Ergonomics of Thumb-based Pointing While Holding Tablets

Carlos A. F. Salazar,
Niels Henze
University of Stuttgart
Stuttgart, Germany
name.surname@vis.uni-stuttgart.de

Katrin Wolf
BTK University of Art & Design
Berlin, Germany
katrin.wolf@acm.org

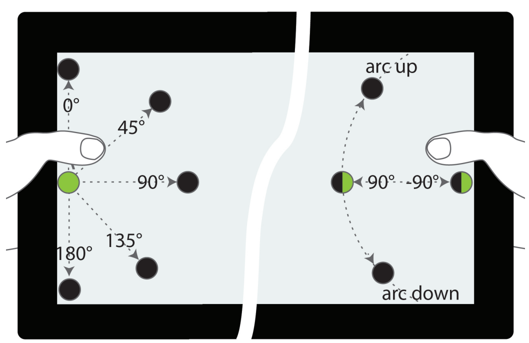

Figure 1: Target selection tasks that challenge the thumbs bio-mechanics and that we use to explore the difficulty of different thumb actions. Start buttons are green, targets are black, target that are green/black switch between these functionalities.

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Abstract
Interaction in mobile computing mainly relies on selecting targets by touch. A large body of work showed the effect of target size and target distance on selection time. Recent work on hand-held devices suggests that size and distance are not the only factors that affect selection time. In this paper, we investigate target selection performance of the thumb when interacting with grasping hands (see Figure 1). In the first study, we show that the relative direction of the target has a significant effect on selection time. In the second study we show that the direction of movement also has a significant effect. The results extend our knowledge about pointing on hand-held devices and can be used to improve transfer functions of mobile GUIs.

ACM Classification Keywords
H.5.2 [User Interfaces]: Ergonomics

Introduction and Background
The required time to select a target while interacting with computers is an important factor when designing graphical user interfaces. Taking the required time to select interactive controls into account can increase users' efficiency and thereby improve the usability of a system. Fitts' Law [5] and its extension to two dimensional tasks [13] predict the time required for rapid aimed movements. Fitts' Law can predict the time it takes to select an interactive control by only con-

sidering the distance and the size of a target and has been described as the most important model in HCI [15]. Fitts' Law has been verified for a very large number of conditions including different movement types, actuating body parts, and user groups [20, 19].

As part of more complex models such as CPM-GOMS [6] and cognitive architectures such as ACT-R [2], Fitts' Law is a powerful tool to automatically asses the usability of user interfaces, including mobile interaction [21, 1]. Previous work, however, suggests that pointing performance does not only depend on the size and distance of a target. A body of work on mouse movement (e.g. [4, 25, 22]) suggests that the angle of approach also has an effect on the time to select a target. Recently, Zhang et al. proposed an extension of Fitts' Law to account for the effects of movement direction on mouse pointing [28].

Compared to mouse pointing, interacting with mobile devices poses additional challenges. Especially for heavier devices, it is typically necessary to use the device with grasping hands to avoid fatigue [17]. However, the center of the device is hard to reach when using the grasping hands for pointing on a hand-held tablet [16, 27], as hand size and orientation determine the accessible area [3]. Furthermore, the hand pose and initial hand orientation influence the performance of touch-based pinch and rotation gestures [10, 11]. Finally, it takes less time to select targets that are located at the position where the thumb joints are in a relaxed pose, whereby selecting targets that are located close to the palm of the hand that is holding the device requires more joint flexing and therefore takes more time [18, 23, 27].

Previous work furthermore showed that the thumb's reach depends on the thumb's orientation and that the selection time depends on the required rotation of the thumb's joint angles [27]. The orientation of the thumb is controlled through its bottom joint (thumb basal joint: TBJ), which has 3 degrees of freedom (DOF) with a maximum rotation angle of 90° in parallel to the palm and 70° towards the palm. The distance of a target pointed at is controlled through stretching the middle joint (thumb metacarpophalangeal joint: TMCP) and the top joint (thumb distal interphalangeal joint: TDIP), when the thumb is initially flexed, e.g. when resting at the bezel. Due to the biomechanics of the thumb, we assume that the pose the thumb has to form to select a target influences pointing performance. The bottom joint allows to rotate the thumb around this joint, which enables to access targets on grasped tablets within a half-circle with a radius of the thumb's length and with the TBJ joint as the center point. Stretching and flexing the middle and top joint allow the user to reduce the radius and consequently enables to access targets within the described half-circle.

