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Target Selection on Hand Held Tablets

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Abstract

The use of mobile devices has been increasing and besides mobile phones, other devices have strongly established themselves in the market, that is the case of tablets. Although tablets might seem similar to modern-day smart phones the truth is that both kind of devices have differences that make their users interact with them in different ways. For instance, the size of a tablet is larger than that of a smart phone and that leads to differences in the grasp, that for a tablet results better to hold it with both hands.

As a result of this two-handed grip, it is only possible to operate the device with the thumbs. Although there is already some body of work that has studied the target selection times with tablets using this kind of grip, nothing has been researched so far about a distinction and influence of the angle of approach to such targets. We believe that the biomechanical configuration of the hand leads to differences in the selection times when moving the thumb since it can be observed that the thumb trajectory does not have the same difficulty in all its points.

We have designed an experiment that evaluates the thumb selection times for different angles on a tablet that is grasped with both hands in landscape mode. Our target was to determine if there are differences in the time to reach a target between different angles of approach. Finding these differences would help to define a proper model that describes such behavior and also understand for which conditions of angle and amplitude it is easier or more difficult for users to interact with these touch screen devices. We also analyzed if the direction of the trajectory followed by the thumb had an influence and could determine which areas and movements of the thumb correspond with fewer errors and fastest times during target acquisition.

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1 Introduction

Modern computing devices, such as smart phones and tablets, have enabled the users to interact in a different and more direct way than the traditional devices. Taking for example the interaction with a personal computer, where the user interacts in an indirect way through the use of the keyboard and mouse to trigger a response on the screen. In contrast, a tablet allows the user to interact directly with the items displayed on the screen.

However, these devices are designed to be portable and their manipulation must be paralleled with its grasping leaving only some of the fingers free and also limiting the movement according to the selected grasping technique.

Motivation

The use of mobile computing devices has been increasing and the most common of these devices is the mobile phone, but tablets are being used more every day. Although both types of devices look similar, the way we interact with them tends to be different, that is why the studies related to improve the experience of mobile phones can not be directly applied to tablets. It is very common to hold a tablet with both hands in landscape mode, but this grip limits our capacity to reach certain areas of the screen at the same time, this influences our performance in the areas within our reach. Unfortunately there are no studies that cover the topic of how to appropriately model selection times of these reachable areas, although attempts to do it have been published for other types of devices. Finding such a model might improve the design of interfaces and the location of elements for a better experience for the users.

State-of-the-art

There has already been some research about the ways to grasp a mobile device and that varies according to the device, for instance grips for mobile phones might not be applicable to larger devices such as tablets. That is the case of the studies presented by Azenkot and Zhai [AZ12], Park et al. [PHPC08] or Parhi et al. [PKB06] that focused on smaller devices like mobile phones or PDAs.

Other studies have tried to describe the most efficient way to grasp a tablet in terms of area of interaction and movement time. For instance, Odell and Chandrasekaran [OC12] evaluated two main grips while Oulasvirta et al. [ORL+13] expanded their grip evaluation to 6 different styles having all in common that the thumbs are the digits used to interact with the device's screen.

Since the thumb, plays an important role in touch screen interactions regardless of device size it has also been subject of research. Previous publications have tried to describe the regions more accessible to the thumb in terms of accuracy and speed, that was the case of Perry and Hourcade [PH08], Karlson and Bederson [KB07], Roudaut et al. [RHL08] and Park et al. [PHPC08] who described regions of small devices' screens where participants were more accurate and regions where they were faster. That is the case of the bottom region of the devices used and the regions located far from the thumb extent.

Odell and Chandrasekaran [OC12] also measured the reachable areas of the thumb, but on tablets finding the centre of the device as impossible to reach and that movements that require thumb flexion are not comfortable to perform. Regarding the grip, they found that the thumb covered a larger area when using side grip than when using the corner grip, which is consistent to what Oulasvirta et al. [ORL+13] stated.

Given that not all areas of a device's screen are accessible, there are also propositions that try to solve this issue. One of these proposed methods is ThumbSpace presented by Karlson and Bederson [KB07], their idea was to provide access to all regions of the screen, even the ones far away from the thumb. Potter et al. [PWS88] presented the concept of dragging technique designed to provide better accuracy in selection tasks. Roudaut et al. [RHL08] designed two other techniques TapTap and MagStick, both designed for better accuracy. These studies have all proposed a new technique and evaluated it against others, and they all concluded that the fastest technique is direct touch, although is also very error prone.

Similarly to the interaction techniques, there have also been attempts to model the time required for the selection tasks, a common procedure is to use Fitts' [Fit54] law. Soukoreff and MacKenzie [SM04] recommend to use the Shannon formulation of the law to calculate the Index of Difficulty (ID) for pointing tasks, but when they [SM12] used it, they found that it does not apply well for key repetitions. Similarly, when Murata [Mur96] applied Fitts' law to evaluate mouse input, he concluded that a multiple regression model predicted the performance in a better way for pointing tasks. Other attempts to adapt Fitts' model to specific needs have been published, like MacKenzie and Buxton [MB92] did to extend the model from 1 dimensional tasks to 2 dimensions, or the refinement proposed by Bi et al. [BLZ13] called FFits' law to model finger input on a smart phone, and the one proposed by Bützler et al. [BVJS12] to be used on a tabletop touch screen device.

Research Gap and Method

Although there exist publications about touch screen interactions, these studies have focused on mobile phones that have smaller screens than tablets and allow interaction with thumbs and other fingers which can not be used with a tablet. There have been also some studies that work with larger devices, but those evaluate the interaction while the user is not holding the device and the studies that cover two-hand grasp tablets have focused in determining the proper way to hold it to have a major area of interaction or higher speed with tapping tasks. Also, there are publications that have introduced refinements to the existing model hinting that it is not well suitable for all selection tasks, however there are no publications that tried to find a modeling technique that takes into account thumb input, grasping a device and thumb movement and flexion, since all attempts to refine the existing Fitts' model work on either different devices (mobile phones, table top) or input techniques (computer mouse).

Our study focuses in evaluating speed and accuracy of tapping tasks on a tablet while it is held by both hands by considering specific angles where the targets appear. Our intention is to find a model that correctly describes the selection time when the thumb has to move, flex and extend for common tapping tasks taking into consideration the angles where the targets are located. Furthermore, we also analyzed the influence of the direction of the movement, that is the trajectory followed by the thumb to cover those angles in order to reach the targets.

We thought that, under these conditions, the angle between starting position and target plays an important role in the calculation of the selection time, since there are regions of the screen that are more easily accessible than others, therefore a selection task would be affected by the angle where the target is located in relation with the initial position. Additionally, we also thought that not only the angle may have an influence on selection tasks, but also the direction followed by the thumb to reach the targets which in turn also affects the accuracy and speed of the tasks.

We designed an experiment to gather data from different participants relative to their tapping times while holding a tablet device in landscape mode with both hands. We have included three target sizes and five angles to test the movement of the thumb as well as four amplitudes that tested its flexion and extension. Regarding the idea of the direction followed by the thumb we also designed an experiment that takes into consideration 4 angles in 2 different directions, either pointing towards the center of the screen or pointing towards the edge of the device.

Outcome and Contribution

We intended to analyze target acquisition tasks with the thumbs with the idea of finding differences in the selection times between the angles of approach evaluated in the experiment and based on those differences be able to provide a model that accurately represents the selection times needed for these targets as well as identify the regions, based on our angles, that are more error prone or provide ease of access.

On the other hand, the intention of the experiment that tests the direction followed by the thumb is to identify if there exists any influence derived from the direction of the movement when selecting targets on a touch screen device. Taking the biomechanics of the thumb as a base, we expect certain trajectories to give a better accuracy and speed than others, since the basic movements of the thumb (flexion, abduction, etc.) represent different difficulties depending on the angle where the targets are located.

We have used Fitts' model as a base to define the difficulty of our tasks, thanks to its definition of Index of Difficulty (ID) and since previous works have already expressed a need for a refinement of the model according to their specific circumstances, we wanted to determine how accurate Fitts' model is in regards of the angles used during our thumb tapping task. Once we analyzed our data, we found that, in general, Fitts' model provided a good fit for our method of thumb tapping with two-hand grasp of a tablet. However, we also observed that, although the existing model can still be applied to calculate the selection times, there exist differences between the angles and directions when analyzed separately. We have concluded therefore, that the angles of approach to the target as well as the direction of the movement followed by the thumb really influence the time and error rates of selection tasks since we found specific angles that had a significant better performance than others and we could identify trajectories that also performed significantly better than others.

Outline of the Thesis

This document is organized in chapters that cover all aspects of the process followed to design and apply the experiment as well as the findings derived from the analysis of the gathered data.

Chapter 2 provides an overview of the publications that we reviewed and found useful because of the relation they have with this work. Every publication covers different topics, therefore we have divided the chapter into sections that explain a particular topic.

In chapter 3 there is a detailed explanation of an experiment on the effect that the angles have on selection tasks. The chapter is also divided into sections according to the phases of the experiment starting with its design, followed by a description of the volunteers that took part in the experiment; there is also a description of the apparatus used, the instructions given to the participants as well as the results obtained. Finally, we have also included a discussion based on our results.

Chapter 4 describes a second experiment conducted to research the effect of the direction of the trajectory taken by the thumb during target selection tasks. The description of this experiment is also organized into sections that cover its design, the characteristics of the participants, the apparatus used and the results derived from the experiment. At the end of this chapter we have included a discussion based on the results.

The last chapter presents a general conclusion that includes our interpretation of the results obtained from both experiments and our suggestions on how to apply the acquired knowledge. Furthermore, we mention future projects that could be useful to better understand these type of interactions.

2 Related Work

A large body of work has investigated target selection on hand held devices. These works focus on different topics such as how the device is held that varies according to the type of device, whether a tablet or a cell phone (or even others like PDAs). Besides being affected by the type of device, the grasping itself affects the operation of it, since in some cases, the interaction might seem more efficient with the thumb, while for a different grasp an index finger tapping might be more suitable. Therefore, another aspect is the area that a user can cover with his hand when using the device. Finally, derived from the reachable area there are techniques developed to help reaching those difficult areas.

We reviewed the existing publications related to these topics to have a better understanding of them and realize what conditions are actually applicable to this project. Our results are exposed in this chapter and we have decided to divide them according to the main idea presented in the findings of each particular publication.

2.1 Grip

An important aspect to consider is the grip to be used. The grip for hand held devices can vary according to the device used, since some grips might not be suitable for every kind of device.

In the case of smaller devices such as mobile phones the grip might be interleaved between one-handed or two-handed operation, that is the case of the study presented by Azenkot and Zhai [AZ12] in which they asked the participants to perform tasks using one thumb, two thumbs and one index finger. The grip postures defined for their experiment were one-hand and two-hand grips. Similarly, a study published by Park et al. [PHPC08] uses one or two hands for the interaction with a small mobile device, but they have the restriction of using, in either case, one thumb only. This grip was also followed by Parhi et al. [PKB06] where they evaluated one handed thumb interaction under standing and walking situations.

Odell and Chandrasekaran [OC12] designed an experiment on tablets, they considered two major grips, the corner grip where the tablet's bottom corner is touched with the palm of the hand, and a side grip where the palm supports the device by its side instead of its corner. This same logic was applied by Oulasvirta et al. [ORL+13] who examined different grips according to the touch area of a tablet's bottom corner on the palm of the hand, they decided to use the corner grip because it showed the lowest movement times on their study, but it covers the smallest region of all the grips analyzed by them.

2.2 Reachable Area by the Thumb

The decision on the grasp of the device affects the area to interact with, which means that, depending on the grasp selected, the user will have different digits (either thumb or fingers) to interact. Each selection will have an impact on the maximum area that can be covered with the respective digit as well as the precision and ease to perform selection tasks.

Perry and Hourcade [PH08] studied target sizes and positions for one handed thumb tapping. They have found that participants were more accurate with targets on the edge of the screen, but were quicker with the targets in the middle of the screen; overall their participants did not have good accuracy with targets located at the bottom of the screen. Similarly, Karlson and Bederson [KB07] found that users are more accurate when hitting near targets. All these conclusions are similar to what Roudaut et al. [RHL08] state about areas farthest from the thumb extent being more difficult to reach; however they also mention that the borders are hard to reach without mentioning any particular border as being more difficult than the others. Park et al. [PHPC08] also applied an experiment for one handed thumb tapping and their results also confirm that accuracy decreases when targets are at the bottom of the screen especially the ones located directly below the thumb. These results are similar to what Avrahami [Avr15] reported in his study, where he found that targets on the edge of a screen have a negative impact on selection times than the targets located in either the centre of the screen or separated of the edge for a certain offset.

On the other side, Odell and Chandrasekaran [OC12] measured the areas reachable by the thumb on a tablet instead of a mobile phone or PDA. Since a tablet has a larger screen it is common to hold it with both hands leaving only the thumbs to interact with it, but it is large enough so the thumbs can not cover areas in the centre of it. They have thus compared the reachable areas for both, corner grip and side grip and according to their participants the regions that require thumb flexion are not comfortable and concluded that the thumb reach is larger in the side grip. This conclusion is in line with what Oulasvirta et al. [ORL+13] found for the corner grip where they state it has the smallest active region of all the 6 grips they evaluated.

2.3 Interaction Technique

Given that the whole screen space is not easily reachable, some techniques have been proposed to address this issue and cover a region as big as possible. Karlson and Bederson [KB07] identified direct touch as the direct screen interaction with a pen or finger which is common for tablet or mobile devices; having in mind the problem of reaching far targets with a one-handed grasp they introduced the concept of ThumbSpace that attempts to represent the screen of the device in a smaller region defined by the user according to his/her thumb reach. They found that users are more accurate and faster selecting near targets with a direct touch than with ThumbSpace, but on the other hand they are more accurate with far targets when using ThumbSpace.

Potter et al. [PWS88] introduced the concept of a dragging technique that allows users to adjust their initial touch until they get the desired position, this technique follows a take-off strategy that consists on validating the selection until the user lifts his/her finger from the screen. Their approach used a cursor above the finger to let users know what the selection would be when they lift the finger. They found that the take off strategy had lower error rates when compared to direct touch, but it was slower. Sears and Shneiderman [SS91] also took this technique and used it to compare it against a computer mouse, they found that take-off can be even faster than the mouse and have a similar error rate for targets as small as 4 pixels.

Roudaut et al. [RHL08] also tested and compared ThumbSpace and the take-off strategy, but they also introduced two techniques known as TapTap and MagStick. TapTap utilizes a first thumb tapping action to magnify an area of the screen and a second tap would actually select the desired target. MagStick is a tap and dragging technique that requires the user to tap and then drag the thumb away from the intended target while a cursor shows and moves in the opposite direction towards the target. After the experiment they found that, overall direct touch still is the fastest pointing technique (ThumbSpace was the slowest one), but is also the most error prone (while TapTap was the most accurate technique).

2.4 Modelling Technique

Fitts [Fit54] published a study in which he modelled the time required to move to a specific target using the concepts of the distance from the starting position to such target and the size of the target. This model has been used in other studies as a predictive model of the movement time when using pointing devices. Soukoreff and MacKenzie [SM04] recommend to use it when evaluating pointing devices and calculate the Index of Difficulty (ID) according to the Shannon formulation of the law (Eq. 2.1) and used it during and experiment [SM12] to model key repeat time finding that Fitts' law does not apply when repeating key presses.

(2.1) $$ID = log_2(\frac{D}{W} + 1)$$

This use of Shannon formulation of Fitts' law is also used by MacKenzie and Buxton [MB92] where they also explain that with circular or squared targets the original 1D Fitts' law can also be applied to 2 dimensional tasks. Since they tried to find a suitable 2D model of the law they presented different interpretations of target width (Eq. 2.2). This same formulation is used again by MacKenzie et al. [MKS01] as part of the accuracy measures presented in their publication, and was used again by MacKenzie and Jusoh [MJ01].

$$W \text{ (common use)}$$
$$W + H$$
$$W * H \quad (2.2)$$
$$min(W, H)$$
$$W' \text{ (width along line of approach)}$$

Nancel et al. [NCP$^+$13] also used Fitts' law to model pointing on large displays with hand held devices, while Murata [Mur96] used Fitts' law to evaluate the performance of a computer mouse together with other models and compared the results. He determined that a multiple regression model (See Eq. 2.3) was better to predict the performance of a pointing task and that Eq. 2.4 could be used to calculate better target sizes.

$$pt = a + b * d + c(1/s - 1.0) \quad (2.3)$$

$$s = \sqrt{W * H} \quad (2.4)$$

An attempt to model finger input on a smart phone with Fitts' law was made by Bi et al. [BLZ13], they developed the FFits model taking into consideration that the finger is less precise than a mouse or a pen, which greatly impacts the accuracy when targets are small. According to them, tapping on small targets can be modelled accurately with FFits model and it converges to Fitts model for larger targets.

Bützler et al. [BVJS12] also presented a refined model based on Fitts' that was tested using a tabletop touch screen device and compared their model with other existing models. They state that their model predicts movement time better than the other models.

2.5 Summary

There exist different grips for the hand held devices and those vary according to the type of device, for instance the size of a tablet would not allow a single hand grip and the two hand grasp in landscape mode has been regarded as common among the users. Besides, the variant of side grip offers a bigger area of interaction than the corner grip. However, having more area for interaction does not imply that all of it will be easily accessible as it has been already stated in previous works that regions particularly near the borders of the screen are harder to reach.

The difficulty to reach certain areas of the screen of the devices has led to the development and assessment of techniques that help overcome this problem. Nevertheless, when these techniques have been compared with direct touch, they do not have better selection times, although some of them can have a higher performance in regards of error rate.

In order to evaluate the pointing techniques Fitts' model has been widely used. But, there are some publications that suggest that the model might not be suitable for all situations, that is the case of its initial publication as a 1 dimensional model, while computer interaction requires 2 dimensional tasks. Additionally, there exists also the problem of finger precision, that is less accurate than other input methods.

In conclusion, although there are publications about touch screen, hand held devices, these are divided in either tablets or smaller devices, such as cell phones. Most of the current literature focuses on smart phones and smaller devices and there are less publications about tablets. Regarding tablets, there have been works that try to discover what would the best grip be and describe the area of interaction that such grip offers, and although there are publications about modelling techniques that overcome the reachability problems, these have also focused on devices smaller than tablets or larger ones not intended to be operated while the user holds them.

Despite some variations of Fitts' law have been suggested, there has been so far no publication that covers a model that predicts the movement time for target acquisition on tablets that are held by the user while he/she operates it with the thumbs.

3 Influence of Angles in Tapping Tasks

The focus of this research is to prove that the angle between a starting position and the target plays an important role in the selection time when thumb tapping such target while grasping a tablet with both hands. To prove this hypothesis we designed and applied an experiment to acquire and analyze the resulting data.

We designed our experiment to have 3 target sizes of 7, 14 and 28 mm. We have chosen 4 amplitudes of 20, 40, 60 and 80 mm. We selected 5 different angles with a 45° spacing between each other (See Fig. 3.2). These conditions allow us to test the two-hands grip covering a wide enough area for each thumb and puts to test its movement, flexion and extension.

We recruited 20 right handed volunteers to take part in the experiment and for each participant, all combinations of amplitude*width*angle as well as the initial hand (either left or right) were fully randomized. We took measures to balance, however the use of the hands and ensure that half of the participants started with their right hand and the other half started with their left hand, and also limited the range of their thumb length according to previous works.

The experiment took place in a close environment to avoid distractions and we used a 13 inches Android tablet with an application that displayed each condition randomly and logged information about elapsed time and missing and correct tapping actions into separate files per participant, we also prepared the tablet to have some guides on its back to help ensure the same grip for all participants.

Additionally, we collected demographic information for each participant regarding their use of touch screen devices, thumb length, age and occupation. We have also applied the NASA-TLX questionnaire to evaluate the users' perception of the experiment's task with both hands.

This chapter describes in detail the process followed to design the experiment that was applied as part of this project to gather the required information for further analysis. The description is presented in different sections as follows:

Design: General description of the experiment.

Participants: Criteria to select the individuals who took part in the experiment.

Apparatus: Equipment used to apply the study.

Procedure: Description of how the study was conducted.

Results: Analysis of the data obtained from the experiment.

3.1 Design

The hypothesis tested during this work required a way to relate target selection times with target width, amplitude and angle of approach. Therefore it was necessary to define a range of all these elements for the purpose of combining them in order to get a wide range of conditions that could be tested and compared.

Background Information

Fitts' law has been used in previous works in order to evaluate and test performance for pointing tasks [MB92, BLZ13, PKB06, SM04, DKM99, KB07] for either specific pointing techniques or devices. Following this reasoning the experiment presented as part of this work takes into consideration the notions of target width (W) and amplitude (A) that form part of the index of difficulty (ID) used in the Shannon's formulation of Fitts' law [MB92, SM04]. Given that this type of analysis requires the usage of many IDs in order to provide enough confidence in the resulting models [SM04], we decided to use more than one width and amplitude.

Target Width

After researching the related literature we found that three [WMA08, WH14, PHPC08, BLZ13, STKB12, DKM99, MJ01] to four [Fit54, CH04, MMRM02, PH08, MB92] different values for W are commonly selected and are usually combined with three or four different amplitudes. Hence the total number of possible combinations would range then from 9 to 16 conditions that consider all Ws and As. However, it should be noted that even from the original Fitts' experiment [Fit54, SM04] a large number of $W * A$ combinations not necessarily means an equally large number of ID values.

Even though it is advisable to use a large range of ID values, according to Soukoreff and MacKenzie [SM04] the range between 2 to 8 bits will suffice for most cases. For almost all cases presented in the current literature the amount of ID values tested is smaller than that of all possible combinations of A/W. Wobbrock et al. [WMA08] used 9 different combinations, but only 6 ID values; even the original experiment of Fitts [Fit54] considered up to 16 conditions that only accounted for 7 IDs (when applying the Shannon formulation), we found similar cases in the experiments published by Bi et al. [BLZ13], Shoemaker et al. [STKB12] and Douglas et al. [DKM99] where the number of combinations exceeds that of the ID values. This can be achieved by selecting W and A values in a way that the next value multiplies the previous one by a certain factor (i.e. $W_2 = 2 * W_1$, similarly $A_2 = 2 * A_1$) this way some of the A/W combinations will result in the same ID values than others, thus reducing the amount of ID values.

