worse if there were no such both landOn and liftOff input technique". Prior research reported that in a smartphone-based target selection technique, where authors only facilitated landOn technique and performance was more error-prone [42, 53]. We want to emphasize that, in smartphones/smartwatches the screen could be seen visually, but in our case, it supports the eyes free temporal tapping on the side mounted touchpad on wearable glasses. From our study it confirms, pair finger simultaneous tapping-based input was suitable, as it had a similar success rate of 85% and faster completion time in both walking and sitting conditions. Our system leverages both landOn and liftOff which allows the user to successfully and comfortably make the selections. We have customized our system in a way that it allows the users to grip on each edge spontaneously, which helped them to accurately input while they were walking. Whereas, single finger tapping based input had the highest success rate of 90% in sitting condition among all conditions which indicate that this type of interactions is feasible in sitting situation on the other hand single tapping had the least success rate of 79% which suggesting us that these type interactions are not suitable while users are in walking condition.

5.3 Limitations and future work

Along with our contribution, we had some limitations as well. Firstly, we did our whole experiment inside the lab environment for both sitting and walking conditions which is not the natural usage of wearable smart glass. If we could do that in the public space outside of the lab environment, it would be more realistic. Because of the wearable device system's compatibility, we had to use feasible lab set up to control the whole experiment process. Secondly, we had to customize our touchpad by ourselves, because there was no such wearable touchpad which could detect all 3 sides of the touches as done by us, but the potential problem of our customized prototype is reliance on capturing the shape of the finger contact region, as it is not common in current devices. But customized hardware techniques, are established in research community [e.g. (5, 28, 43, 44, 50, 51, 59)]. Thirdly, we did not consider the encumbered and standing situation because as previous research used dominant hand, non-dominant hand [42, 53]. By carrying bags or holding boxes up to the shoulder level is not suitable and participants would feel more fatigue in a mobility situation. While they are doing targeting they have no visual access also to the touchpad which means targets needed to perform as eyes free. But for the case of smartphone-based experiment, it is viable because hand needs to be lifted up to the waist level and while they are doing targeting they have visual access to the screen. In smart wearable products, the touchpad usually mounts on the right side of the glass, we have applied a similar technique here. Because of those reasons we did not do the standing and encumbrance situation. Future work should be done on an application demo, we are thinking about it for our future work about this research. First, approach to doing that would be conducting an elicitation study/workshop by allowing the participant to experience the device touch and how they interact with the touchpads. By that way we can propose and demonstrate interactive applications likewise previous work have explored [2, 21, 34, 43].

References

[1] Ahn, S., et al. (2017). Typing on a Smartwatch for Smart Glasses. Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces, ACM.

[2] Ahn, S., et al. (2018). "Evaluation of edge-based interaction on a square smartwatch." 109: 68-78.

[3] Azuma, R. T. J. P. T. and V. Environments (1997). "A survey of augmented reality." 6(4): 355-385.

[4] Bailly, G., et al. (2012). ShoeSense: a new perspective on gestural interaction and wearable applications. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[5] Chan, L., et al. (2015). Cyclops: Wearable and single-piece full-body gesture input devices. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[6] Cheng, L.-P., et al. (2013). iGrasp: grasp-based adaptive keyboard for mobile devices. Proceedings of the SIGCHI conference on human factors in computing systems, ACM.

[7] Cheng, L.-P., et al. (2013). iRotateGrasp: automatic screen rotation based on grasp of mobile devices. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[8] Chung, J. C., et al. (1989). Exploring virtual worlds with head-mounted displays. Three-Dimensional Visualization and Display Technologies, International Society for Optics and Photonics.

[9] Colaço, A. (2013). Sensor design and interaction techniques for gestural input to smart glasses and mobile devices. Proceedings of the adjunct publication of the 26th annual ACM symposium on User interface software and technology, ACM.

[10] De Luca, A., et al. (2013). Back-of-device authentication on smartphones. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[11] Desai, P. R., et al. (2014). "A review paper on oculus rift-a virtual reality headset."

[12] Deshpande, S., et al. (2013). "Google Glass." 4(12): 0-4.