We also found that for other previous works the sizes of the targets differ from experiment to experiment. We concluded that this phenomenon occurs because of the original goal of the study in question. For instance, there have been studies focused on thumb tapping [KB07], other works focus on the size of the targets for a better performance [CH04] while others focus on evaluating tapping actions carried out both, on the front and the back of the device [WMA08, WH14]. All these studies differ, since for some of them the thumb might or might not play and important role. For instance, in a study that aims to compare the differences between front-of-device and back-of-device tapping it makes sense that, at least for certain conditions, other fingers (index for instance) are used, which leads to the possibility of having a range of target sizes that covers smaller widths due to the fact that finger tips tend to be smaller than thumb tips [PKB06]. On the other hand, studies that try to discover more appropriate target sizes that minimize the error rate during selection or tapping tasks might as well cover an even wider range of target sizes, since it is worth to explore as many options as possible in order to compare the results obtained with different sizes.

Overall, a wide range of target sizes has been used for tapping tasks in previous work. That is why we decided to review more carefully the publications that involve thumb tapping. Colle and Hiszem [CH04] found that an ideal size for targets to be hit with the thumb is 20 mm, which can be used as a reference for the upper bound of our experiment. As per the lower bound, it is difficult to state, since it is expected that the smaller the target the higher the error rate will be. However, based on Mizobuchi's et al. [MMRM02] work we have determined that a target smaller than 5 mm will be really difficult to tap with the thumb, since in the case of pen tapping this size can be classified as the minimum and pen tapping offers a better accuracy than the thumb. As a result, we thought in using a target no smaller than 5 mm. On the other hand, it is also possible that such a target size is difficult to hit for the users since it can be considered rather small. For instance, in Roudaut's [RHL08] experiment they found that a size of 9.2 mm can be set as the minimum for easy thumb accessibility. Having these factors in mind we decided to proceed with 5 mm for the smallest target size, 10 mm for the medium size and 20 mm for the largest one, but from an informal testing it was discovered that having a 5 mm target size made the experiment hard and led to high error rates for all conditions involving that particular size.

Considering these difficulties for the future application of the experiment, and referring to Henze et al. [HRB11], who state that according to the iOS guidelines an element of 6.74 mm offers an acceptable error rate when tapping on the screen, we decided to change the smallest target size to 7 mm, since it is not as difficult to hit as the 5 mm size and still offers room for errors which can be analyzed and compared against larger sizes. Once the smallest target size was fixed at 7 mm and considering the idea of reducing the amount of ID values, the second target size was fixed at 14 mm and the third and largest one was set at 28 mm.

Amplitude

In regards of the amplitude (A), the published literature shows a mixture of amplitudes per experiment ranging from single amplitude [PH08] experiments to up to four different values [MB92, Fit54]. The goal of this study depends on the capability to evaluate different ID values and having already defined the number of target sizes, the only possible way to achieve a sufficient amount of IDs is to use more than one amplitudes. We decided to set four different amplitude values for the experiment since having three amplitudes would have resulted in only a few different IDs thanks to the duplicated ID values for some of the cases, hence having four amplitudes yields to more $A * W$ combinations, which in turn produce more ID values.

When the amount of amplitudes was decided, the values had to be calculated in a similar way than the width values, that is selecting a minimum value and get the next ones by adding a certain factor to the existing one. Although the process might seem simple, it is actually restricted by other factors. First of all, MacKenzie and Buxton [MB92] have already stated that the minimum value that A can take is $W/2$, which means that the effective minimum A for this experiment was determined by the largest W value set in the previous step; this means that for a $W = 28mm$ the minimum supported A is 14 mm; nonetheless this 14 mm amplitude accounts for an initial position marker of size 0 that is impractical and impossible to tap. The initial position marker's size was set at 10 mm to comply with the sizes of 9.2 mm for discrete tasks and 9.6 mm for serial tasks found by Parhi et al.[PKB06] and was increased just enough without reaching the level of 20 mm described by Colle and Hiszem [CH04]. With this new parameter in place, the minimum A for this experiment is determined by $W_M/2 + W_L/2$ where W_M is the width of the initial marker and W_L is the largest target width resulting in $5mm + 14mm = 19mm$. Reason for which we set the smallest amplitude value to 20 mm.

The following step in the design was to set the next three amplitude values, but this time multiplying by a certain factor would have yield a maximum amplitude value of 160 mm which is actually not possible to reach with the thumb even when extended at full length. We realized, that for this phase, there were more limiting factors, such as the already mentioned thumb length as well as the physical dimensions of the tablet that was going to be used. In the existing literature there are mentions to the average thumb length, unfortunately the values measured vary according to the population where those were taken. That is why we decided to take as boundaries the values of 60 mm found by Hirotaka [Hir03] as lower bound and that of 76.5 mm found by Perry and Hourcade [PH08] as upper bound for the thumb length as defined by Greiner [Gre91] (See Fig. 3.1). With this information we made the decision to provide amplitude values in increments of 20 mm that yields a maximum amplitude of 80 mm. This maximum amplitude can be reached with a thumb shorter than 76.5 mm by having help of the palm of the hand that is holding the device and since the device used was a 13 inches tablet that in landscape mode has a width of 180 mm and setting the start marker right at the middle of it would leave 90 mm, both above and below the marker, just enough place to accommodate the largest amplitude.

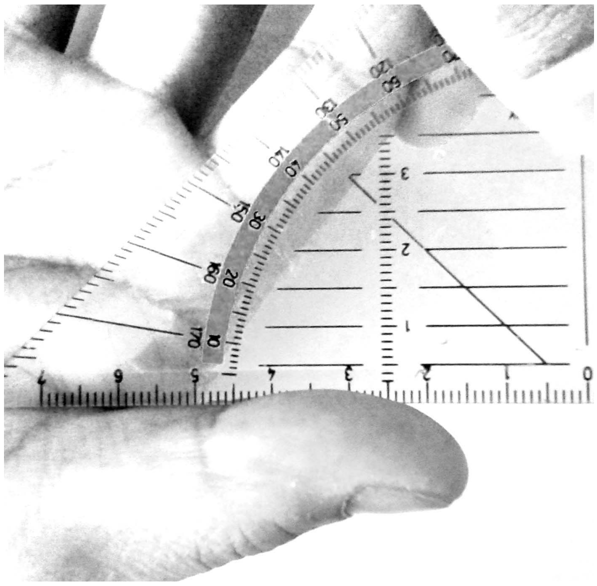


Figure 3.1: Example of Thumb Length Measurement

Angles

Finally, the last part of the design was to define the angles to be used. According to Roudaut et al. [RHL08], Parhi et al. [PKB06] and Odell and Chandrasekaran [OC12] there are areas on a touch screen device that are more comfortable to tap than others, for example the regions closer to the borders and corners of the screen are difficult to reach and according to Park et al. [PHPC08] require more flexion or extension of the thumb. Odell and Chandrasekaran [OC12] found that there are two main grips when holding a tablet known as corner grip and side grip. Corner grip refers to support the bottom corner of the tablet with the palm, while side grip refers to hold the device with the hand located along the side of the tablet, but not directly on the corner. Since the first type of grip only allows for the thumb to move 90° it would be not suitable for the purpose of our experiment that tries to evaluate the differences in selection time considering a larger screen area as possible. Therefore we chose side grip and two angles were initially marked as necessary, these are the completely vertical line above the initial marker and another one below the initial marker. The rest of the angles were defined by dividing the 180° space in equal steps of 45° with respect to the previous angle (see Fig. 3.2). This configuration allows the experiment to analyze the full 180° space with a side grip that contemplates an initial target located right in the middle of the side of the tablet.

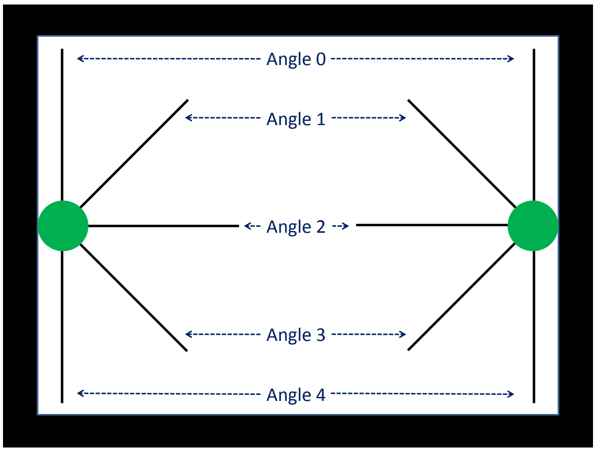


Figure 3.2: Diagram that shows the angles tested for both hands

3.2 Participants

To apply the study, we referred to the works of Bützler et al. [BVJS12], Oulasvirta et al. [ORL+13] and Parhi et al.[PKB06] who recruited 20 participants for their respective studies. Since the majority of the published works use right handed people [KB07, CH04, Fit54, MMRM02, Mur96, ORL+13, WH14] we decided to stick to that decision during the application of our study; 23 people took part in the experiment, but three of them were left-handed which meant that their results had to be ignored for the final analysis.

All participants were recruited from the University of Stuttgart, but they had different backgrounds. The average age of the participants is 28 years (SD: 5.6) and ranged from 21 to 45 years, there were 13 males and 7 females; as previously stated all considered participants were right handed and all of them had previous experience using touch screen devices with the vast majority mentioning a daily usage of a portable touch screen device. A mobile phone/smart phone was marked as the most common device used by the participants, followed by the usage of tablets and in third place other devices.

The thumb length as defined by Greiner [Gre91] is the distance from the proximal flexion crease of the metacarpo-phalangeal joint to the tip of the thumb and has been consistently used in previous studies [PH08, Hir03, LKM13], thus we used it for our study and employed it as a discrimination factor to try to exclude participants with either too small or too large hands according to the values found by Hirotaka [Hir03] and Perry [PH08]. Participants thumbs are 61 - 75 mm long. On average their thumb length is 67.3 mm (SD: 4.5 mm).

Figure 3.3: Velcro stripes used to always ensure the same grip

3.3 Apparatus

The apparatus used for the experiment was a 13.3 inches ODYS Aeon tablet with Android 4.1 (Jelly Bean) operating system. To ensure the grip a pair of Velcro stripes were glued to the back of the device in the position where the fingers were expected to be set (See Fig. 3.3). These stripes were added on both, left and right side of the tablet to ensure both hands remained in the same position during the experiment.

An Android application was written for the purpose of displaying the different targets on screen, the initial position marker and log the required information to a file per participant. The application was programmed to display on either left or right side of the screen a green starting marker and at the same time one of the black targets.

The application was programmed to randomly select one of the width-amplitude-angle conditions, ensuring the order of combinations was never repeated among the participants; we also ensured that the initial hand was randomly selected for each session, but balanced to have a total of half of the participants starting with their right hand and the other half starting with their left hand. The application also counted the elapsed time from the moment of the release of the starting position until a successful hit on the current black target was registered. However, all hit attempts, either successful or failed were written to the log file. We decided as well to make the application to create a file per participant. The approximate time to complete the experiment was 30 minutes, taking 10 minutes to complete all tapping tasks for each hand, around 5 minutes for the explanation of the instructions and purpose of the study and the rest to fill the required questionnaires.

3.4 Procedure

Environment

We conducted the experiment in a closed office environment to avoid distractions. At the beginning of the activity we explained the participants how the experiment was going to be performed. The instructions included detailed description of the scenario presented by the application.

Participants

Although only right handed people were considered for this experiment, both hands were tested for all participants. The initial hand was randomly assigned for every participant and half of the cases started with the right hand while the other half used their left hand as the initial hand.

Instructions

For either case, right or left hand, there was at all times two circles on the screen, a green circle with the role of the starting position and a black one representing the current target to be hit. We instructed the participants to tap with their thumb, first the green circle and then lift the thumb and tap the black target. As soon as the initial position circle was correctly hit it turned red indicating that the tapping action was successful and therefore the participant could lift his or her thumb and tap the black target as quickly as possible. In case that the black circle was successfully tapped the initial marker turned from its current red color back to the initial green. In the event that the black target was not successfully hit then the initial circle remained red meaning that the user had to try again to hit the target until the action was successful. In order to counteract the problem of occlusion a label was added at the top center of the screen that kept a count of the number of targets and repetitions per target completed so far.

Each black target was to be hit 5 times after which the application randomly selected a new combination of amplitude-width-angle to be displayed. The activity was exactly the same for every new target displayed and users were instructed to keep on tapping until the initial green marker was automatically moved to the other side of the screen's tablet. At this moment they had a pause and afterwards they could continue with the experiment, now using their other hand.

Once we gave all the instructions regarding the activity to be performed, we also gave additional instructions about the expected grasping of the device. At this point, we explained to all participants about the stripes on the back of the device and its purpose. We also told them that they could move their hands along such stripes in case any of the targets was far from

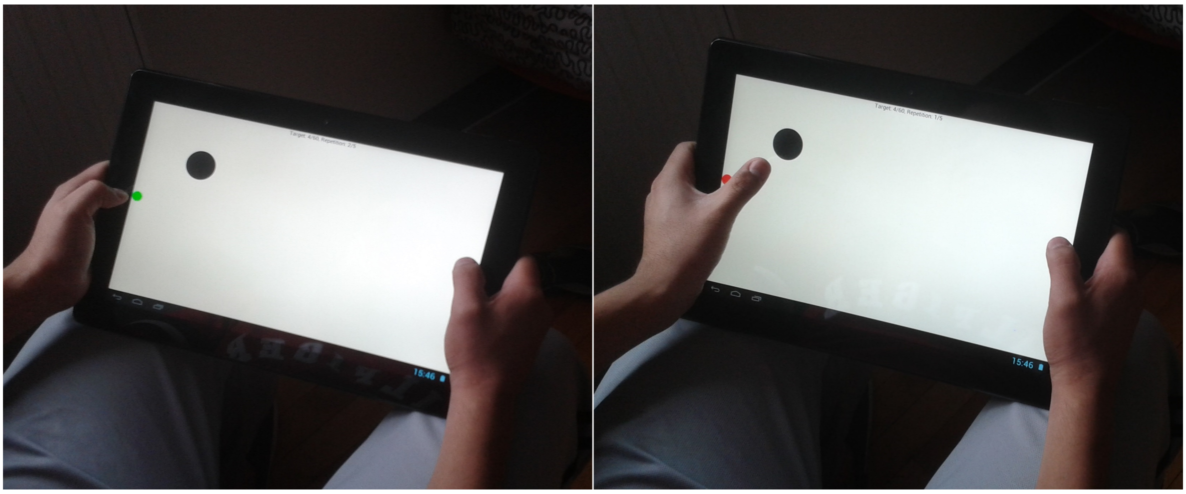


Figure 3.4: Example of grip and interaction with the application's interface. Left side shows the apparition of the target. Right side shows the task to tap the target.

their reach, but under no circumstance they were allowed to move their hands up or down alongside the frame of the tablet. We also mentioned that, given the dimensions and weight of the tablet the participants were allowed to support the bottom part of the tablet on their laps so they could concentrate in looking for the next black target and moving the thumb towards it rather than in balancing the tablet in order not to drop it (See Fig. 3.4).

Documentation

During the pause at the end of the first half of the experiment we asked the participants to fill a NASA-TLX [Gro] questionnaire to evaluate their experience with the experiment for that particular hand. After the questionnaire was filled, the participants were allowed to continue with the second half of the experiment which followed the same dynamic previously explained with the only difference of being performed with their other hand. At the end of this half of the experiment, we asked participants again to fill a NASA-TLX questionnaire, this time to evaluate their experience with the other hand.

Having explained these instructions, we asked all participants to fill a demographic survey to collect data regarding their use of touch screen devices, age, occupation and thumb length. Additionally, they signed an agreement stating that they were aware of the experiment's purpose and data to be collected from it. Once these two documents were properly filled and signed, we handed the tablet over to the participants and started the Android application to begin with the experiment.

3.5 Results

The data of our study is formed by two sections. We have the evaluation of the task, represented by NASA-TLX questionnaires and we also have the task selection times with all successful and failed attempts logged by the application.

To do the analysis, we first took the NASA-TLX data and calculated the corresponding rating. But, to analyze the selection task, we have divided the data into two sections, first we present the error rates and then, we analyzed the selection times.

For a better explanation of the analyzed data, we have decided to take the angles presented in Fig. 3.2 and rename them with degrees starting from the top corners of the tablet, our new naming convention is shown in Fig. 3.5 and will be used from this section onwards to facilitate the review of the data.

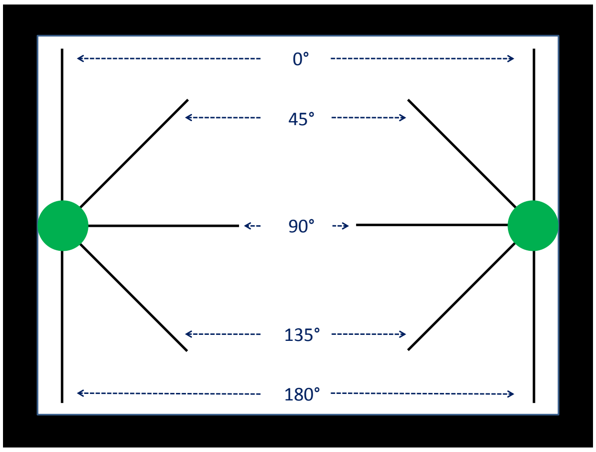


Figure 3.5: Angles measured in degrees

3.5.1 NASA-TLX Analysis

We asked the participants to fill the NASA-TLX questionnaire for both hands. To analyze the influence of fatigue, we have decided to compare the NASA-TLX results in two ways, first we have calculated the rating [Gro] of the tasks according to the first and second hand used, then we calculated the rating after dividing the results into right and left hand (See Fig. 3.6). A detailed chart with all separate scales can be seen in Fig. 3.7.

We can see that users perceived more effort when using their left hand than with their right hand. However, when rating on a first-hand and second-hand basis we see that the first hand had a higher score than the second one. This might suggest a learning effect from one hand to the other, since in this case, both left and right hands, are mixed but still do not reach the same level, having the first hand a higher rating than that of the second hand.

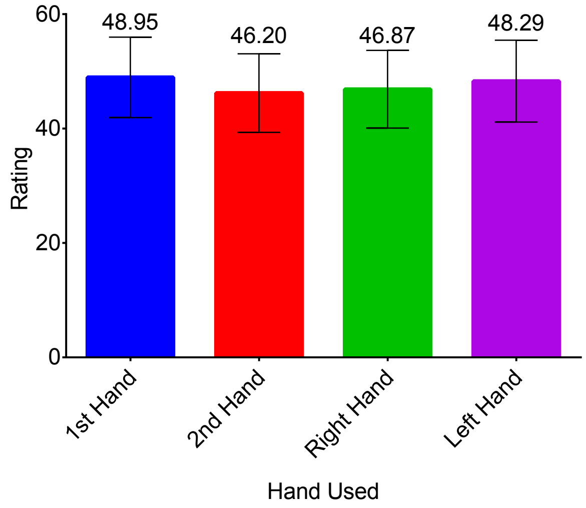


Figure 3.6: Analysis of the NASA-TLX data by Initial Hand and by Dominant Hand. Bars represent 5% confidence interval.

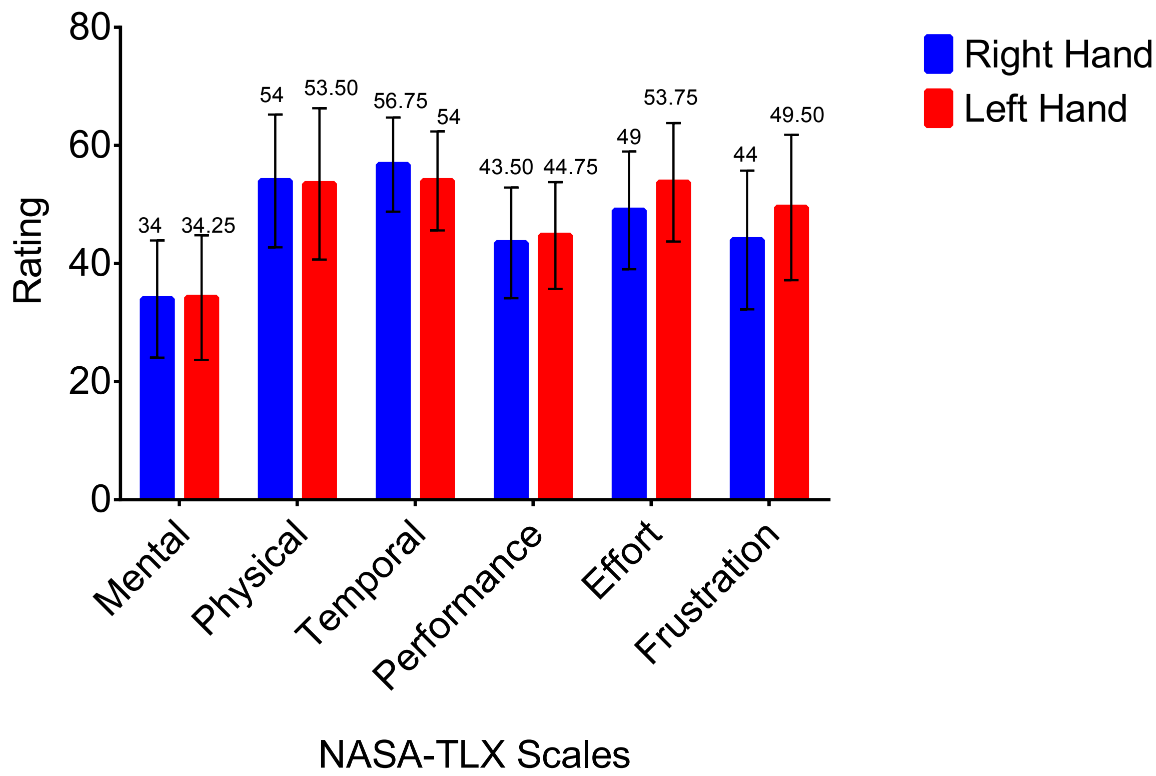


Figure 3.7: NASA-TLX scales shown separately for both hands.

3.5.2 Error Rates

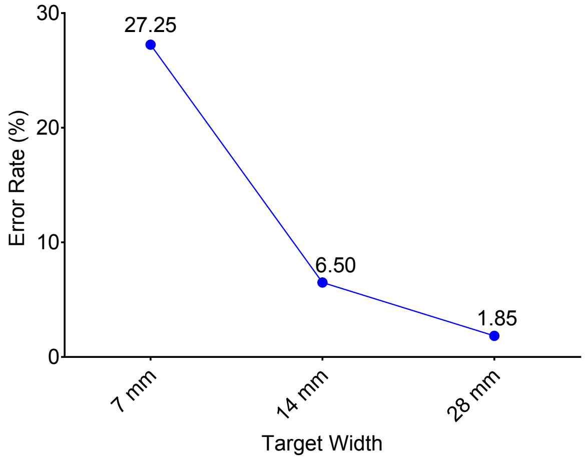
Having 3(target widths) * 4(amplitudes) * 5(angles) per hand for every participant, the total amount of combinations was 60 per hand. However, each of these conditions was to appear 5 times in order to calculate an average selection time for each condition, making a total of 300 tapping actions for each one of them. Nevertheless, we also made the application to display each target repetition until a successful tap on the target was recorded. With this condition in mind, we expected, due to accuracy errors from the participants, to have log files longer than 300 records per hand per participant.

Since each hand was intended to produce 300 records, each participant had to tap 300 * 2(hands) = 600 targets. When we calculated these 600 * 20(participants) we got an expected amount of 12000 records for the whole experiment. As stated before, due to participants' errors, this amount of records was also expected to be higher and the log files revealed we had 14640 tapping events recorded.

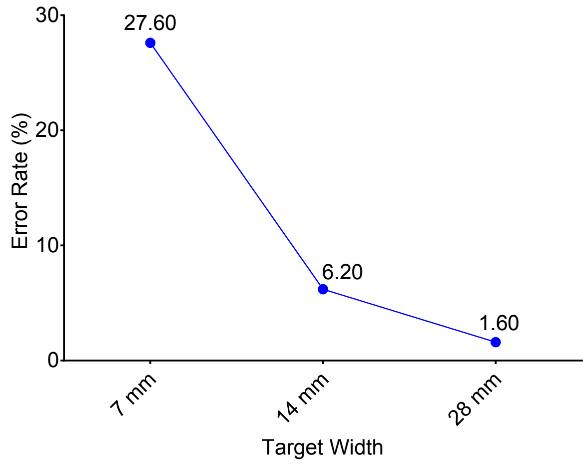
In order to calculate the error rates, we have considered the totality of the data. We have taken the number of records that were successful at the first trial and compared them against the expected value per variable (target width, amplitude and angle), our results are shown in Fig. 3.8. It can be seen that accuracy increases, as expected, according to the target size. The middle section of the figure shows error rate charts for the amplitudes used in the experiment, there we see, for the right hand, how the errors increase from the smallest amplitude to the second value and then drop for the third value, only to increase again for the largest amplitude used. This behaviour is in line with what Wolf and Henze [WH14] found regarding excessive thumb flexion producing poorest performance and with Park et al. [PHPC08] where they also mention considerable thumb extension as a factor for poor accuracy. Nevertheless, the pattern observed for the right hand differs from the one of the left hand.

Regarding the angles, some of them are easier to reach (lower error rate), but a comparison between right-hand and left-hand data showed that the angle of 90° had the lowest error rate for the right hand while that same angle had the highest error rate for the left hand; and the same was found for the highest error rate on the right hand (180°) that turned out to be the lowest error rate case of the opposite hand.

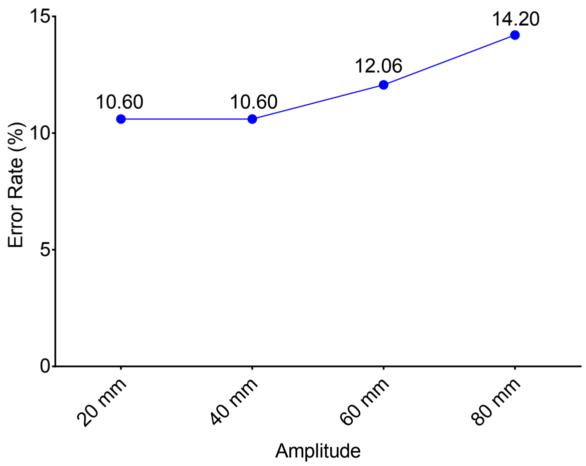
To better understand the relation between the amplitude and angle error rates, we have detailed the respective charts to show what the values are for the specific angles (from the amplitudes charts) and amplitudes (from the angles charts). Our results can be seen in Fig. 3.9. Chart Fig. 3.9 (b) shows that for the angles of 0°, 45° and 90° there is an increment in the error rate from the first amplitude value to the second one, a decrement for the third amplitude and again an increment for the largest amplitude value, but for the angle of 180° the error rate increases consistently when the amplitude increases. The other exception was the angle of 135° which starts with its highest error rate and decreases until reaching its lowest point at an amplitude of 60 mm and shows an increment for the largest amplitude tested. When compared to the charts of the left hand, we could see that the error rates for the right hand



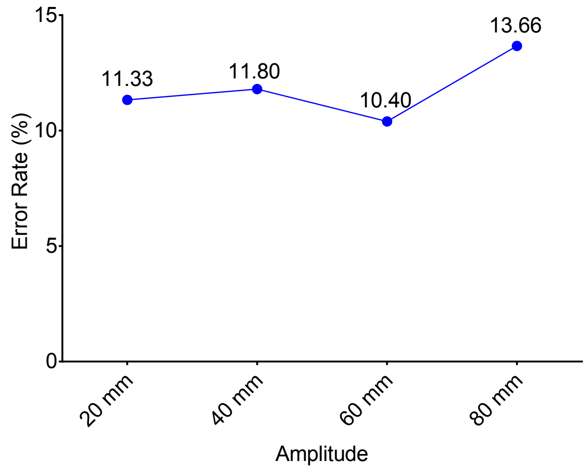
(a) Error Rate per Target Size (Left Hand)



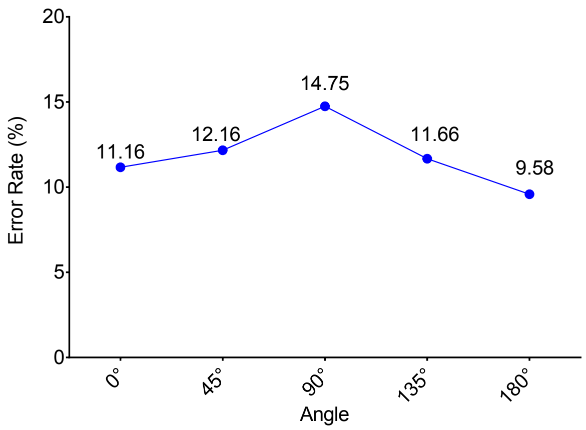
(b) Error Rate per Target Size (Right Hand)



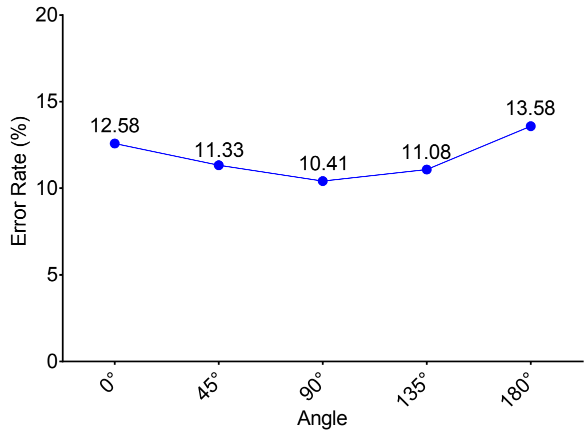
(c) Error Rate per Amplitude (Left Hand)



(d) Error Rate per Amplitude (Right Hand)

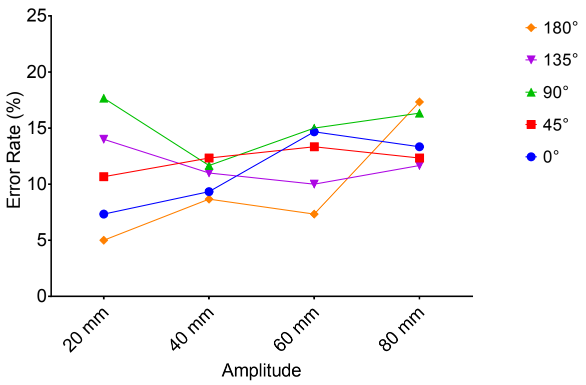


(e) Error Rate per Angle (Left Hand)

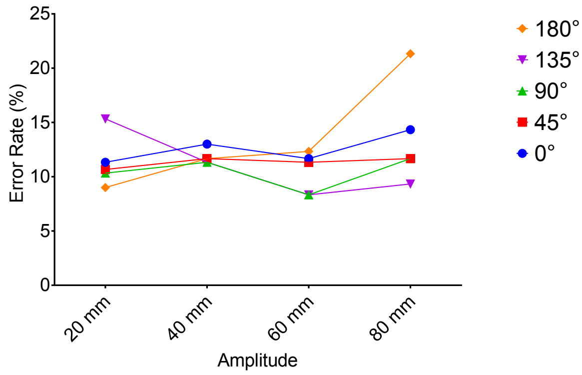


(f) Error Rate per Angle (Right Hand)

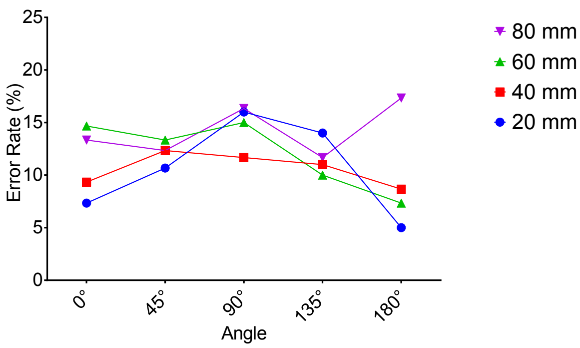
Figure 3.8: Error Rate Charts divided per Variable (Width, Amplitude and Angle)



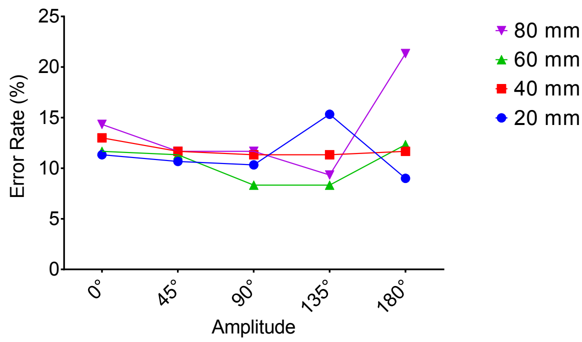
(a) Amplitude Error Rate Detailed by Angle (Left Hand)



(b) Amplitude Error Rate Detailed by Angle (Right Hand)



(c) Angle Error Rate Detailed by Amplitude (Left Hand)



(d) Angle Error Rate Detailed by Amplitude (Right Hand)

Figure 3.9: Detailed Error Rates. Top: Relation Amplitude-Angle. Bottom: Relation Angle-Amplitude

tend to cluster towards a certain value (except for the largest amplitude and the angles of 135° and 180°), while for the left hand the error rates are more dispersed; this can be attributed to the handedness of the participants.

We can see from this chart that the highest accuracy obtained for the shortest amplitude belongs to the 180° angle and the poorest accuracy at this level appears when the targets are located on the 135° angle. For the amplitudes of 40 mm and 60 mm the highest accuracy is located at the angles of 90° and 135° and for the largest amplitude, the best accuracy was found at the angle of 135°. These findings suggest that for short amplitudes it is easier to hit targets located directly below the thumb while for longer amplitudes the space between our 90° and 135° angles might be easier to tap and when a maximum thumb extension is required, then the 135° angle offers better accuracy.

A	W	ID	A	W	ID
20	7	1.947	60	7	3.258
20	14	1.280	60	14	2.402
20	28	0.777	60	28	1.652
40	7	2.747	80	7	3.635
40	14	1.947	80	14	2.747
40	28	1.280	80	28	1.947

(a) Initial Calculation of ID values

ID	ID
0.777	2.402
1.280	2.747
1.652	3.258
1.947	3.635

(b) List of Unique ID values

Table 3.1: Tables of ID values

3.5.3 Completion Times

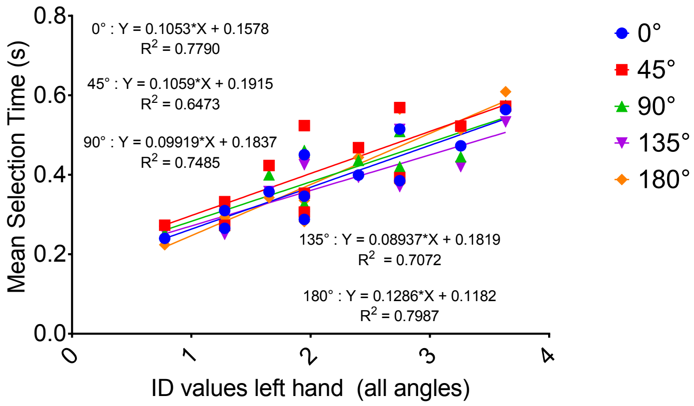
We considered only the tapping events that were successful at the first attempt, reducing our initial data to 10580 records. Since each $W * A * Angle$ condition was repeated 5 times, we took the remaining records and calculated the average of the five repetitions per condition. Given that some of the repetitions were removed in the previous step, for these cases, we had to calculate an average selection time with less than 5 repetitions, reducing our data to 2392 records (of the expected 2400 that correspond to 120 conditions for all 20 participants) since for a few of the conditions there were no successful selections at the first attempt on any of the 5 repetitions.

From this new set of data, we tried to reduce noise by filtering out all those mean selection times whose value differs more than 3 standard deviations from the general mean [ORL+13, WH14]. Having a mean selection time of 0.3889 seconds and a standard deviation of 0.1498 seconds, we ended up considering only 2370 tapping events.

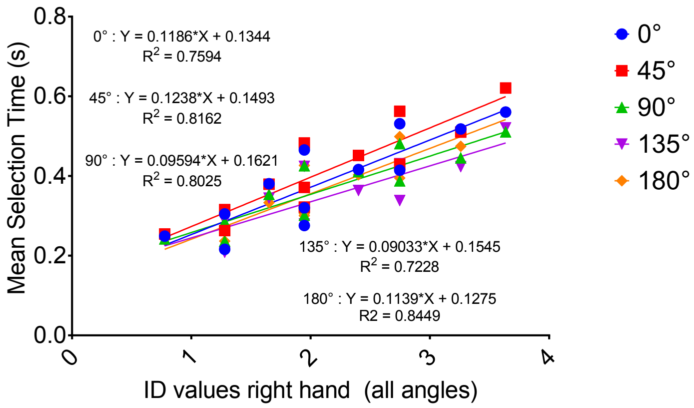
We also analyzed the angle selection times in relation with the index of difficulties tested during the experiment, the initial calculation of the ID values is shown in Table 3.1a. From this table we then merged the repeated ID values and obtained Table 3.1b. This list of unique values is the one we used for our analysis, since the A/W combinations that yield to the same ID, should be treated as targets with equal difficulty to be reached.

We took first, the combinations of A/W shown in Table 3.1a and obtained the mean selection times corresponding to each one of them (See Fig. A.1 and Fig. A.2). Then, we calculated the mean selection time of all points that fall under the same A/W combination and obtained the corresponding trend line and its equation (See Fig. A.3 and Fig. A.4). Taking the values from Table 3.1b we grouped the mean selection times corresponding to the same ID together and obtained their respective trend line.

Figure 3.10 shows the mean selection times per ID value before merging the markers with the same ID, from this figure we then combined all markers with the same ID value and obtained Figure 3.11 that shows the mean selection times for the five angles considered. We have



(a) Mean Time per Angle (Left Hand)



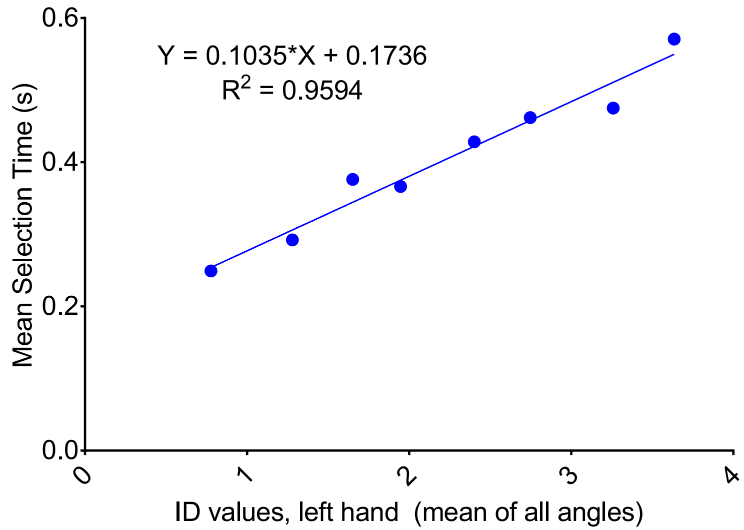
(b) Mean Time per Angle (Right Hand)

Figure 3.10: Relation between Mean Selection Time and ID values per Angle without combining the repeated Markers

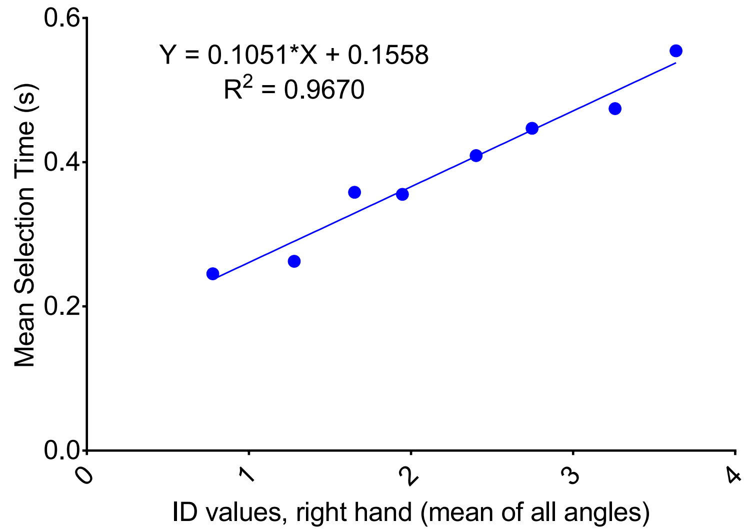
calculated a single value per ID and based on the resulting distribution of the values, the corresponding trend line is presented. Additionally we have also calculated trend lines per individual angle to compare them with the general trend line described before.

From Fig. 3.11 (c) and (d) we see that the line belonging to the angle of 180° shows an even better fit than the one showed in Fig. 3.11 (a) and (b).

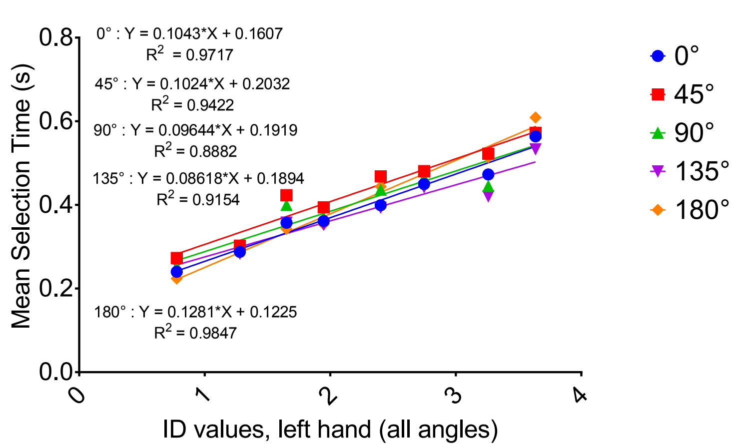
The charts that depict the break down into individual angles (Fig. 3.11 (c) and (d)), show that the markers for the 45° angle tend to be higher than any other angle on the right hand. This means that users take longer time to select the targets that appeared on that region of the screen. As for the left hand, the trend is similar except for the largest ID value where the 180° angle surpasses the markers of the 45° angle, however this could be explained because of the handedness of the participants.



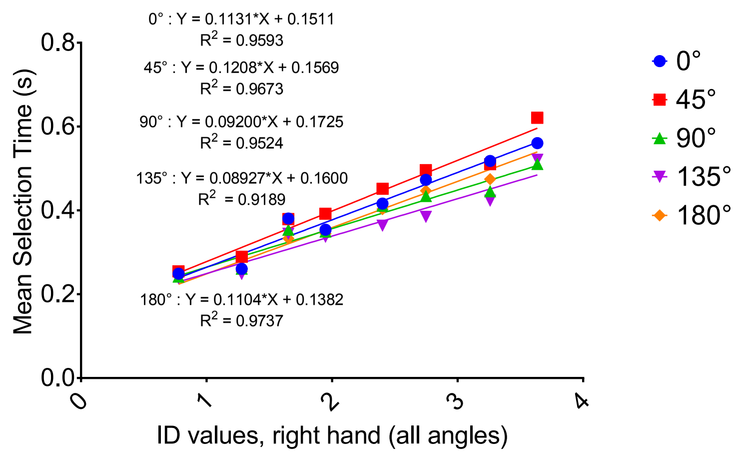
(a) Mean Time for all Angles (Left Hand)



(b) Mean Time for all Angles (Right Hand)



(c) Mean Time per Angle (Left Hand)



(d) Mean Time per Angle (Right Hand)

Figure 3.11: Relation between Mean Selection Time and ID values for the general mean of all Angles

When we analyzed the task selection times we noticed that, again as expected, times decreased for larger target widths and also increased for larger amplitude values. Regarding the selection times per angle, we could only identify that, for both hands, the fastest selection time corresponds to the angle of 135° while the slowest time is that of the 45° angle (See Fig. 3.12).

In order to better understand the times observed per angle, we have divided the mean selection time of each angle into the different amplitudes used, our results are shown in Fig 3.13. From these charts, we see that, as expected, for all angles the lowest selection time corresponds to the smallest amplitude and increases accordingly to the increments in the amplitude.

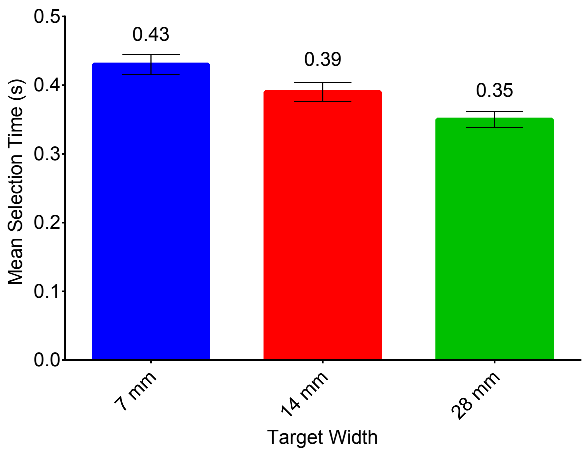
However, in a more detailed analysis, we observed that for the right hand the angle of 45° always holds the highest selection times for every amplitude tested. While for the left hand, the tendency is similar except for the two smallest amplitudes, that have the same selection times in both, 45° and 90° angles. Furthermore, the fastest selection times are presented, for every amplitude, on the 135° angle for the right hand. But, for the left hand, the fastest times for the 20 mm correspond to the 0° and 180° angles, for the 40 mm amplitude correspond to the 135° and 180° angles and for the last two amplitude values, the fastest selection times belong to the 135° angle.

From these observations we can conclude that users are faster when tapping on the 135° while they are slower when the targets are positioned in our 45° area.