[13] Dobbelstein, D., et al. (2015). Belt: An unobtrusive touch input device for head-worn displays. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[14] Dobbelstein, D., et al. (2017). The effects of mobility, encumbrance, and (non-) dominant hand on interaction with smartwatches. Proceedings of the 2017 ACM International Symposium on Wearable Computers, ACM.

[15] Dvorak, J. L. (2007). Moving wearables into the mainstream: Taming the Borg, Springer Science & Business Media.

[16] Esteves, A., et al. (2015). Orbits: Gaze interaction for smart watches using smooth pursuit eye movements. Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, ACM.

[17] Esteves, Augusto, et al. "SmoothMoves: Smooth pursuits head movements for augmented reality." Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology. ACM, 2017.

[18] Goel, M., et al. (2015). Tongue-in-Cheek: Using Wireless Signals to Enable Non-Intrusive and Flexible Facial Gestures Detection. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[19] Google, Inc. Google Glass Help: Pictures and video: Wink. 2015. url: https:// support.google.com/glass/answer/4347178?hl=en.

[20] Grossman, T., et al. (2015). Typing on glasses: adapting text entry to smart eyewear. Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services, ACM.

[21] Gugenheimer, J., et al. (2016). Facetouch: Enabling touch interaction in display fixed uis for mobile virtual reality. Proceedings of the 29th Annual Symposium on User Interface Software and Technology, ACM.

[22] Gutwin, C., et al. (2014). Faster command selection on tablets with FastTap. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[23] Haque, F., et al. (2015). Myopoint: Pointing and clicking using forearm mounted electromyography and inertial motion sensors. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[24] Harrison, C., et al. (2010). Skinput: appropriating the body as an input surface. Proceedings of the SIGCHI conference on human factors in computing systems, ACM.

[25] Hinckley, K., et al. (2016). Pre-touch sensing for mobile interaction. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM.

[26] Ishimaru, S., et al. (2014). In the blink of an eye: combining head motion and eye blink frequency for activity recognition with Google Glass. Proceedings of the 5th augmented human international conference, ACM.

[27] Ishimaru, S., et al. (2014). Shiny-an activity logging platform for Google Glass. 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, UbiComp 2014, Association for Computing Machinery, Inc.

[28] Islam, M., et al. (2018). GlassPass: Tapping Gestures to Unlock Smart Glasses. Proceedings of the 9th Augmented Human International Conference, ACM.

[29] J. Hincapié-Ramos, J. D., et al. (2014). Consumed endurance: a metric to quantify arm fatigue of mid-air interactions. Proceedings of the 32nd annual ACM conference on Human factors in computing systems, ACM.

[30] Jing, L., et al. (2013). Magic Ring: a self-contained gesture input device on finger. Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia, ACM.

[31] Kim, D., et al. (2012). Digits: freehand 3D interactions anywhere using a wrist-worn gloveless sensor. Proceedings of the 25th annual ACM symposium on User interface software and technology, ACM.

[32] Kim, J., et al. (2007). The gesture watch: A wireless contact-free gesture based wrist interface. Wearable Computers, 2007 11th IEEE International Symposium on, IEEE.

[33] Kollee, B., et al. (2014). Exploring gestural interaction in smart spaces using head mounted devices with ego-centric sensing. Proceedings of the 2nd ACM symposium on Spatial user interaction, ACM.

[34] Lafreniere, B., et al. (2016). Faster command selection on touchscreen watches. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM.

[35] Le, H. V., et al. (2018). InfiniTouch: Finger-Aware Interaction on Fully Touch Sensitive Smartphones. The 31st Annual ACM Symposium on User Interface Software and Technology, ACM.

[36] Li, Y., et al. (2018). Self-Powered Gesture Recognition with Ambient Light. The 31st Annual ACM Symposium on User Interface Software and Technology, ACM.

[37] Lucero, A. and A. Vetek (2014). NotifEye: using interactive glasses to deal with notifications while walking in public. Proceedings of the 11th Conference on Advances in Computer Entertainment Technology, ACM.

[38] Lv, Z., et al. (2015). "Touch-less interactive augmented reality game on vision-based wearable device." 19(3-4): 551-567.

[39] Lyons, K., et al. (2004). Augmenting conversations using dual-purpose speech. Proceedings of the 17th annual ACM symposium on User interface software and technology, ACM.