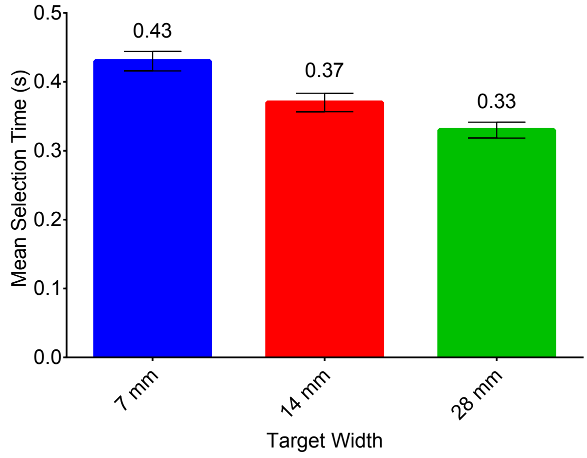
We also conducted a 4-way ANOVA to examine the effect of our variables of Amplitude, Width and Angle, and since the experiment also took in consideration both hands, we have also decided to include it as another variable. For this analysis we have set our confidence level at 5% and our results show that the hand has no significant effect on the selection times ($F_{1,10} = 0.442, p = 0.521$), while target width ($F_{2,20} = 69.367, p < 0.001$), amplitude ($F_{3,30} = 314.3, p < 0.001$) and angle ($F_{4,40} = 9.937, p < 0.001$) did have a significant effect.

There is also a significant interaction between width and amplitude ($F_{6,60} = 11.541, p < 0.001$), between amplitude and angle ($F_{12,120} = 2.002, p = 0.030$) and between hand and angle ($F_{4,40} = 3.538, p = 0.015$).

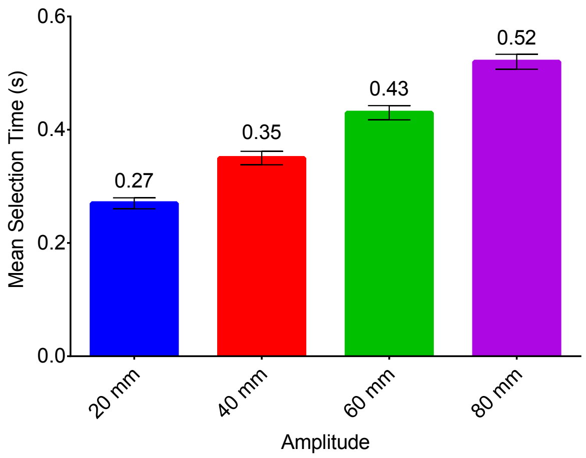
Pairwise comparisons showed that there is no significant difference between left and right hand, but there is significant difference between all target widths ($p < 0.001$) and amplitudes ($p < 0.001$). Regarding the angles, we found that there are significant differences only for the following angles: 0° and 45° ($p = 0.005$), 45° and 90° as well as 45° and 135° (both with $p < 0.001$).



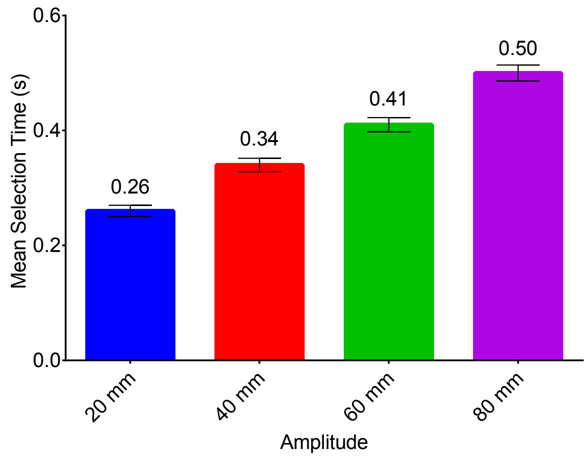
(a) Width Selection Times (Left Hand)



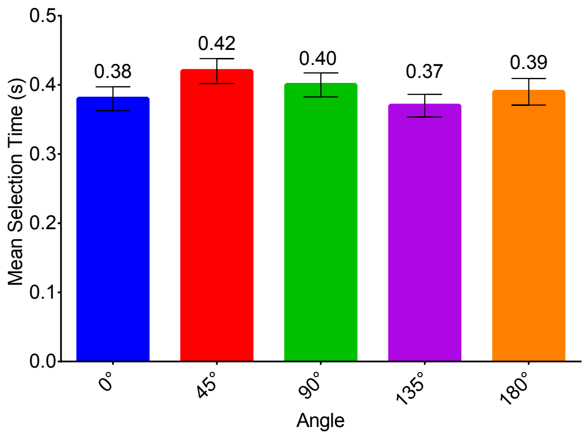
(b) Width Selection Times (Right Hand)



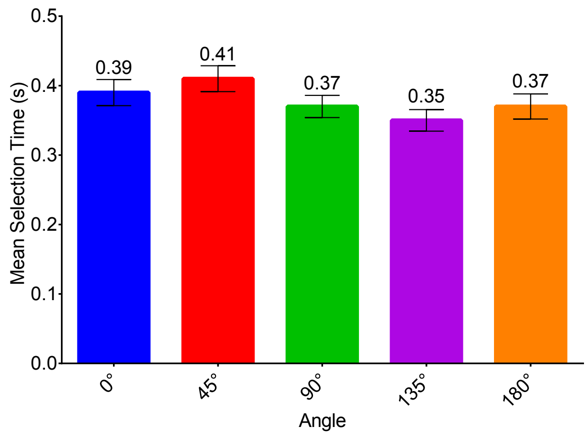
(c) Amplitude Selection Times (Left Hand)



(d) Amplitude Selection Times (Right Hand)

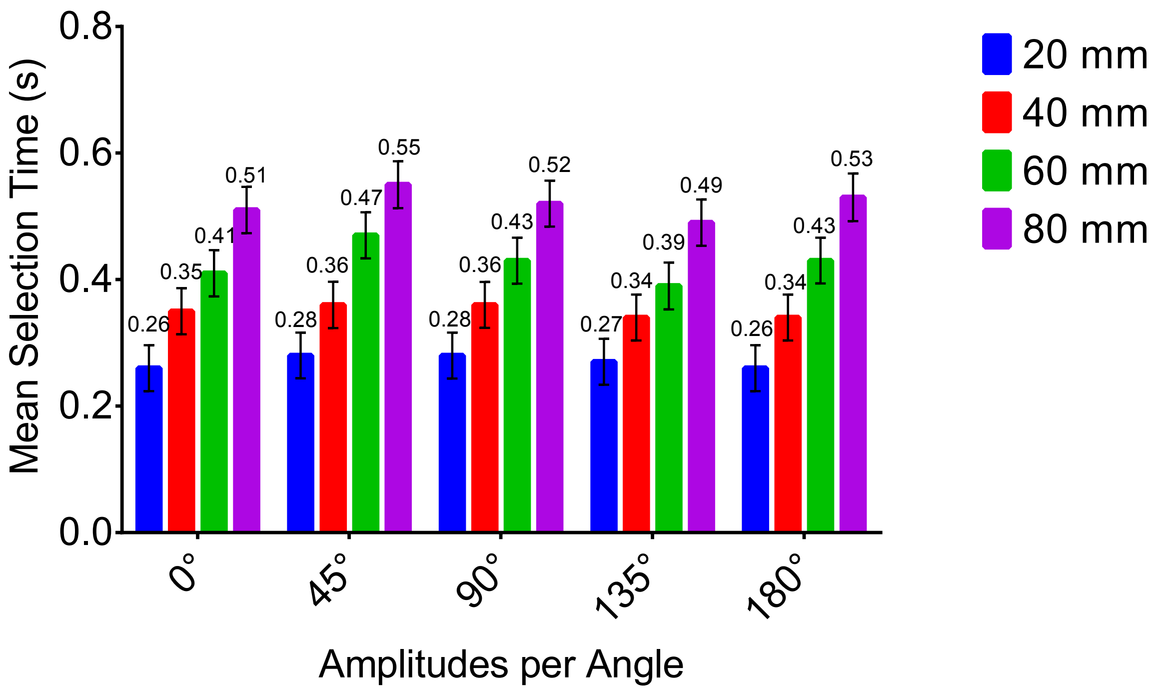


(e) Angle Selection Times (Left Hand)

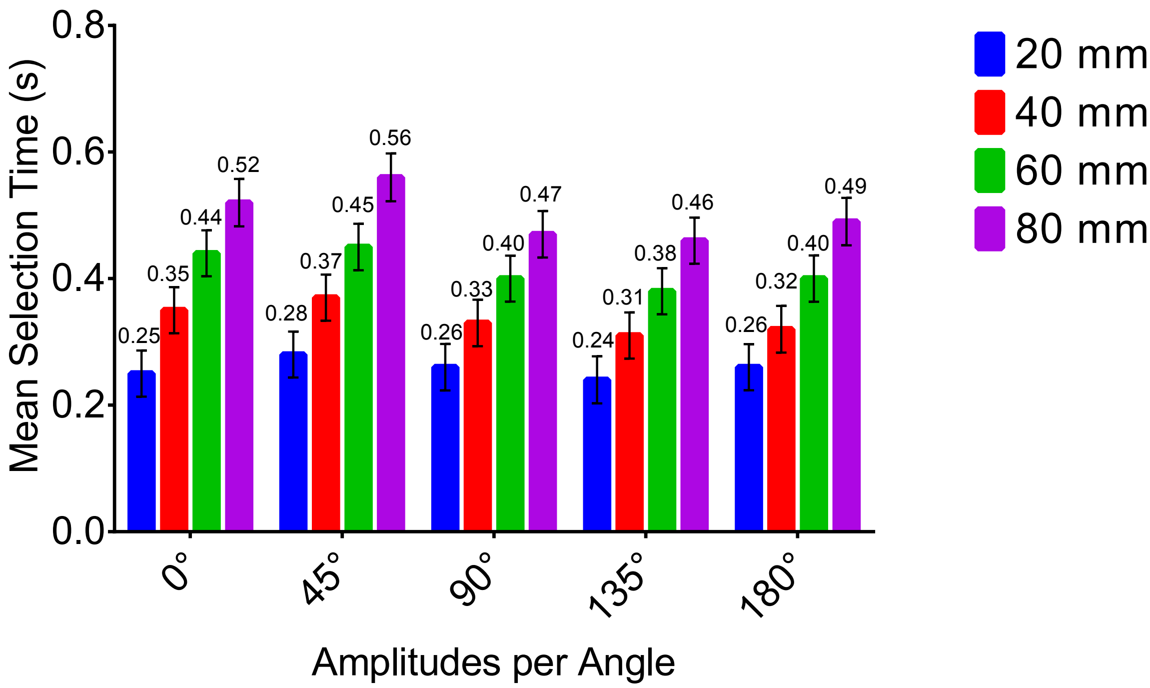


(f) Angle Selection Times (Right Hand)

Figure 3.12: Mean Selection Times per Width (top), Amplitude (centre) and Angle (bottom)



(a) Amplitude Selection Times per Angle (Left Hand)



(b) Amplitude Selection Times per Angle (Right Hand)

Figure 3.13: Mean Selection Times per Angle divided per Amplitude

3.6 Discussion

There are already studies that evaluate target selection times on mobile touch screen devices, and although those studies consider amplitude and target width to describe the selection tasks, there is no study that analyzes the relation that the angle where the targets are located, has with such tasks and having referenced the location of our targets with specific angles we have determined, after analyzing our results, that the angle has an effect on the selection task. In our experiment we could see that the occurrence of errors varies not only with target size and amplitude, but it is also determined according to the angle. This same effect was also seen in terms of selection times, where the time varies as well depending on the particular angle where targets were located and we could observe how the angle of 135° had always a better performance regardless of the distance between start point and target than any other of the considered angles.

According to our results, users perceived the selection task to be less demanding when using their right hand than when using their left hand, but also, independently of the hand, the rate of the first hand used was higher than that of the second hand.

In regards of accuracy, we could identify regions of the screen that favor precision, but it also depends on the amplitude used. For instance, targets located directly below the thumb offered a better accuracy with the shortest amplitude, this contradicts the findings of Trudeau et al. [TYJD12] who stated that targets requiring excessive thumb flexion lead to poorest accuracy. However when amplitudes increase, then our angles of 90° and 135° offer a better performance. These results are in line with the findings of Perry and Hourcade [PH08] where they reported that their participants were more accurate when targets were located on the edge of the screen; since their study was conducted on a smaller device those locations correspond with the ones provided by our 90° and 135° angles when considering the grips used in both studies.

We conducted an analysis of the Index of Difficulty as per Fitts' model and we discovered that, in general this model provides a very good fit for the conditions considered during our experiment. Additionally, we also performed the same analysis individually per angle and found again that the model provides a good fit for all angles given, although there were slight variations between the angles.

In a more detailed analysis of the selection times per angle, we also discovered that the relation between amplitude and angle impacts the selection times, according to our data users were significantly faster when selecting targets on the 135° angle and this holds when we compared all amplitudes individually. In contrast, the highest selection times were found on the 45° angle and this also holds when the comparison is made per individual amplitudes. Our results are similar to what Park et al. [PHPC08], Odell and Chandrasekaran [OC12] and Wolf and Henze [WH14] found regarding excessive thumb flexion and extension yielding to poorest performance. However, this contradicts the findings of Trudeau et al. [TYJD12] and Wolf et al. [WSMH14] where they state that the best performance corresponds to a relaxed position of the thumb, which would mean that our angle of 45° would have the fastest selection times, however this was not the case for our experiment.

We can therefore conclude that, in order to evaluate and analyze target selection tasks researchers should consider not only amplitude and target width, but also the angle of approach between the start position and the targets since we have shown that this angle has a significant impact in the error rates and times during selection tasks.

4 Influence of Thumb Direction in Tapping Tasks

After conducting the experiment on the angles and analyzing its results, we have determined to create a second experiment this time to evaluate selection tasks when pointing towards different directions. Since the biomechanical configuration of the thumb allows it to extend and flex, but also to rotate, we have thought that these movements together with the angle where the targets are located have also an influence in the selection tasks, therefore we have decided to design another experiment including different directions that force the thumb to execute flexion and extension movements combined with its rotation.

We designed our experiment to have 3 target sizes of 7, 14 and 28 mm. We have chosen 4 amplitudes of 20, 40, 60 and 80 mm. We selected 4 different angles (See Fig. 4.1). These conditions allow us to test the two-hands grip covering the situation where the thumb has to move towards the center and also towards the edge of the screen's device.

We recruited 20 right handed volunteers to take part in the experiment and for each participant, all combinations of amplitude*width*angle as well as the initial hand (either left or right) were fully randomized. We took measures to balance, however the use of the hands and ensure that half of the participants started with their right hand and the other half started with their left hand, and also limited the range of their thumb length according to previous works.

The experiment took place in a close environment to avoid distractions and we used a 13 inches Android tablet with an application that displayed each condition randomly and logged information about elapsed time and missing and correct tapping actions into separate files per participant, we also prepared the tablet to have some guides on its back to help ensure the same grip for all participants.

At the end of the experiment, we requested the participants to use a shorter version of the application to record a video with samples of the trajectories they used to move their thumbs for each angle and direction in order to exclude trajectories if necessary.

Additionally, we collected demographic information for each participant regarding their use of touch screen devices, thumb length, age and occupation. We have also applied the NASA-TLX questionnaire to evaluate the users' perception of the experiment's task with both hands.

This chapter describes such experiment and is organized as follows:

Design: General description of the experiment.

Participants: Description of the volunteers who took part in the experiment.

Apparatus: Equipment used to apply the study.

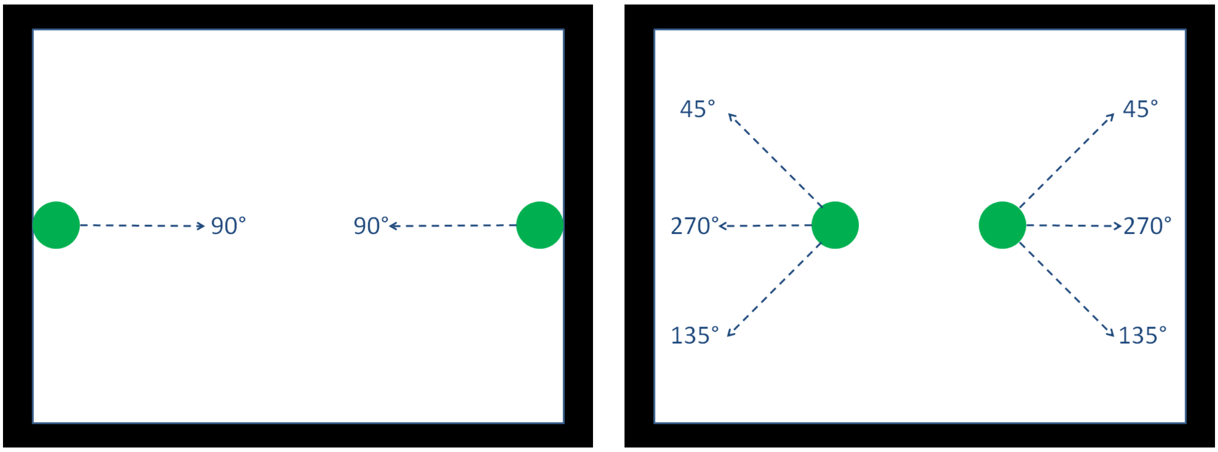
Procedure: Description of how the study was conducted.

Results: Analysis of the data obtained from the experiment.

4.1 Design

As with the experiment of the angles, we wanted to find a relation between target selection times and target width, amplitude, angle and direction of movement. Therefore, we have included the situation where the thumb has to move not only to different angles but also towards different directions. We have taken as a base the design of the experiment of the angles and generated a new one with the following description.

In this experiment we tested selection tasks both when the thumb is moving towards the center of the screen and when it moves towards the edge of the device. For these conditions we needed to establish two starting points. One of the starting points remained in the same position used for the experiment of the angles while the second starting point was located similarly but shifted towards the center of the screen (See Fig. 4.1).



(a) Start Point at the edge of the screen

(b) Start Point shifted towards the center of the screen

Figure 4.1: Positions of the two starting points and angles where their respective targets appeared.

In this case, we have decided to decrease the amount of angles tested for a total of 4, while keeping the same 4 amplitudes and 3 target widths. This decision was made taking into consideration the space available when pointing towards the edge of the screen and that for this case we would have two possible starting positions. We expect the participants to follow

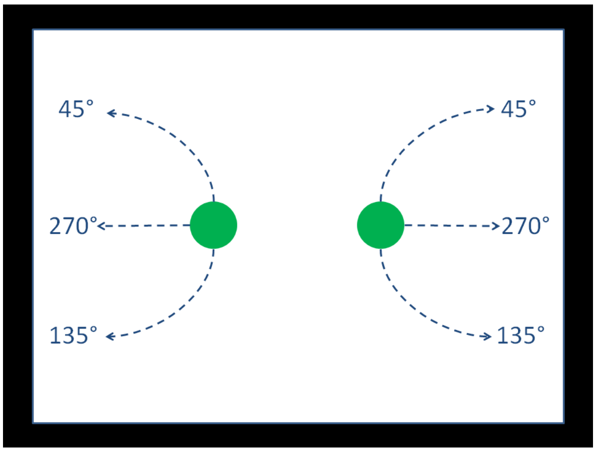


Figure 4.2: Expected trajectories followed by the thumb to reach the respective angles

a certain curve-like trajectory to reach some of the targets' positions (See Fig. 4.2) and we expect this to be faster and more precise than a straight-line trajectory due to the biomechanics of the thumb.

4.2 Participants

Following the same guidelines established in the angles experiment, we have applied this experiment to 20 participants. All participants were volunteer right-handed students, 16 of them were males and 4 were females. The average age of the participants is 23 years (SD: 3.5) ranging from 19 to 32 years. All participants stated they had previous experience with touch screen devices, using some kind of hand held device on a daily basis. The most common type of devices used are mobile/smart phones and tablets.

We applied again the notion of thumb length as defined by Greiner [Gre91] as the distance from the proximal flexion crease of the metacarpo-phalangeal joint to the tip of the thumb and used it as a discrimination factor to exclude participants with either too small or too large hands. Participants thumbs were 60 - 75 mm long. On average their thumb length was 68.4 mm (SD: 4.8 mm).

4.3 Apparatus

The apparatus used for this experiment was a 13.3 inches tablet. Since we needed to ensure the same grip for every participant, some Velcro stripes were glued to the back of the device (See Fig. 3.3). These stripes were added on both, left and right side of the tablet to ensure both hands remained in the same position during the experiment.

An Android application was written for the purpose of displaying the different targets on screen, the initial position markers and log the required information to a file per participant. The application was programmed to display on either left or right side of the screen a green starting marker and at the same time one of the black targets.

The application was programmed to randomly select one of the width-amplitude-angle conditions with its corresponding starting point, ensuring the order of combinations was never repeated among the participants; we also ensured that the initial hand was randomly selected for each session, but balanced to have a total of half of the participants starting with their right hand and the other half starting with their left hand. The application also counted the elapsed time from the moment of the release of the starting position until a successful hit on the current black target was registered. However, all hit attempts, either successful or failed were written to the log file. We decided as well to make the application to create a file per participant. The approximate time to complete the experiment was 20 minutes, taking 6 minutes to complete all tapping tasks for each hand, around 5 minutes for the explanation of the instructions and purpose of the study and the rest to fill the required questionnaires and record the sample trajectories video.

4.4 Procedure

Environment

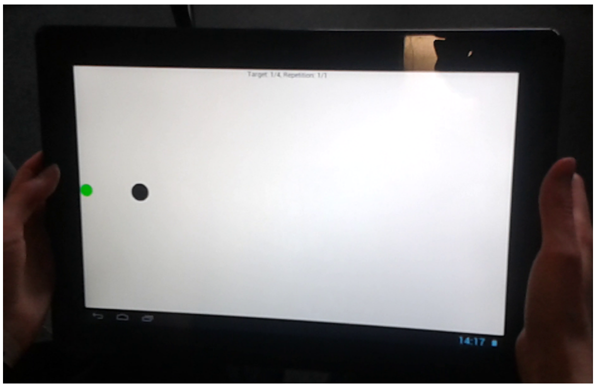
We conducted the experiment in a closed environment. At the beginning of the activity we explained the participants how the experiment was going to be performed. The instructions included detailed description of the scenario presented by the application.

Participants

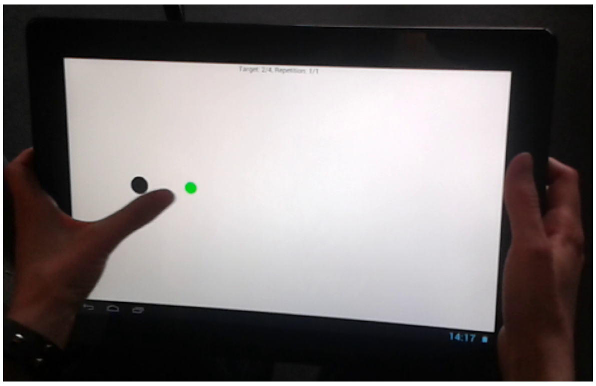
Although only right handed people were considered for this experiment, both hands were tested for all participants. The initial hand was randomly assigned for every participant and half of the cases started with the right hand while the other half used their left hand as the initial hand.

Instructions

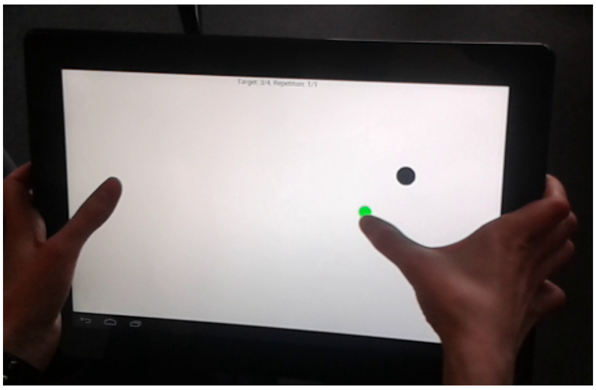
For either case, right or left hand, there was at all times two circles on the screen, a green circle with the role of the starting position and a black one representing the current target to be hit. We instructed the participants to tap with their thumb, first the green circle and then lift the thumb and tap the black target. As soon as the initial position circle was correctly hit it turned red indicating that the tapping action was successful and therefore the participant could lift



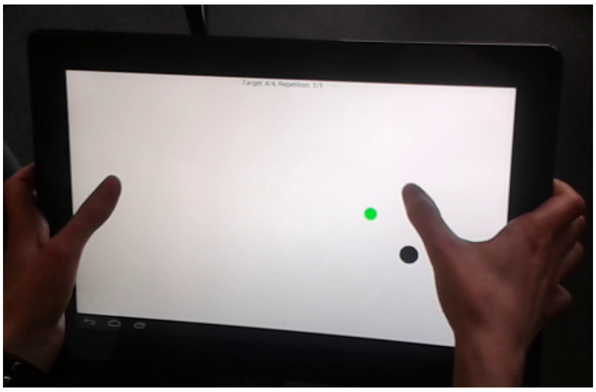
(a) Pointing horizontally towards the center of the screen



(b) Pointing horizontally towards the edge of the screen



(c) Pointing towards the edge of the screen with an angle on the upper half of the device



(d) Pointing towards the edge of the screen with an angle on the lower half of the device

Figure 4.3: Application's interface showing different combinations of starting points and targets.

his or her thumb and tap the black target as quickly possible. In case that the black circle was successfully tapped the initial marker turned from its current red color back to the initial green. In the event that the black target was not successfully hit then the initial circle remained red meaning that the user had to try again to hit the target until the action was successful. In order to counteract the problem of occlusion a message was added at the top center of the screen that kept a count of the number of targets and repetitions per target completed so far. Figure 4.3 shows examples of the combinations of targets and starting positions used during the experiment.

Each black target was to be hit 5 times after which the application randomly selected a new combination of amplitude-width-angle as well as a corresponding starting point to be displayed. The activity was exactly the same for every new target displayed and users were instructed to keep on tapping until the initial green marker was automatically moved to the other side of the screen's tablet. At this moment they had a pause and afterwards they could continue with the experiment, now using their other hand.

Once we gave all the instructions regarding the activity to be performed, we also gave additional instructions about the expected grip of the device. At this point, we explained to all participants about the stripes on the back of the device and its purpose. We also told them that they could move their hands along such stripes in case any of the targets was far from their reach, but under no circumstance they were allowed to move their hands up or down alongside the frame of the tablet. We also mentioned that, given the dimensions and weight of the tablet the participants were allowed to support the bottom part of the tablet on their laps so they could concentrate in looking for the next black target and moving the thumb towards it rather than in balancing the tablet in order not to drop it.

An important remark was done before starting the experiment that in this case we required to record a video of the hands of the participants operating the device to determine variations of the trajectories followed by the thumbs for each target condition. This was done at the end of the main task asking the users to interact with a shorter version of the application that showed only one target size and one repetition per condition. This video was determined to be used after a pre-test showed results of possible differences in the trajectories when moving the thumb from the initial position to the target for some of the conditions.

Documentation

During the pause at the end of the first half of the experiment we asked the participants to fill a NASA-TLX [Gro] questionnaire to evaluate their experience with the experiment for that particular hand. After the questionnaire was filled, the participants were allowed to continue with the second half of the experiment which followed the same dynamic previously explained with the only difference of being performed with their other hand. At the end of this half of the experiment, we asked participants again to fill a NASA-TLX questionnaire, this time to evaluate their experience with the other hand.

Having explained these instructions, we asked all participants to fill a demographic survey to collect data regarding their use of touch screen devices, age, occupation and thumb length. Additionally, they signed an agreement stating that they were aware of the experiment's purpose and data to be collected from it. Once these two documents were properly filled and signed, we handed the tablet over to the participants and started the Android application to begin with the experiment.

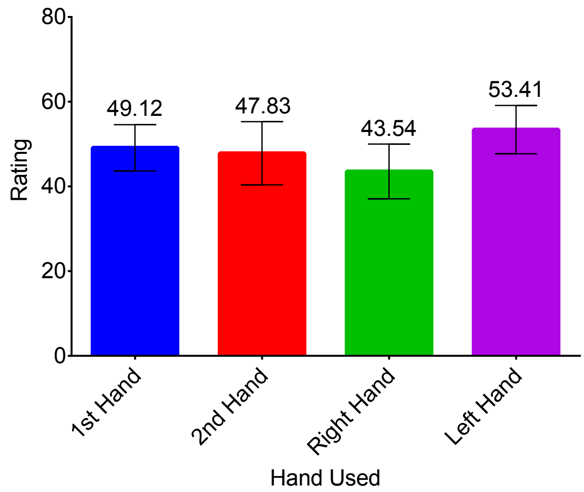


Figure 4.4: Analysis of the NASA-TLX data by Initial Hand and by Dominant Hand. Bars represent 5% confidence interval.

4.5 Results

We have divided the data from the experiment into three sections, the first section will cover our findings regarding the NASA-TLX questionnaires. Then we will analyze the error rates of the selection task and finally we will show the analysis of the target selection times. We will refer during this analysis to the diagram presented in Figure 4.1 to make reference to the angles where the targets appeared.

4.5.1 NASA-TLX Analysis

We wanted to discover if there was a fatigue effect during the selection task and have therefore analyzed the NASA-TLX ratings taking into consideration the relation of first hand and second hand used as well as right hand and left hand (See Fig. 4.4). Additionally we have also calculated the individual ratings of each scale for both hands (See Fig. 4.5).

We can see from Figure 4.4 that users rated their left hand with higher scores meaning that they perceived more effort when using it than when using their right hand. However when we analyzed the data in a first-hand and second-hand basis, we found that the first hand was rated with higher scores than the second one, which might suggest a learning effect given that both, righ and left hands, are mixed in this analysis. Furthermore, we analyzed the individual ratings of each score (See Fig. 4.5)and could corroborate that, indeed the right hand is in general considered to require less effort than the left hand, this can be explained, however due to the handedness of the participants, since all of them were right handed.

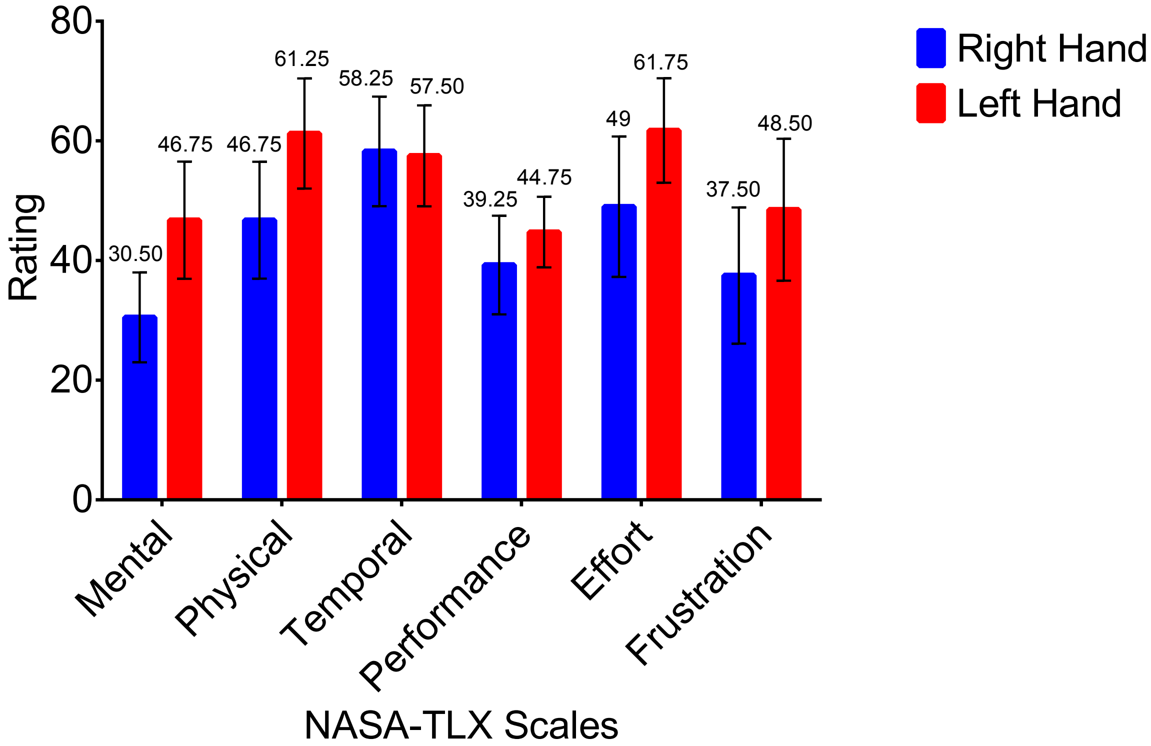


Figure 4.5: NASA-TLX scales shown separately for both hands.

4.5.2 Error Rates

Having 3(target widths) * 4(amplitudes) * 4(angles) per hand for every participant, the total amount of combinations was 48 per hand. However, each of these conditions was to appear 5 times in order to calculate an average selection time for each condition, making a total of 240 tapping actions for each hand. Nevertheless, we also made the application to display each target repetition until a successful tap on the target was recorded. With this condition in mind, we expected, due to accuracy errors from the participants, to have log files longer than 240 records per hand of the participants.

Since each hand was intended to produce 240 records, each participant had to tap 240 * 2(hands) = 480 targets. When we calculated these 480 * 20(participants) we got an expected amount of 9600 records for the whole experiment. As stated before, due to participants' errors, this amount of records was also expected to be higher and the log files revealed we had 11200 tapping events recorded.

We have used the total set of data to calculate the error rates. We have taken the records that were successful at the first trial and compared them against the expected value per variable (target width, amplitude and angle), our results are shown in Fig. 4.6. As expected, accuracy increased according to the target size. The middle section of the figure shows error rate charts for the amplitudes used in the experiment, there we see for both hands that the smallest amplitude resulted in the lowest error rates, unfortunately no pattern could be identified as of how each amplitude value affects the accuracy of the selection tasks.

The analysis of the error rates per angle only let us distinguish which angles offer lowest error rates per hand, for instance the angle of 270° performed better than the other angles of the right hand, but for the left hand the best performance was found in the angle of 90°. Again, we could not identify any pattern that could help us determine what role plays the angle in the occurrence of errors.

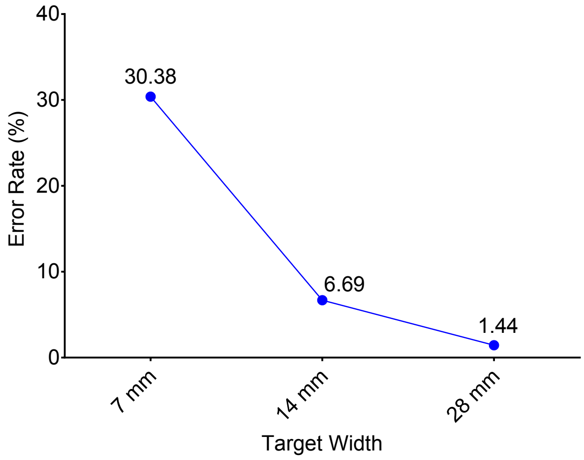
To better understand the relation between the amplitude and angle error rates, we have detailed the respective charts to show what the values are for the specific angles (from the amplitudes charts) and amplitudes (from the angles charts). Our results can be seen in Fig. 4.7. Chart Fig. 4.7 (b) shows that for the amplitude of 40 mm all angles provide similar levels of accuracy, and this can also be seen on Chart Fig. 4.7 (a) where only the angle of 270° shows a greater offset in comparison with the rest of the angles. From Chart Fig. 4.7 (d) we can see that for the intermediate amplitudes (40 mm and 60 mm) the angles of 45° and 135° offer similar performance between them and distinct to the rest of the angles.

We could also see from these charts that the highest accuracy for the shortest amplitude is located in the 135° , followed by the angles of 45° , 270° and lastly the angle of 90° . For the 40 mm amplitude all four angles behave similarly; for the 60 mm amplitude the lowest error rate is again offered by the 135° angle and for the largest amplitude value the best performance is offered by the angle of 90° closely followed by its symmetric angle of 270° while the other symmetric pair (45° and 135°) had the highest error rates, being the 135° angle the worst of all in terms of errors.

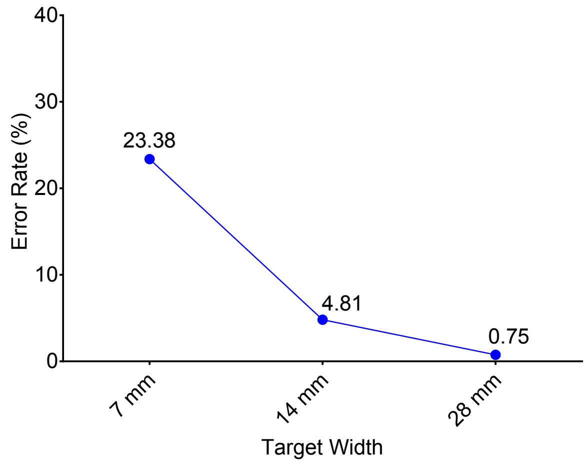
4.5.3 Completion Times

We considered only the tapping events that were successful at the first attempt, reducing our initial data to 8521 records. Since each $W * A * Angle$ condition was repeated 5 times, we took the remaining records and calculated the average of the five repetitions per condition. Given that some of the repetitions were removed in the previous step, for these cases, we had to calculate an average selection time with less than 5 repetitions, reducing our data to 1919 records (of the expected 1920 that correspond to 96 conditions for all 20 participants) since for a few of the conditions there were no successful selections at the first attempt on any of the 5 repetitions.

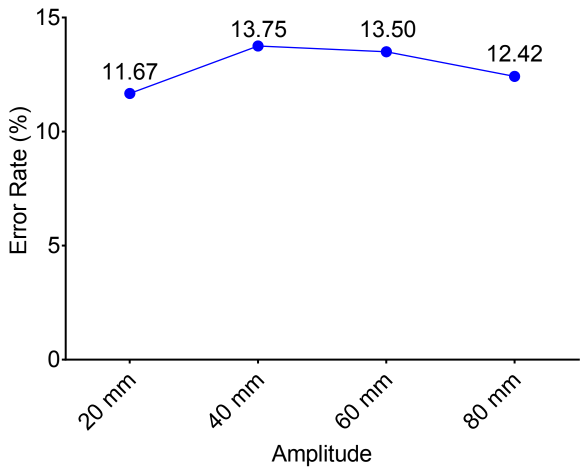
From this subset of data, we reduced noise by filtering out all those selection times whose value differs more than 3 standard deviations from the general mean [ORL$^+$13, WH14]. With



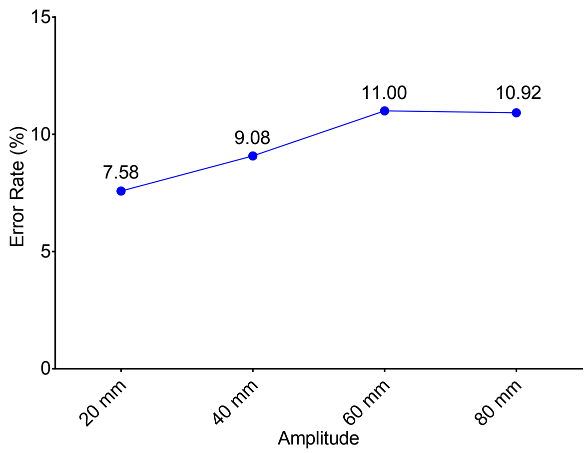
(a) Error Rate per Target Size (Left Hand)



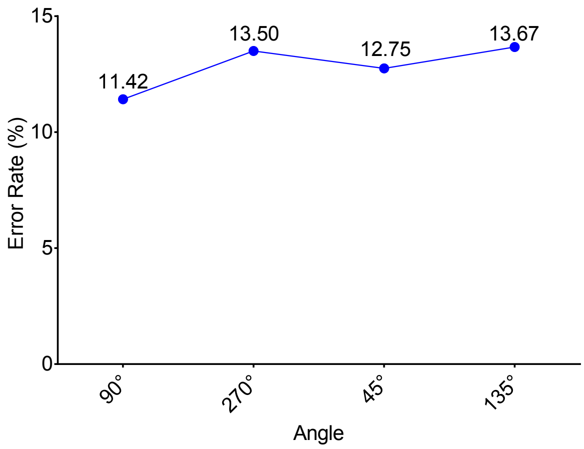
(b) Error Rate per Target Size (Right Hand)



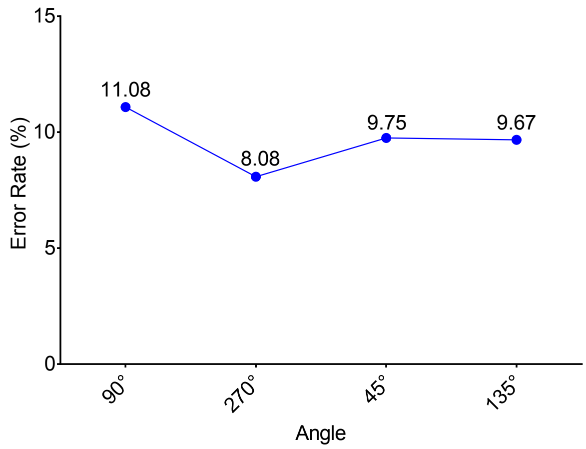
(c) Error Rate per Amplitude (Left Hand)



(d) Error Rate per Amplitude (Right Hand)

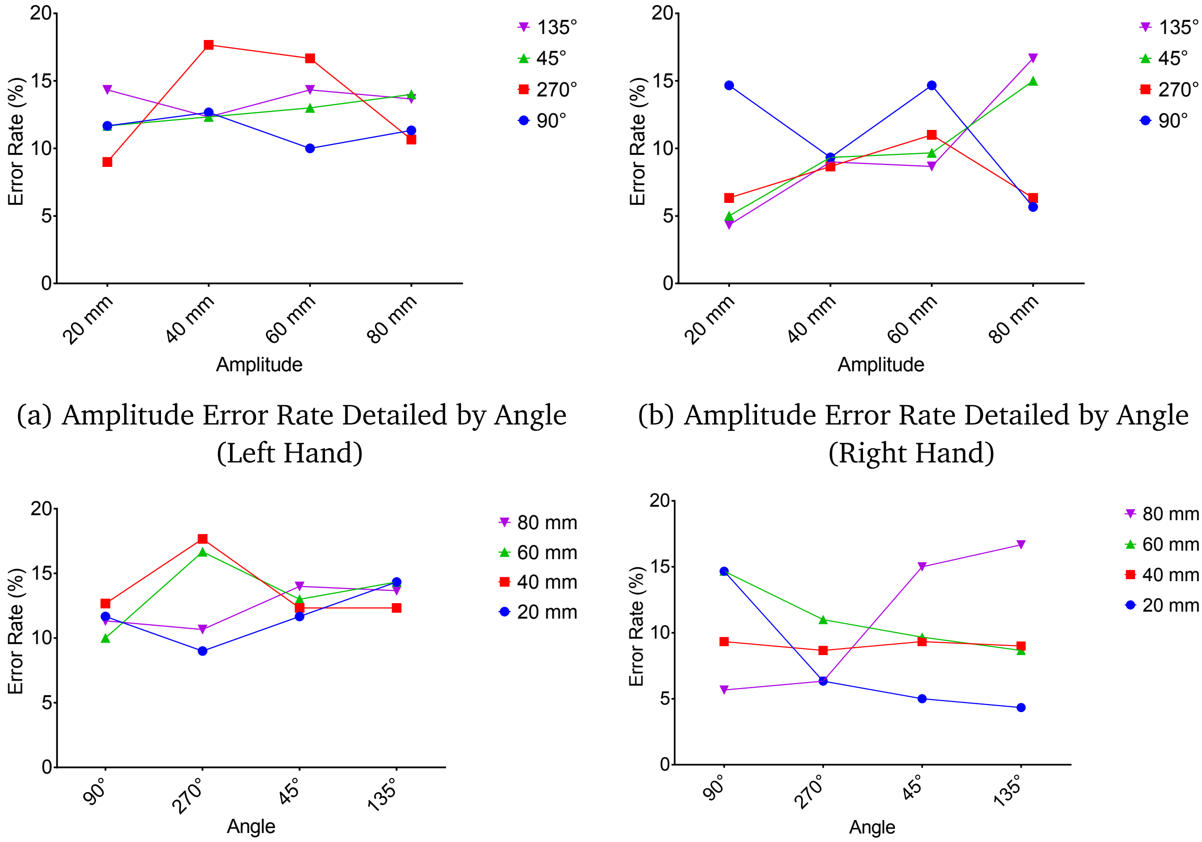


(e) Error Rate per Angle (Left Hand)



(f) Error Rate per Angle (Right Hand)

Figure 4.6: Error Rate Charts divided per Variable (Width, Amplitude and Angle)



(a) Amplitude Error Rate Detailed by Angle (Left Hand)

(b) Amplitude Error Rate Detailed by Angle (Right Hand)

(c) Angle Error Rate Detailed by Amplitude (Left Hand)

(d) Angle Error Rate Detailed by Amplitude (Right Hand)

Figure 4.7: Detailed Error Rates. Top: Relation Amplitude-Angle. Bottom: Relation Angle-Amplitude

a mean selection time of 0.3884 seconds and a standard deviation of 0.1249 seconds, we ended up considering only 1907 tapping events.