[40] Lyons, K., et al. (2004). Twiddler typing: one-handed chording text entry for mobile phones. Proceedings of the SIGCHI conference on Human factors in computing systems, ACM.
Martins, T., et al. (2008).

[41] Gauntlet: a wearable interface for ubiquitous gaming. Proceedings of the 10th international conference on Human computer interaction with mobile devices and services, ACM.

[42] Ng, A., et al. (2014). Investigating the effects of encumbrance on one-and two-handed interactions with mobile devices. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[43] Oakley, I. and D. Lee (2014). Interaction on the edge: offset sensing for small devices. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[44] Oakley, I., et al. (2015). Beats: Tapping gestures for smart watches. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[45] Oakley, I., et al. (2016). The flat finger: Exploring area touches on smartwatches. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM.

[46] Oakley, I., et al. (2018). The Personal Identification Chord: A Four Button Authentication System for Smartwatches. Proceedings of the 2018 on Asia Conference on Computer and Communications Security, ACM.

[47] Park, T., et al. (2011). E-gesture: a collaborative architecture for energy-efficient gesture recognition with hand-worn sensor and mobile devices. Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems, ACM.

[48] Peng, G., et al. (2015). Poster: A continuous and noninvasive user authentication system for google glass. Proceedings of the 13th Annual International Conference on Mobile Systems, Applications, and Services, ACM

[49] Profita, H. P., et al. (2013). Don't mind me touching my wrist: a case study of interacting with on-body technology in public. Proceedings of the 2013 International Symposium on Wearable Computers, ACM.89–96.

[50] Rogers, S., et al. (2011). AnglePose: robust, precise capacitive touch tracking via 3d orientation estimation. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[51] Roudaut, A., et al. (2009). MicroRolls: expanding touch-screen input vocabulary by distinguishing rolls vs. slides of the thumb. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[52] Rzayev, R., et al. (2018). Reading on Smart Glasses: The Effect of Text Position, Presentation Type and Walking. Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, ACM.

[53] Schildbach, B. and E. Rukzio (2010). Investigating selection and reading performance on a mobile phone while walking. Proceedings of the 12th international conference on Human computer interaction with mobile devices and services, ACM.

[54] Schuchert, T., et al. (2012). Sensing visual attention using an interactive bidirectional HMD. Proceedings of the 4th Workshop on Eye Gaze in Intelligent Human Machine Interaction, ACM.

[55] Serrano, M., et al. (2014). Exploring the use of hand-to-face input for interacting with head-worn displays. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[56] Sridhar, S., et al. (2015). Investigating the dexterity of multi-finger input for mid-air text entry. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[57] Starner, T. J. I. P. C. (2013). "Project glass: An extension of the self." (2): 14-16.

[58] Sutherland, I. E. (1968). A head-mounted three-dimensional display. Proceedings of the December 9-11, 1968, fall joint computer conference, part I, ACM.

[59] Taylor, B. T. and V. M. Bove Jr (2009). Graspables: grasp-recognition as a user interface. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM.

[60] Toyama, T., et al. (2014). A mixed reality head-mounted text translation system using eye gaze input. Proceedings of the 19th international conference on Intelligent User Interfaces, ACM.

[61] Tung, Y.-C., et al. (2015). User-defined game input for smart glasses in public space. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[62] Wang, C.-Y., et al. (2015). PalmType: Using palms as keyboards for smart glasses. Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services, ACM.

[63] Weigel, M., et al. (2015). Iskin: flexible, stretchable and visually customizable on-body touch sensors for mobile computing. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[64] Withana, A., et al. (2015). zsense: Enabling shallow depth gesture recognition for greater input expressivity on smart wearables. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

[65] Yeo, H.-S., et al. (2016). WatchMI: pressure touch, twist and pan gesture input on unmodified smartwatches. Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services, ACM.

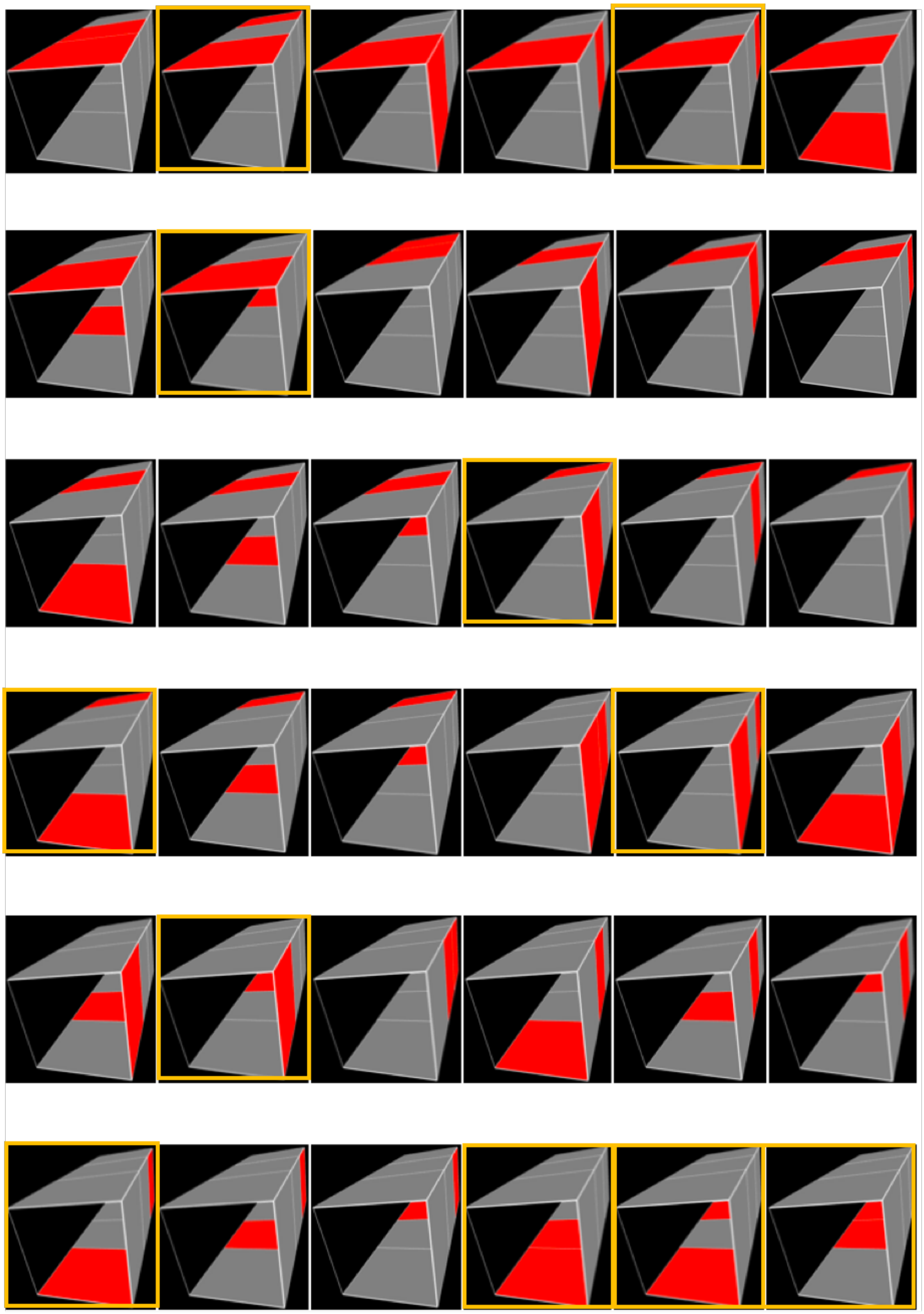
[66] Yoon, S. H., et al. (2015). TIMMi: Finger-worn Textile Input Device with Multimodal Sensing in Mobile Interaction. Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction, ACM.

[67] Yu, C., et al. (2016). One-dimensional handwriting: inputting letters and words on smart glasses. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM.

[68] Zheng, X. S., et al. (2015). Eye-wearable technology for machine maintenance: Effects of display position and hands-free operation. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM.

Appendix

1 Study Combinations and Yellow Highlighted Furthest Pairs



2 Study Instruction

Thank you for agreeing to complete this study. It will take around **45-60 minutes** to finish.

Please ask the experimenter if you need help in understanding how to interpret any instruction in this study.