When we analyzed the selection times according to the index of difficulty we initially calculated the ID values as shown in Table 4.1a. Then we merged repeated ID values and obtained Table 4.1b which presents a list of unique IDs that was used given that targets with the same ID represent equal difficulty to be reached.

We took all combinations of A/W and calculated the mean selection times that each angle had for each one of those cases (See Fig. A.7 and Fig. A.8), then we calculated a single mean selection time for each A/W combination (See Fig. A.9 and Fig. A.10) and then we obtained the corresponding index of difficulty for every resulting A/W combination (See Fig. A.11 and Fig. A.12), finally we calculated a single mean time per ID value resulting in Fig. 4.8 (a) and (b).

A	W	ID	A	W	ID
20	7	1.947	60	7	3.258
20	14	1.280	60	14	2.402
20	28	0.777	60	28	1.652
40	7	2.747	80	7	3.635
40	14	1.947	80	14	2.747
40	28	1.280	80	28	1.947

(a) Initial Calculation of ID values

ID	ID
0.777	2.402
1.280	2.747
1.652	3.258
1.947	3.635

(b) List of Unique ID values

Table 4.1: Tables of ID values

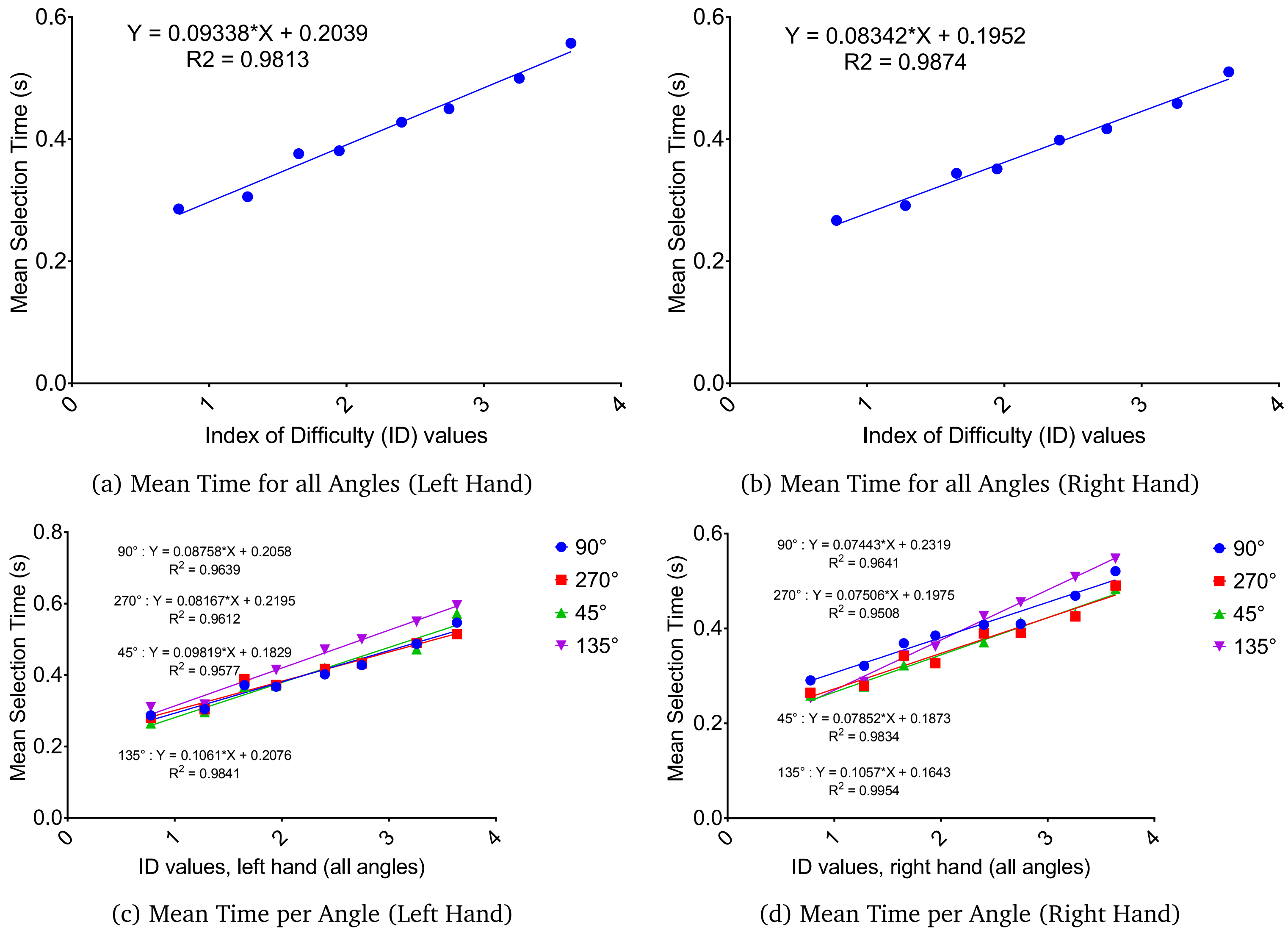
From these charts we can notice that their respective trend line suggests that Fitts' model can provide a very good fit for our results. However, we also calculated individual trend lines for each angle tested (See Fig. 4.8 (c) and (d)) where it can be seen again that even for each angle the model provides a very good fit.

For the analysis of the selection times we expected lower times for both, larger widths and shorter amplitudes, and as expected we found that in our experiment (See Fig. 4.9 (a) and (b)). However we could not identify a pattern for the times regarding the angles, in this case the angles can be divided into two groups according to their symmetry, for instance 90° and 270° angles are similar, but point towards different directions and for this pair we could identify that for the right hand the angle of 270° was faster than its counterpart that point towards the center of the screen.

Likewise the other two angles have a similarity since both point towards the edge of the screen but one (45°) runs on the upper half of the device while the other (135°) runs on the lower half; and for this pair of angles we can notice from the data that the angle of 45° presented better times than the angle of 135°(See Fig. 4.9 (c) , (d) , (e) and (f)).

To have a better understanding of the selection times per angle, we also analyzed the relation of the angles with the amplitudes. In our results (See Fig. 4.10) we see how for every angle their fastest selection times correspond to the shortest amplitude and the slowest time is located on the largest amplitude.

Furthermore, we could also see that if we divide again the angles according to their similarities and compare them, the angles of 45° and 270° have for all amplitudes shortest selection times than their respective counterparts on the right hand. Whereas for the left hand the tendency is similar with the exception that for the pair of 90° and 270° angles the shortest and largest amplitudes have better selection times on the angle of 270° and the other two amplitudes (20 mm and 60 mm) have better times on the angle of 90°.



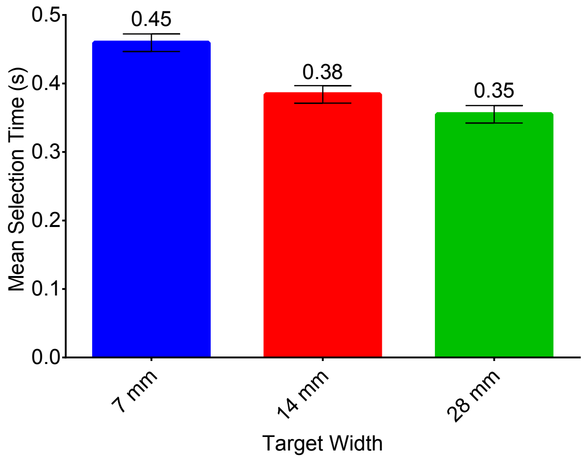
(a) Mean Time for all Angles (Left Hand)

(b) Mean Time for all Angles (Right Hand)

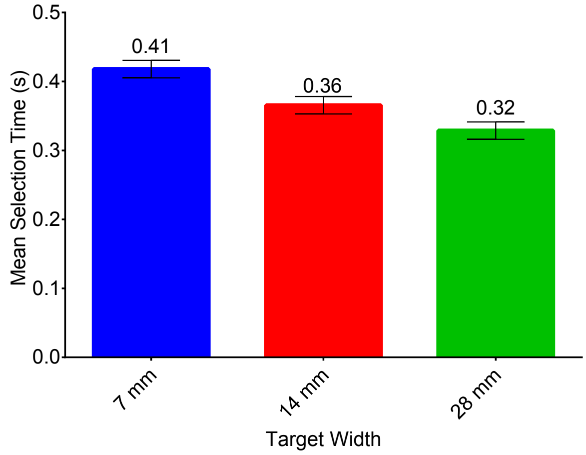
(c) Mean Time per Angle (Left Hand)

(d) Mean Time per Angle (Right Hand)

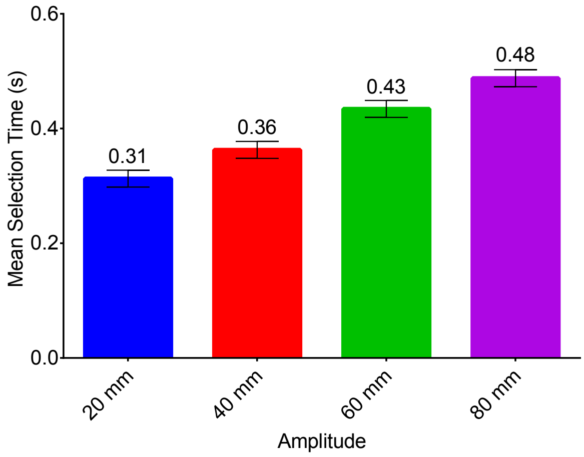
Figure 4.8: Relation between Mean Selection Time and ID values per Angle. Top section shows the relation with a general mean of all angles together. Bottom section shows the relation broken down per angle.



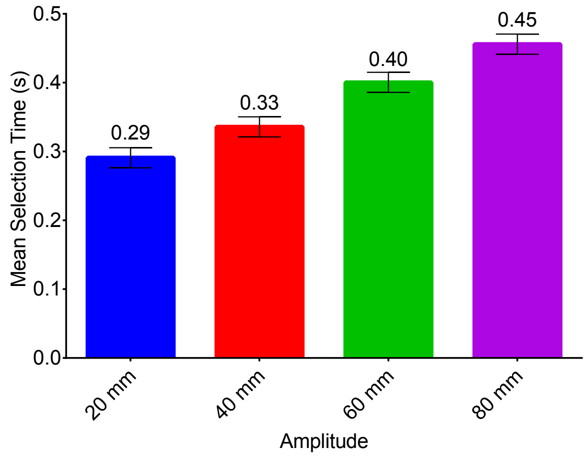
(a) Width Selection Times (Left Hand)



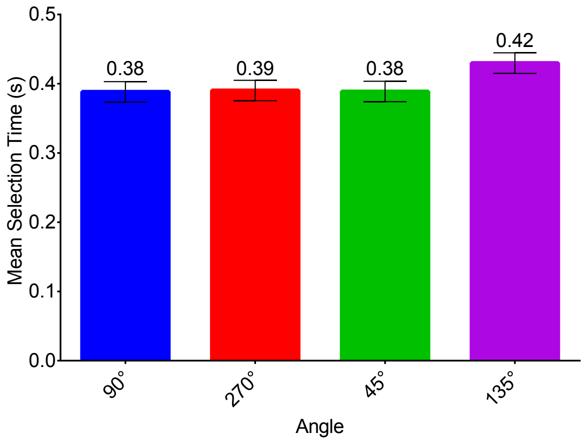
(b) Width Selection Times (Right Hand)



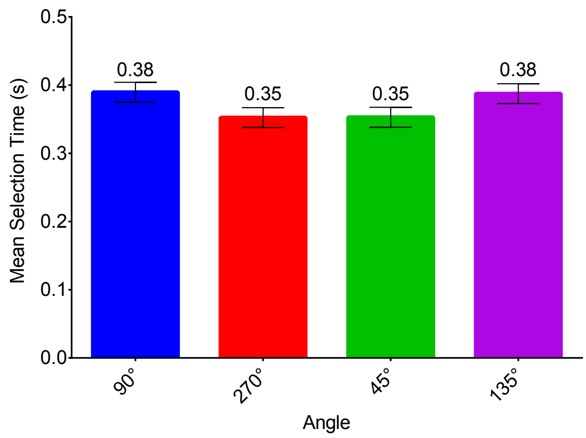
(c) Amplitude Selection Times (Left Hand)



(d) Amplitude Selection Times (Right Hand)

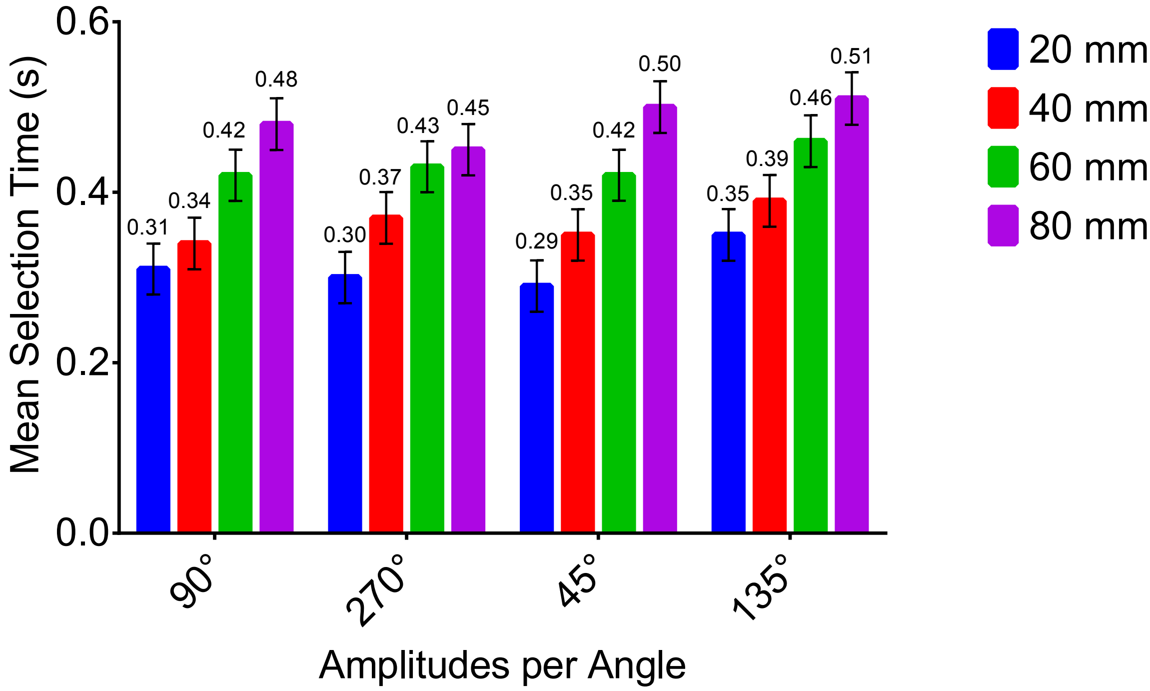


(e) Angle Selection Times (Left Hand)

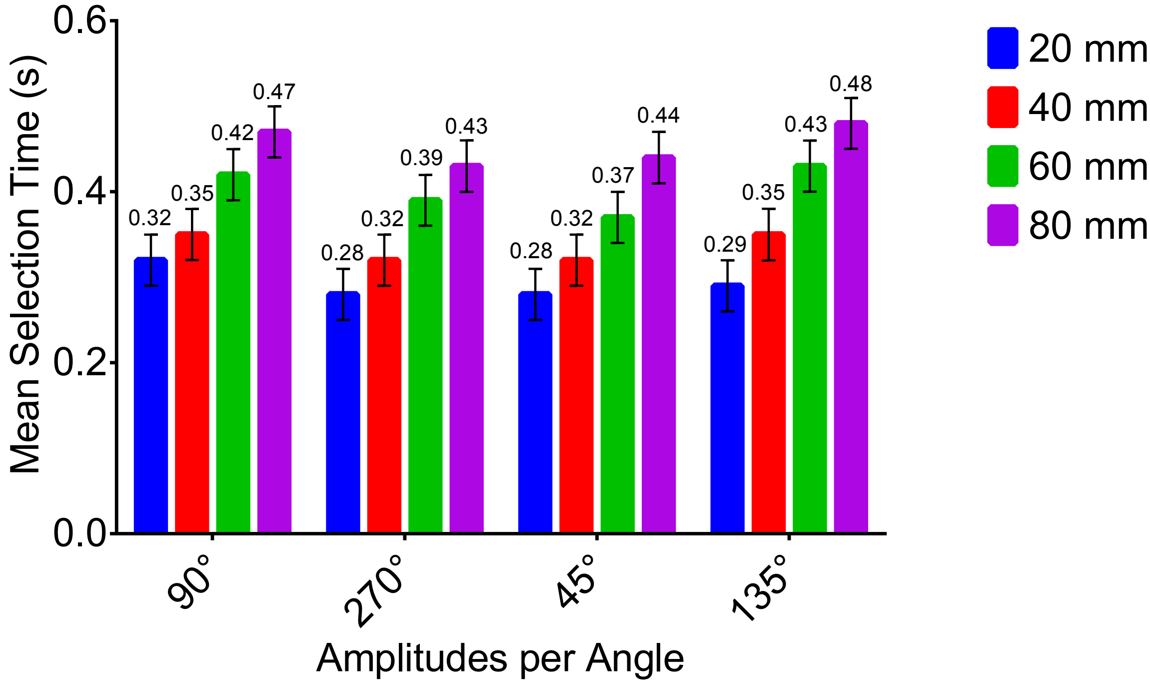


(f) Angle Selection Times (Right Hand)

Figure 4.9: Mean Selection Times per Width (top), Amplitude (centre) and Angle (bottom)



(a) Amplitude Selection Times per Angle (Left Hand)



(b) Amplitude Selection Times per Angle (Right Hand)

Figure 4.10: Mean Selection Times per Angle divided per Amplitude

From these results we conclude that target selection tasks can be performed faster when pointing towards the edge of the screen than towards the center of it; and it is faster as well to point to targets that are located above the thumb than below it.

Given that our results show that the angles have an effect on the selection times but such effect could not be explained with Fitts' model we also conducted a 4-way ANOVA to examine the effect of our variables of Amplitude, Width and Angle, as well as the hand used. For this analysis we have set our confidence level at 5% and our results show that the hand has no significant effect on the selection times ($F_{1,11} = 4.424, p = 0.059$), while target width ($F_{2,22} = 170.572, p < 0.001$), amplitude ($F_{3,33} = 44.804, p < 0.001$) and angle ($F_{3,33} = 19.474, p < 0.001$) did have a significant effect.

Furthermore we also checked for significant interactions and found them between width and amplitude ($F_{6,66} = 125.449, p < 0.001$), between width and angle ($F_{6,66} = 2.863, p = 0.015$) and between hand and angle ($F_{3,33} = 5.739, p = 0.003$).

Pairwise comparisons showed that there is no significant difference between left and right hand, but there is significant difference between all target widths ($p < 0.001$) and amplitudes ($p < 0.001$). Regarding the angles, we found that there are significant differences for all of them except between 90° and 135° ($p = 0.447$) and between 270° and 45° ($p = 1.0$).

4.6 Discussion

We believe that besides the angles, the direction of the thumb to execute the selection task also affects such tasks. Having this idea in mind we have designed an experiment that tests not only the angles, but also the direction that the thumb follows to reach the targets. We have considered for this purpose two directions, one was pointing towards the center of the screen and the other was pointing towards the edge of the device. We discovered that the error rates and selection times present variations for the same angles in different directions which suggests an influence of the direction of the movement in the selection task.

According to our results users perceived the activity to be more demanding when using their non dominant hand and also gave a higher rating to the first hand used regardless of their handedness.

Our analysis of the error rates showed that there are more errors in the cases where excessive thumb flexion was required, that was the case of targets located below the thumb and also the targets near the hand, this behavior had been previously described by Park et al. [PHPC08] stating that targets that require excessive flexion or extension of the thumbs lead to poor precision. This explains the difference on error occurrences in targets located above and below the thumb where the thumb has to be flexed to reach those below it resulting in less precision than when using abduction/adduction movements to reach targets located above.

We analyzed the data as per Fitts' model and found that the model provides in general a very good fit for the experiment, we also conducted an analysis per angle and our results showed that the model also gives a good fit for every angle used.

Similar to Hirotaka [Hir03] who studied the measurement of the thumb's rotation and Trudeau et al. [TYJD12] and Wolf et al. [WSMH14] who showed that the best performance for target acquisition corresponds to the positions where the thumb is not fully extended or flexed, we found that our fastest selection times correspond to the areas where the thumb is naturally relaxed (angle of 45°). We also found that the movements of abduction/adduction of the thumb had a better performance than flexing or extending the thumb which is in line with the findings reported by Odell and Chandrasekaran [OC12] as well as by Trudeau et al. [TYJD12]. In general we can state that the selection times presented in our experiment were significantly affected by the direction of the thumb's movement and not only by the angle, since there are better selection times for the targets located where the thumb has a relaxed position and can be reached by means of abduction and adduction movements rather than relying on flexion or extension of the thumb.

We can conclude thus, that even on conditions with the same angle and amplitude values the direction of the movement executed by the thumb has an influence in determining the performance of the task.

5 Conclusions and Future Work

There have been some efforts to understand the interactions with touch screen devices and most of the existing works have focused on mobile phones. However, tablets have become quite popular as well and have therefore been analyzed. The existing publications about tablets have increasingly grown and covered a plethora of topics among which we can find tablet grip, area of interaction and even target selection. Nevertheless even when target selection has been evaluated and studied, there have not been a study that relates such selection task with the angle where the targets are located. We thought that this angle is an important factor in target selection tasks, since the thumb experiences different levels of difficulty when executing a certain trajectory which means that accuracy and speed are affected during the movement.

Based on the idea that the angle of approach to the target has an effect in the selection task, we designed two experiments. Our first experiment consisted in evaluating different angles and find a relation that those had while using the thumb to select targets. In the second experiment we tested not only the angle, but also the direction followed by the thumb to execute the selection.

We could discover with our experiment on the influence that the angles have in target selection, that although there are regions of the screen that have been previously described by other researchers as more error prone, the accuracy that the users have when reaching targets located in such areas depends not only on the size of the target and its distance from the starting point, but also depends on the angle. This phenomenon has its roots in the biomechanical configuration of the hand which allows the thumb to reach certain areas with different levels of difficulty, based on the effort required to extend and flex it. For instance, we found that targets located directly below the thumb are accessible even with great accuracy when their distance to the starting position is short. However, the performance of this location drops when the distance is increased; in which case other specific areas experience a better performance. That is the case of the region that can be reached below the thumb by extending it in diagonal.