You will be **tapping on the top, front and right sides of a touch input sensor mounted on right side of a pair of smart glasses**. You can use **any combination of your fingers and thumb** on your right hand. The study is concerned with **both speed and accuracy** – please try to complete all tasks **rapidly but also correctly**. There are total of **four conditions** and you will receive specific instructions for each. Between conditions there will be a short 3-minute break. You can also take a break between individual trials in the study at any time you wish.

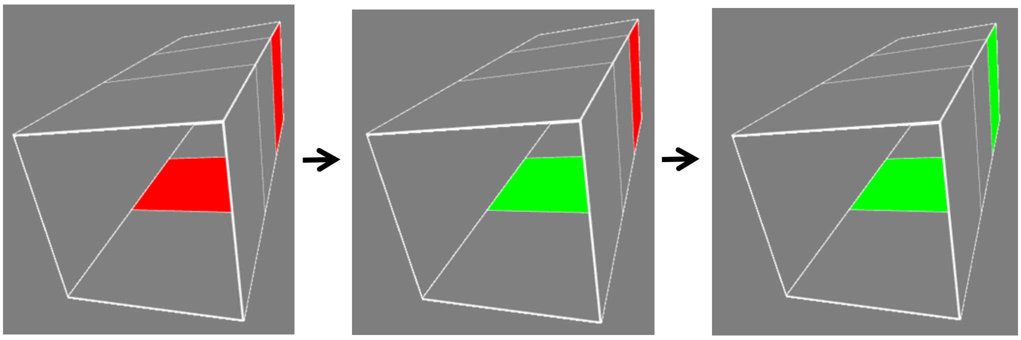
Equipment you will wear in this study includes a pair of smart glasses fitted with a custom touch sensor and a light backpack containing equipment to operate these devices.

Each condition will study will start with a written instruction to tap the touch input sensor to begin. Each trial is also started by a tap**,** followed by instructions to touch two specific regions on the touch sensor. At the end of each trial, you will receive **feedback** as to whether or not you **tapped the correct areas**. After finishing all the trials in a condition, you will see a message informing you the study condition is complete.

2.2 Single sequential tapping in sitting

Sit on the chair and place your **elbow on the desk** so that **your right hand can comfortably reach the touch input sensor on the smart glasses.** Adjust the chair height to achieve a comfortable posture. Then begin the condition.

In each trial, **two target areas** will be shown on the smart glasses in a 3D view. They are initially **red.** If you touch either of them, it will become **green.** You need **select both targets** to complete the trial, but can do so in **whatever order and with whatever combination of fingers you want**. You can also **move your fingers backwards and forwards along the sides of the device** to refine a selection and **lift your finger when over the correct target**. **Releasing your finger** when **not over a target** will result in an **error**. There is an example below.



Two
targets

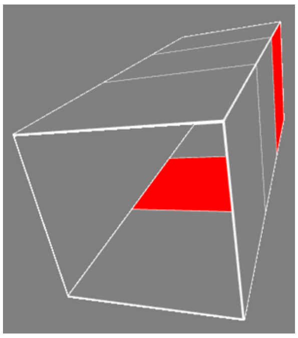
First target
selected

Second target selected

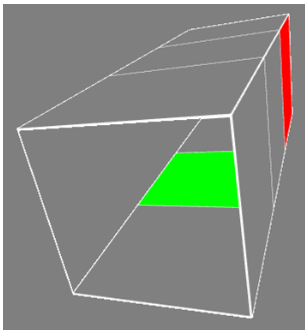
2.2 Single sequential tapping in walking

During this condition, you should try to **walk at your normal walking speed** around the study environment (clockwise)– specifically, a repeating route around a large table. While you do this, you should keep **your right hand raised so it can comfortably reach the touch input sensor on the smart glasses.** Begin the condition after you have begun walking.

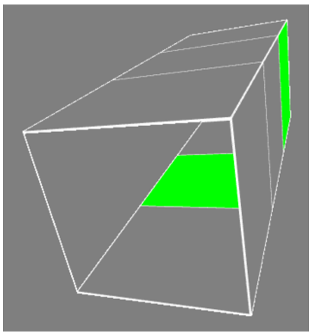
In each trial, **two target areas** will be shown on the smart glasses in a 3D view. They are initially **red.** If you touch either of them, it will become **green.** You need **select both targets** to complete the trial, but can do so in **whatever order and with whatever combination of fingers you want**. You can also **move your fingers backwards and forwards along the sides of the device** to refine a selection and **lift your finger when over the correct target**. **Releasing your finger** when **not over a target** will result in an **error**. There is an example below.