It is important to distinguish this area from another similar region, the one located above the thumb, that can also be reached by means of extending the thumb and using an abduction/adduction movement, since the accuracy presented in this upper region is worse than the one shown in the bottom area. Since we were using the same combinations of distances between the starting position and the targets and target sizes for every region tested, we could consider all conditions to have the same difficulty, however we could see these variations in the occurrence of errors which means that the angles where the targets are located, play indeed an important role for the accuracy of selection tasks.

We also analyzed the selection times and discovered that each angle presented a unique mean time and that there were significant differences between them. Our data showed that users were faster at selecting the targets that appeared on the diagonal below the thumb than those targets shown in any other place. It is worth noticing as well that the users were slowest when the targets appeared on the diagonal above the thumb. Although all considered angles had their own selection times, it is important to notice that these two regions previously described had significant differences when compared against one another and help us conclude that the angles are also an important factor for the speed of selection tasks.

In our experiment about the direction followed by the thumb, we wanted to prove that not only the angles where the targets appeared had an influence on the task, but also the direction of the trajectory followed by the thumb. This can also be explained because of the biomechanics of the thumb, since it requires the use of different movements such as extension, abduction, etc. to reach certain areas and, for instance, excessive thumb flexion has already been identified as offering bad performance.

When we analyzed the error rates of this experiment, we could identify that targets that require excessive flexion of the thumb had more errors, this could be observed on the targets that were located near the palm of the hand as well as the area below the thumb. This area below the thumb is similar to one located above it however, to reach the targets below, the thumb needs to be flexed which causes a higher number of errors, while for reaching the targets above, the thumb describes abduction/adduction movements that resulted in a significant better performance.

Another example of difference in the errors related to the direction of the movement was found in the targets that required a completely horizontal movement, since in those cases the thumb executes either a flexion or an extension motion. We could see that targets positioned near the palm of the hand had a poor performance and that in most cases the regions above and below the thumb offer lower occurrence of errors. These findings mean that the direction where the movement is executed is also important to determine the accuracy of target selection tasks.

When we analyzed the selection times we discovered that there are two regions that provide significantly low selection times. That is the case of the targets that were located above the thumb and when the thumb started completely extended and had to move horizontally while flexing. This means that pointing towards the edge of the tablet's screen results in a faster movement than pointing from the edge towards the center of it, revealing that the direction is directly influencing the selection times for these movements. A similar case was found between the already described region above the thumb and the similar region below it. In this case, the selection of targets above the thumb proved to be faster than that of targets below, confirming that the direction of the thumb's trajectory has a significant effect in the speed of the task since both angles were the same relative to the thumb.

We conclude therefore that both, time and error rate are strongly affected by the direction of the movement executed by the thumb as well as the angle where the targets are located. We can attribute this differences in precision and speed to the biomechanics of the thumb since, it has been already stated that the movements of flexion and extension perform poorly when trying to reach targets on the limits of the thumb's range of motion, and that abduction and adduction result in a better performance. Therefore, it is advisable to place targets in locations that require no excessive flexion or extension of the thumb and use the areas above the thumb or the diagonal below it for better performance depending on the direction of the movement.

Based on our results we propose possible scenarios where to apply this knowledge:

Main Menu Design

Currently the "Home" and "Main Menu" buttons of tablets and other mobile devices are located in places that do not match the best locations found in this study, this makes said buttons more difficult to reach and slow down the experience of the user. Furthermore, once inside the main OS interface the user has frequently the option to add elements to it, but the grid arrangement provided can be improved taking into consideration the places that we have found that favor accuracy and speed.

Application GUI Design

Similar to the previous point, but this one is focused on individual application interfaces. Applications can be improved not only by arranging their menu items, but also by structuring the controls and GUI elements that the users manipulate to interact with the application. Changes done taking into consideration our findings would improve the quality of the user's experience, given that an application is often used for a certain interaction and placing its GUI elements as per the areas that we propose as better options in terms of speed and errors would result in a faster interaction by the user.

Focus on Handedness

Although we have considered only right-handed people in our study, both experiments can be taken and applied to left-handed people. The expectation of this new set of experiments for left-handed people is to have similar results than the ones obtained from our study, since we think that the differences observed between left and right hands are a product of the level of dexterity that the participants had with each hand; nevertheless, it should be properly confirmed. The results found can be applied by the designers in order to provide a better interaction experience after considering the user's handedness. That is, the interfaces of the applications can be adjustable to focus in either the left or the right hand of the screen's device and not be limited to the right-handed results here presented.

Soft Keyboard Enhancement

Although there exist already proposals for soft keyboards that try to take advantage of the two-handed grip, these can be improved by analyzing, both the handedness of the users and the regions were the keys offer a better performance. In this way typing on a soft keyboard would be faster and could also be adapted according to the handedness of the user.

Future Work

We have conducted this study on a specific set of conditions such as target selection tasks with a two-handed grip on a tablet, this requires that the users interact exclusively with their thumbs relying on their thumb length and the movements that it can execute, however suggestions for future projects can be made. Taking as a base this study we present a few of this future projects below:

Target Selection on a Tabletop

As a continuation of this study, it could be interesting to apply it on a different kind of device, a proposal would be to use a tabletop where the participants would be free of holding the device, but the experiment would have to account for the arm length and its degrees of freedom instead of the thumb's. Additionally, the position of the participant and the device should be researched.

Target Selection with Different Gestures

We have considered only tapping tasks, however it has been shown in previous works that this kind of interaction, although the fastest, is also the most error prone; it is possible that an evaluation of other gestures such as drag give a better performance in regards of error rates and, since there was no existing study describing the influence of the angles in this kind of tasks, it is also possible that for certain angles other gestures have also a better performance in terms of speed than a purely tapping task.

Soft Keyboard Layout Based on Angles of Better Performance

Although there exist already proposals for soft keyboards that take advantage of a two handed grip, a new approach can be used, for instance using a fixed side grip and generating a keyboard layout based on positioning the most common letters on the places defined in this study as being less error prone or fastest to reach. It is possible that this layout proves to be faster than approaches that distribute the keys based on the minimum distance to travel from one key to another given that we have found already that some of the regions facilitate their reachability independent of the other considered regions.

A Appendix

A.1 Charts

Fitts' analysis for the experiment of the angles was done in different steps. The following figures represent those steps and are divided into left hand and right hand.

Figure A.1 shows the mean selection times for every amplitude and target width combination for each angle evaluated on the left hand. It can be seen at every A/W combination how every angle performed in terms of selection time.

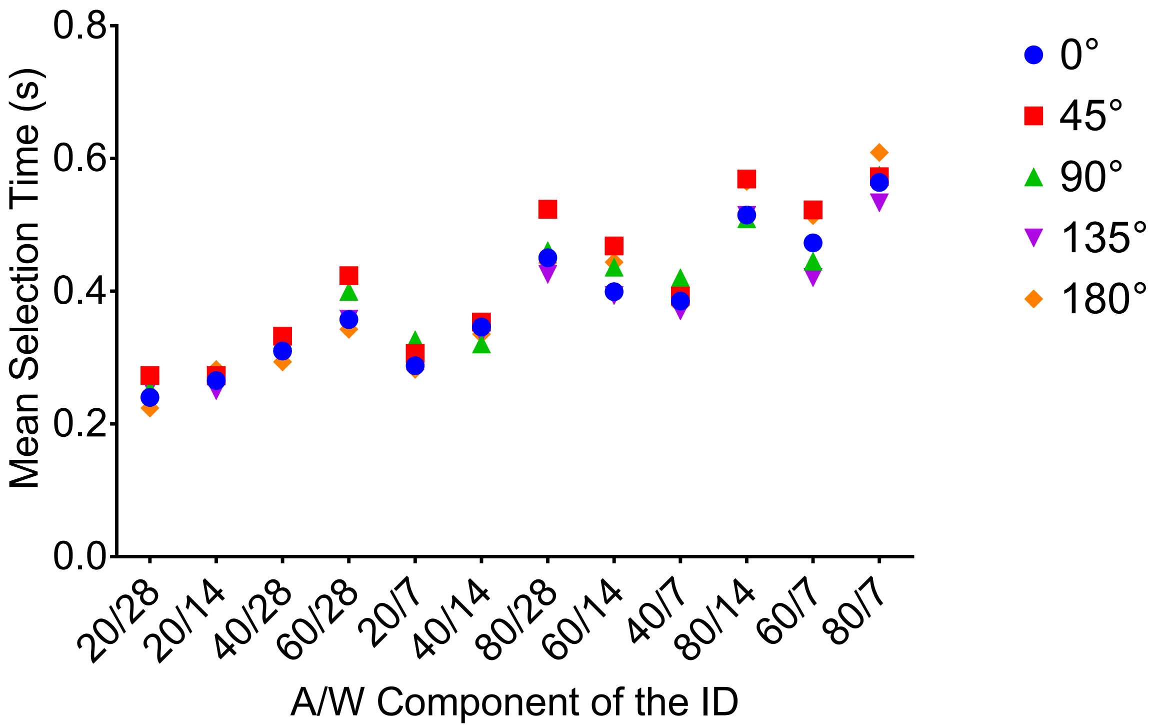


Figure A.1: All A/W Combinations for every Angle (Left Hand). Experiment of Angles

Figure A.2 shows the mean selection times for every amplitude and target width combination for each angle evaluated on the right hand. It can be seen at every A/W combination how every angle performed in terms of selection time.

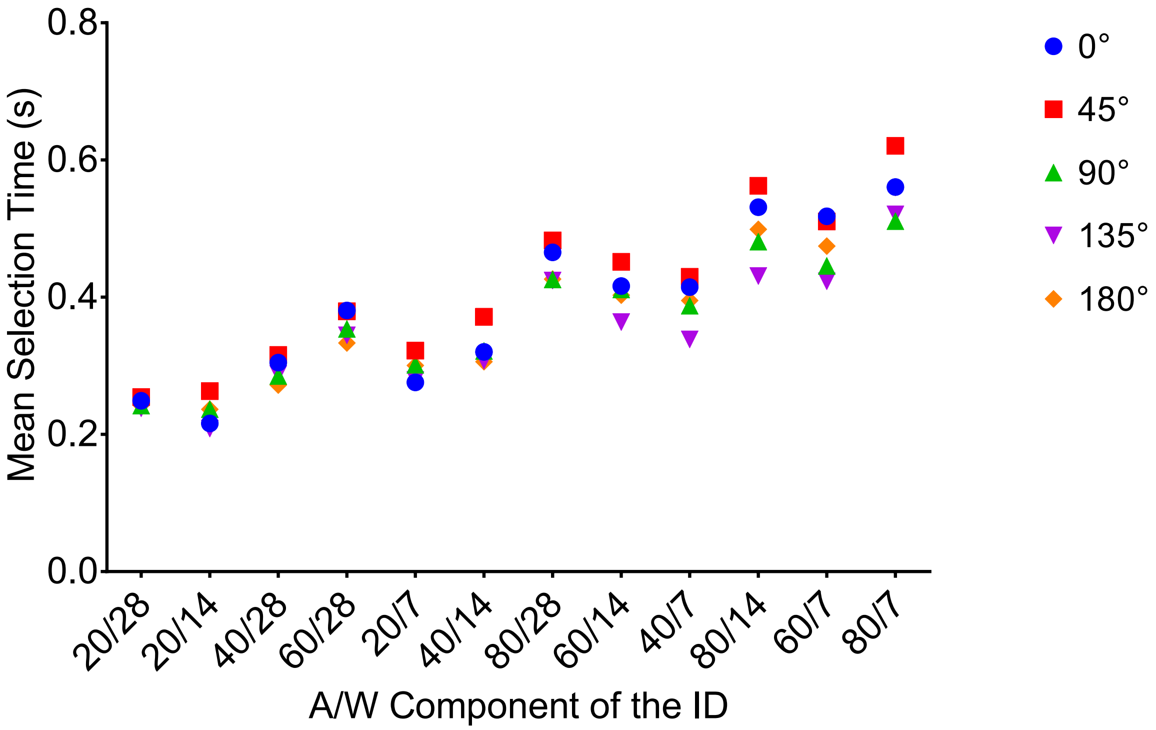


Figure A.2: All A/W Combinations for every Angle (Right Hand). Experiment of Angles

From Figure A.1 we have calculated the mean selection times at every A/W combination resulting in Figure A.3. This values correspond to the left hand.

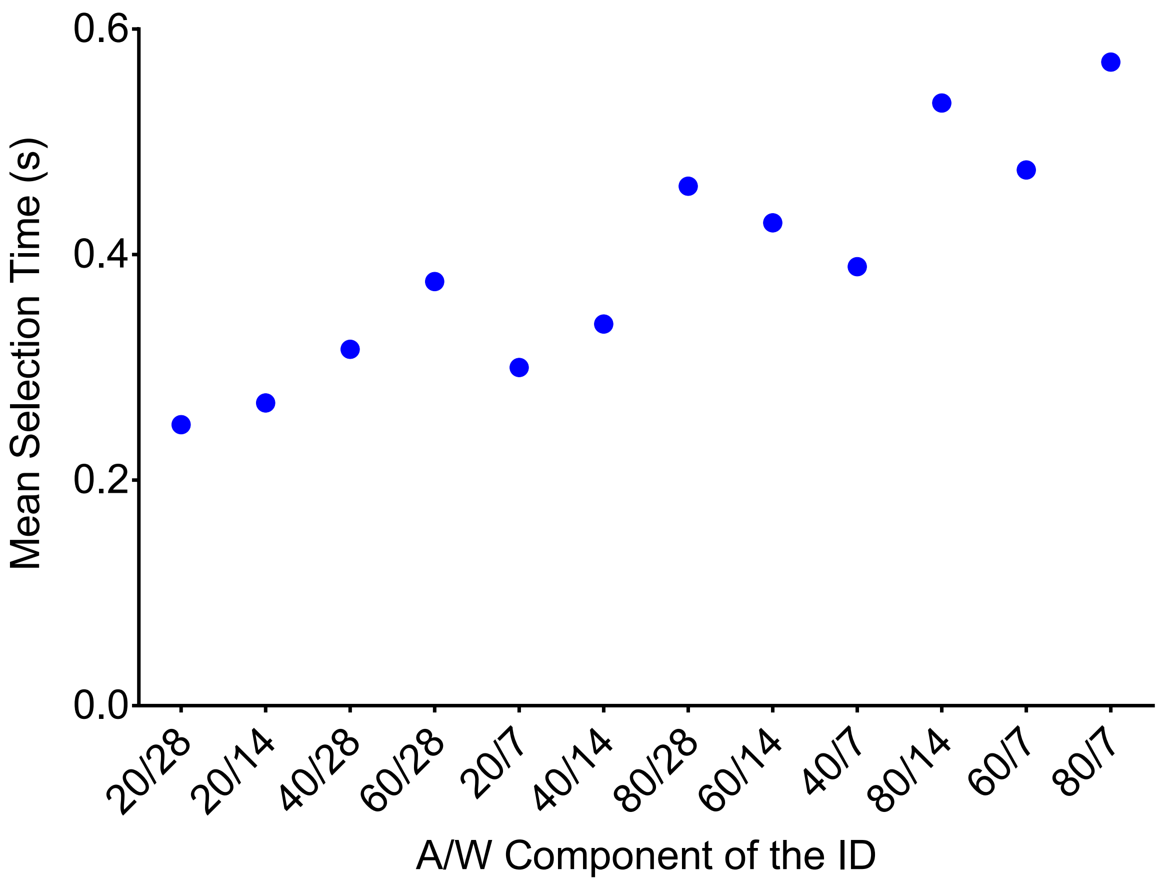


Figure A.3: All A/W Combinations for the mean time of all angles (Left Hand). Experiment of Angles

From Figure A.2 we have calculated the mean selection times at every A/W combination resulting in Figure A.4. This values correspond to the right hand.

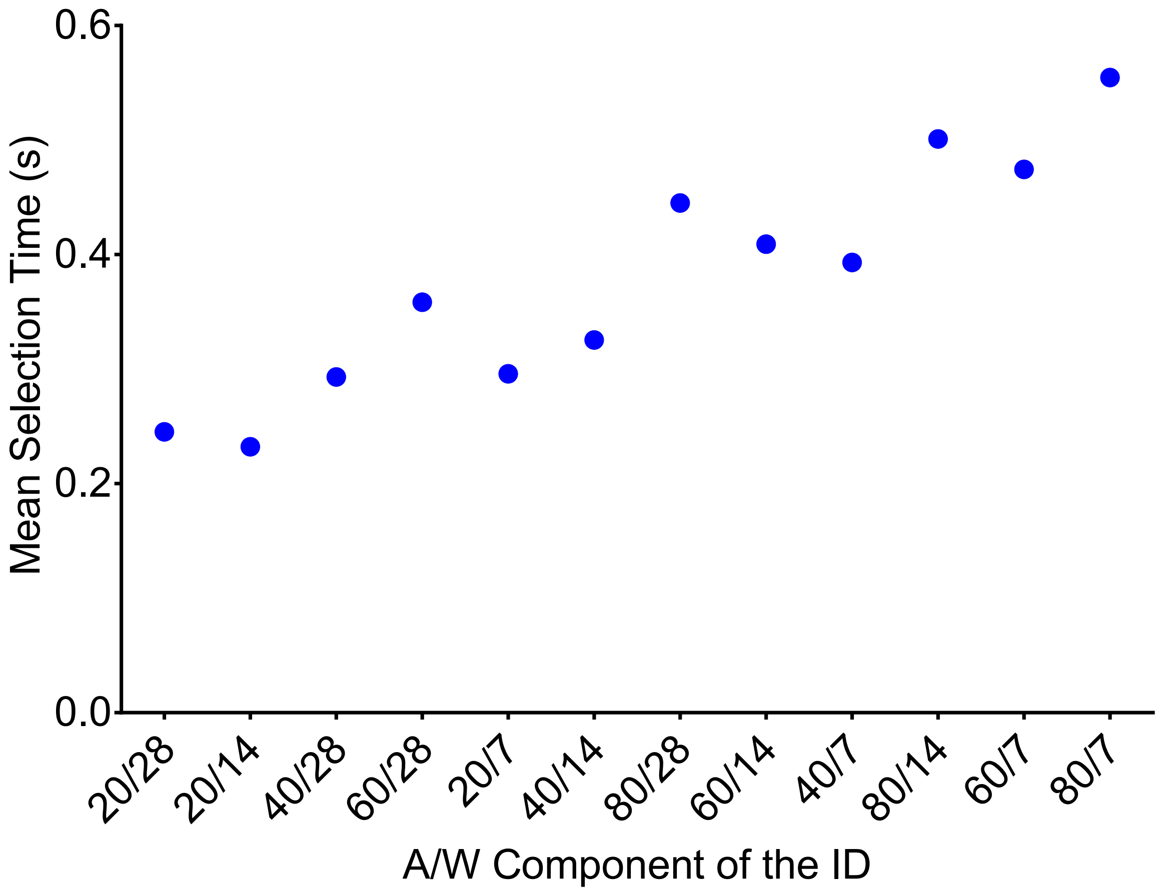


Figure A.4: All A/W Combinations for the mean time of all angles (Right Hand). Experiment of Angles

The following step was to calculate the actual Index of Difficulty (ID) of every A/W combination. Since some of the A/W combinations resulted in repeated ID values there are multiple selection times for those cases. Figure A.5 shows this step for the left hand.

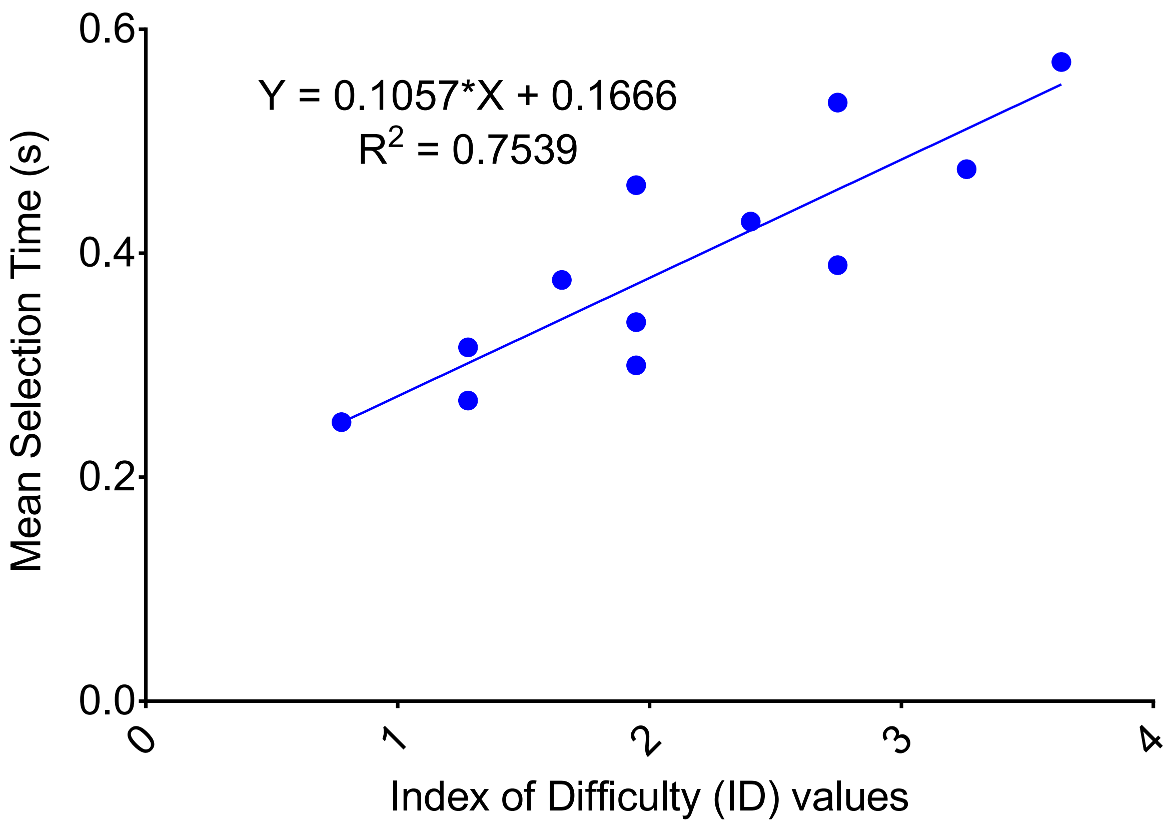


Figure A.5: All different ID values for the mean time of all angles (Left Hand). Experiment of Angles

The following step was to calculate the actual Index of Difficulty (ID) of every A/W combination. Since some of the A/W combinations resulted in repeated ID values there are multiple selection times for those cases. Figure A.6 shows this step for the right hand.