Two
targets



First target
selected

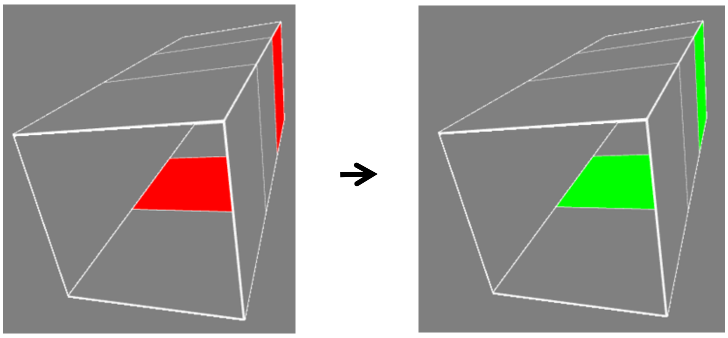


Second target selected

2.3 Pair simultaneous tapping in sitting

Sit on the chair and place your **elbow on the desk** so that **your right hand can comfortably reach the touch input sensor on the smart glasses.** Adjust the chair height to achieve a comfortable posture. Then begin the condition.

In each trial, **two target areas** will be shown on the smart glasses in a 3D view. They are initially **red.** If you touch either of them, it will become **green.** You need **select both targets** to complete the trial and **must do so simultaneously** – touches to the targets must be **by different fingers** and must **overlap in time**. You can use **any combination of fingers and thumb** on your right hand. During a touch you can **move your finger(s) forwards and backwards to make adjustments to your selection** as needed – the trial will be complete when **both fingers are lifted from the sensor**. **Releasing your finger** when **not over a target,** or **failing to overlap your selections**, will result in an **error**. There is an example below.



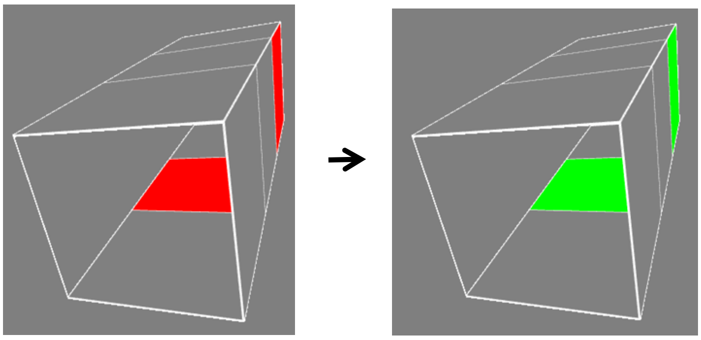
Two
targets

Both targets
selected

2.4 Pair simultaneous tapping in walking

During this condition, you should try to **walk at your normal walking speed** around the study environment (clockwise) – specifically, a repeating route around a large table. While you do this, you should keep **your right hand raised so it can comfortably reach the touch input sensor on the smart glasses.** Begin the condition after you have begun walking.

In each trial, **two target areas** will be shown on the smart glasses in a 3D view. They are initially **red.** If you touch either of them, it will become **green.** You need **select both targets** to complete the trial and **must do so simultaneously** – touches to the targets must be **by different fingers** and must **overlap in time**. You can use **any combination of fingers and thumb** on your right hand. During a touch you can **move your finger(s) forwards and backwards to make adjustments to your selection** as needed – the trial will be complete when **both fingers are lifted from the sensor**. **Releasing your finger** when **not over a target,** or **failing to overlap your selections**, will result in an **error**. There is an example below.



Two targets

Both targets selected

3 Demographics

Participant Number:

Age _______

Gender Male / Female

Nationality ____________________

Level of Education ____________________
(e.g. school, college, graduate or higher)

On a scale from never-used-before (1) to daily-use (5), rate your experience with:

Computers ____________________ (favorite)

Touch screens ____________________

Smart phones ____________________

Smart watches ____________________

Smart glasses ____________________

Other wearable devices ____________________ (least favorite)

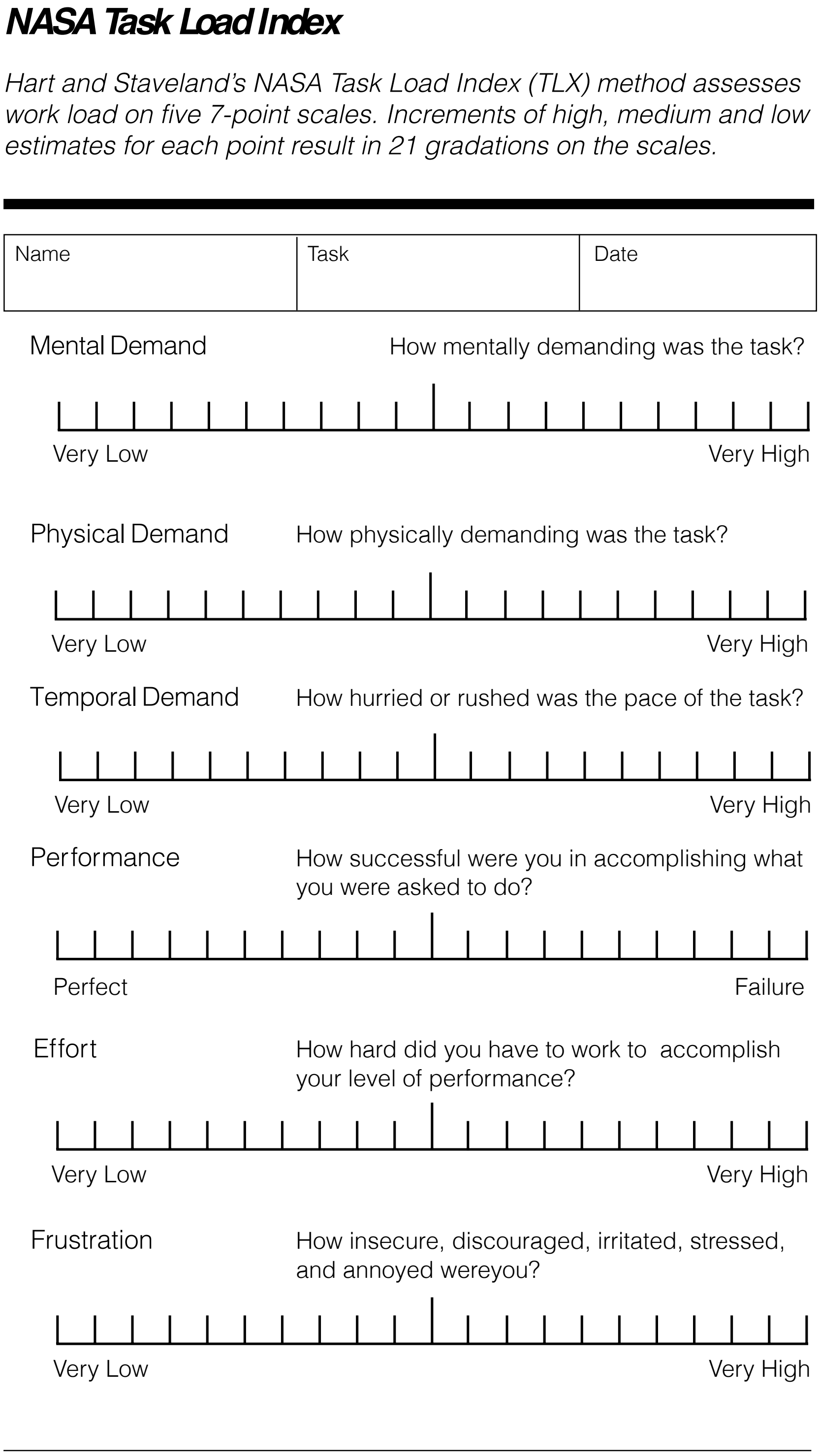
Please explain your ranking- what is good about your favorite condition and combinations?

____

What is bad about your least favorite condition and combinations?

____

4 Workload NASA TLX



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High