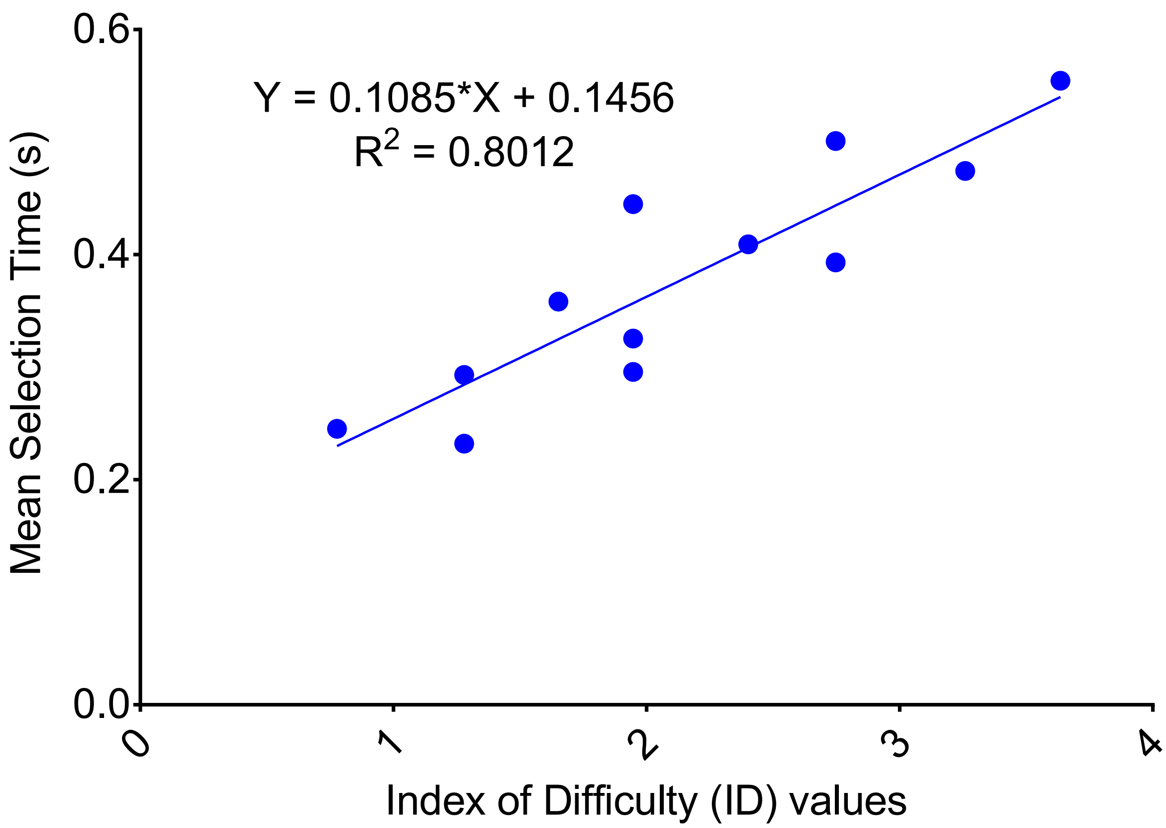


Figure A.6: All different ID values for the mean time of all angles (Right Hand). Experiment of Angles

The experiment of thumb direction required a Fitts' analysis that was carried out in steps. The following figures represent the steps followed to get the final Fitts' analysis and are divided into left and right hand.

Figure A.7 shows the mean selection times for every amplitude and target width combination for each angle evaluated on the left hand. It can be seen at every A/W combination how every angle performed in terms of selection time.

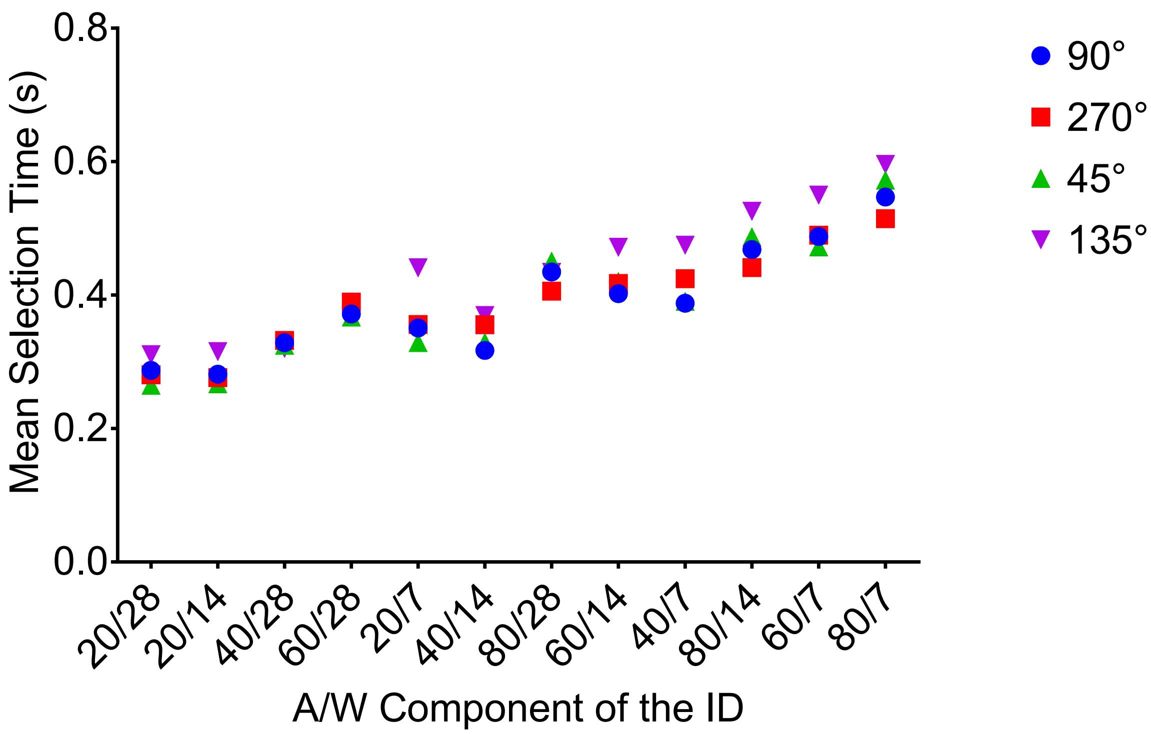


Figure A.7: All A/W Combinations for every Angle (Left Hand). Experiment of Direction

Figure A.8 shows the mean selection times for every amplitude and target width combination for each angle evaluated on the right hand. It can be seen at every A/W combination how every angle performed in terms of selection time.

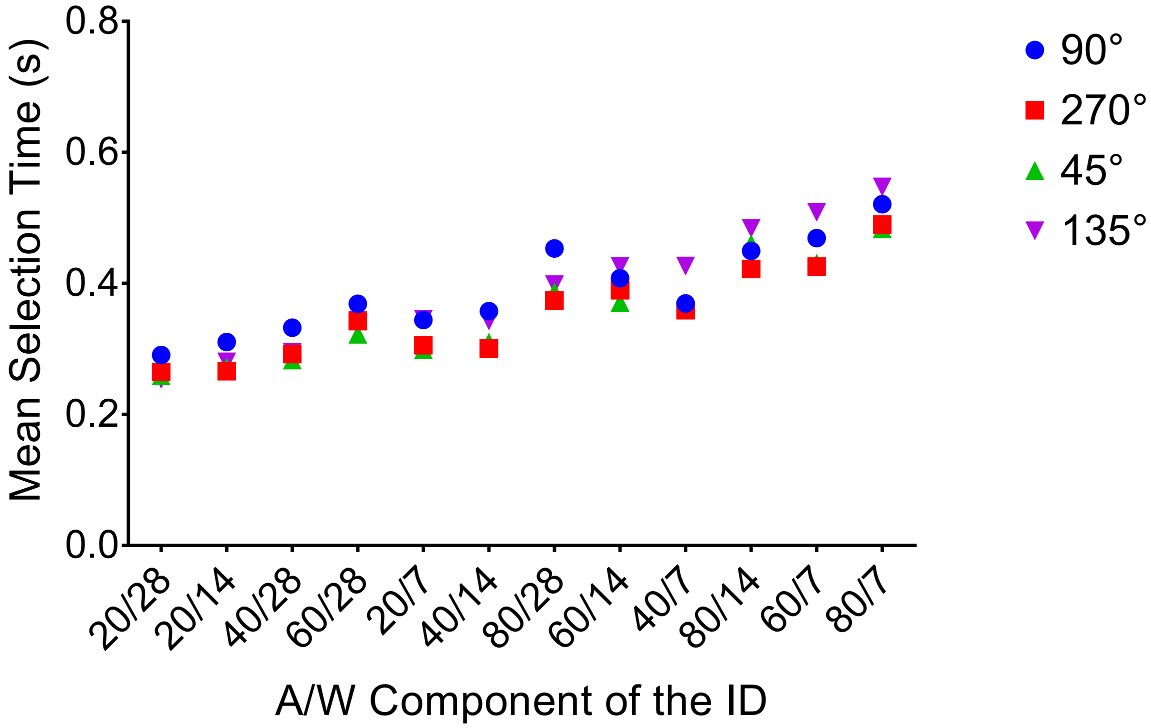


Figure A.8: All A/W Combinations for every Angle (Right Hand). Experiment of Direction

From Figure A.7 we have calculated the mean selection times at every A/W combination resulting in Figure A.9. This values correspond to the left hand.

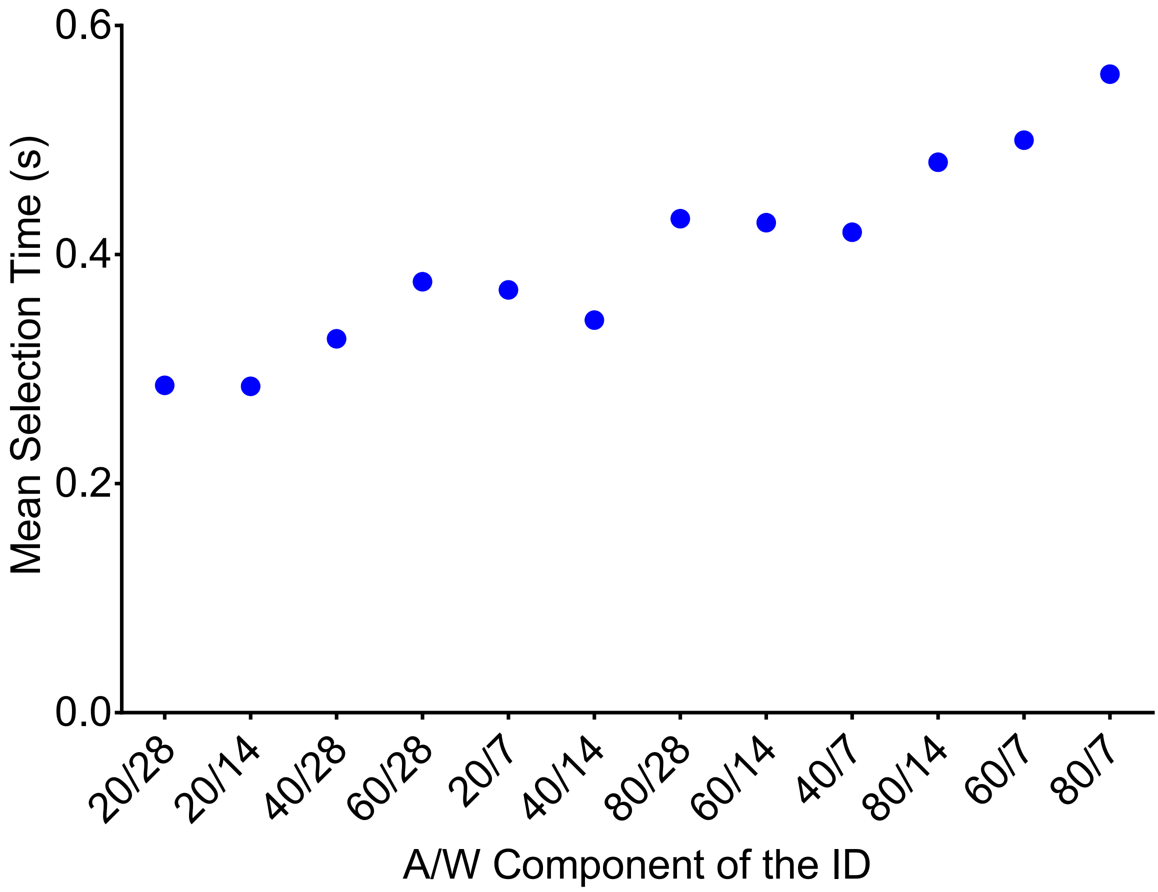


Figure A.9: All A/W Combinations for the mean time of all angles (Left Hand). Experiment of Direction

From Figure A.8 we have calculated the mean selection times at every A/W combination resulting in Figure A.10. This values correspond to the right hand.

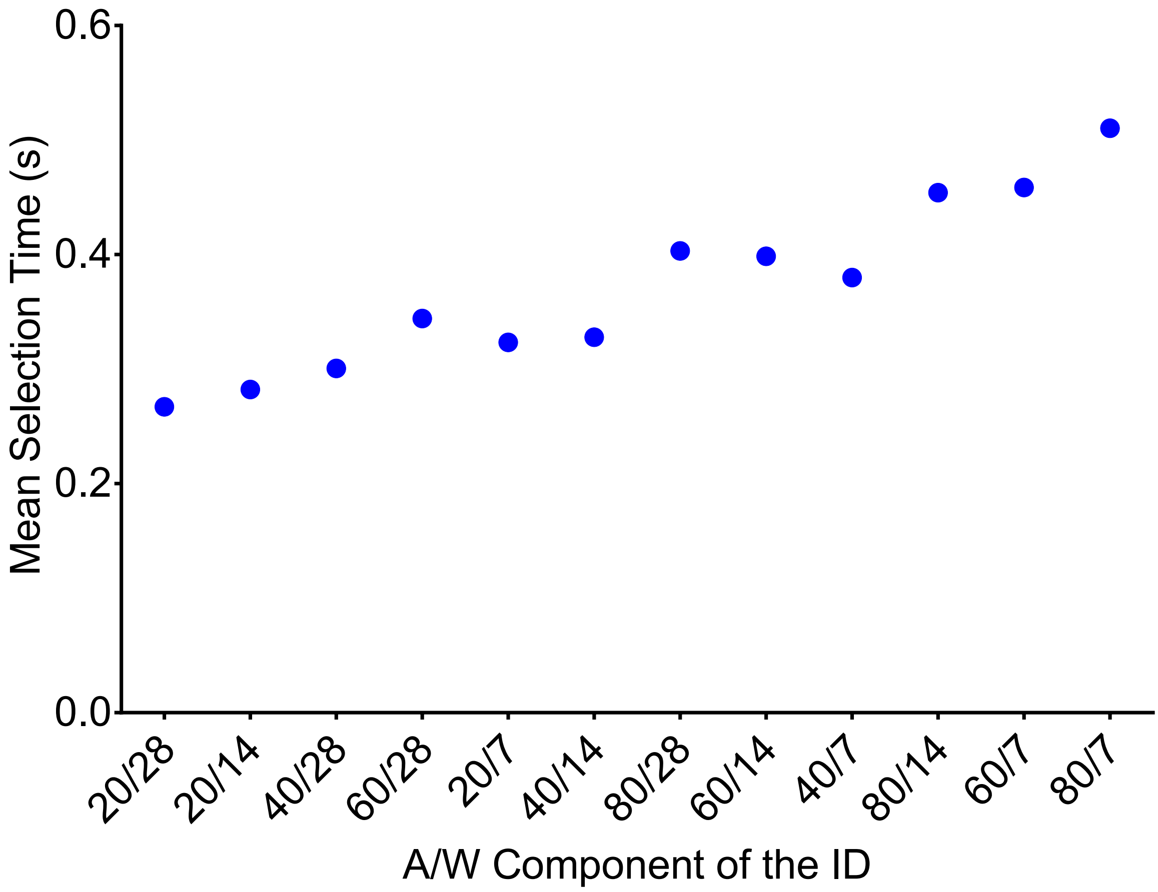


Figure A.10: All A/W Combinations for the mean time of all angles (Right Hand). Experiment of Direction

The following step was to calculate the actual Index of Difficulty (ID) of every A/W combination. Since some of the A/W combinations resulted in repeated ID values there are multiple selection times for those cases. Figure A.11 shows this step for the left hand.

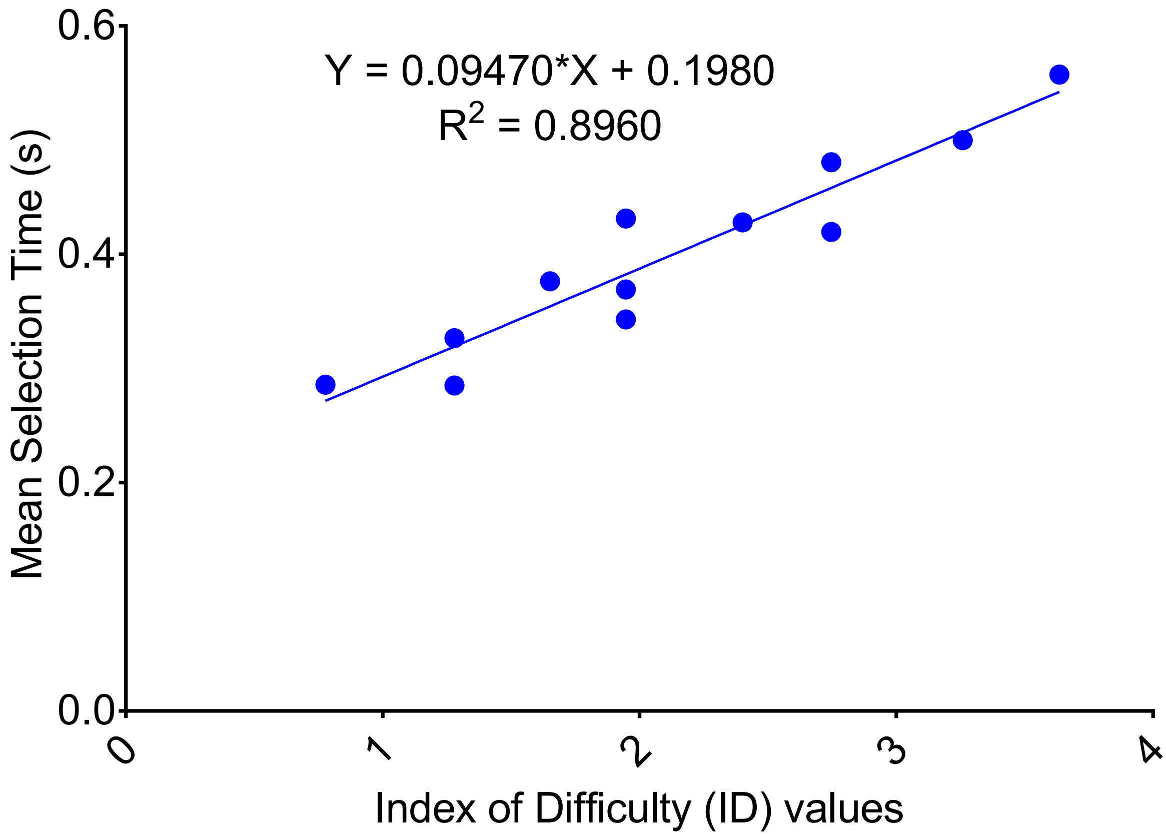


Figure A.11: All different ID values for the mean time of all angles (Left Hand). Experiment of Direction

The following step was to calculate the actual Index of Difficulty (ID) of every A/W combination. Since some of the A/W combinations resulted in repeated ID values there are multiple selection times for those cases. Figure A.12 shows this step for the right hand.

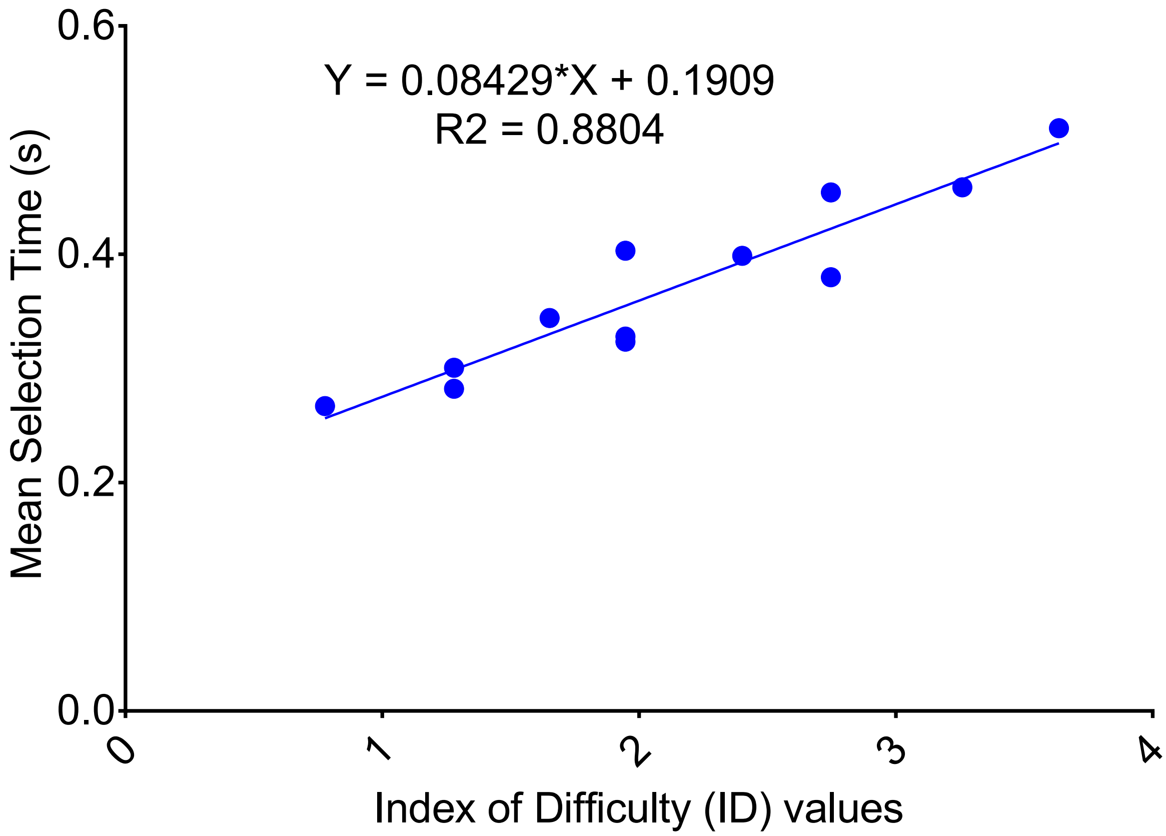


Figure A.12: All different ID values for the mean time of all angles (Right Hand). Experiment of Direction

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All links were last followed on February 2015.

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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