To investigate how the thumb pose influences pointing performance on grasped tablets, we designed a set of pointing tasks that require different thumb joint rotations. Due to the large number of degrees of freedom the thumb has, a single experiment would have had taken too long. Hence, we conducted two controlled experiments. We first investigate the effect of the direction into that the thumb has to be stretched to access a target. Afterwards, we explore the effect of four basic thumb movement direction, including stretching, flexing, and bottom joint rotation up- and downwards.

Influence of thumb orientation

In the first experiment we investigated how the direction from which the thumb approaches a target affects the pointing performance.

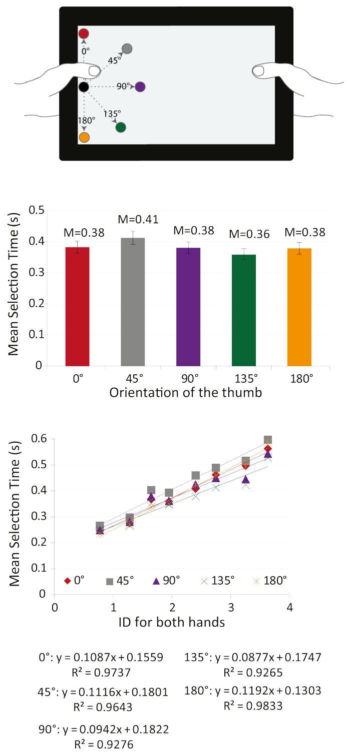

Figure 2: Top: The black starting position and targets in the five investigated directions. Center: Task completion time for the five angles. Bottom: Fitts' Law models for the five angles.

Method

Design

The study followed a 2x5x4x3 within subjects design with the independent variables hand (left and right hand), orientation (0°, 45°, 90°, 135°, and 180°, see Figure 2 left), distance (20, 40, 60, and 80mm), and target width (7, 14, and 28mm). Each condition was repeated 5 times. The distances were chosen according to the nearest and furthest possible distance, considering the tablet bezel as well as an average thumb length [12]. The target widths are consistent with the sizes recommended in previous work [9, 14, 26]. The dependent variables were target selection time and error rate. We also measured the perceived task load using the NASA TXL questionnaire [8] after half of the trials and at the end to test for fatigue effect. We recruited 20 participants, 13 males and 7 females, through our university's mailing list, aged from 21 to 45 (M=28, SD=5.6). All participants were right-handed. To avoid biasing the results due to very short or very long thumbs, we screened for participants with a thumb length between 60 and 75mm. Participants had a thumb length between 61 and 75mm (M=67.3, SD=4.5), applying the measure technique of Greiner [7].

Apparatus

We used a 13.3 inch ODYS Aeon tablet running Android 4.1 for the experiment. The device has a resolution of 1,200x800 pixels and is 20.04cm wide, 15.4cm high and 1.2cm thick. As hand motions would completely change the ergonomics of our tested input technique, we ensured that participants used the same grip through gluing Velcro stripes as tactile feedback to the back of the device at the position where participants had to place their fingers. An Android application displayed the start point for the pointing tasks and the targets. The application recorded the target selection time and errors in log files.

Task & procedure

The task was to tap at the start point, displayed as a 14mm large green dot in the vertical center directly at the vertical bezel where the hand was holding the device. That start point corresponds with the thumb position in a natural pose [27]. Participants were asked to tap as precise and as fast as possible at the targets displayed in black. The color of the start point change to red after the point was successfully selected, and its color switched back to green if the target was successfully hit. Half of the participants started selecting targets with their right hand and the other half started with their left hand. The order of the orientations, distances, and target sizes were randomized. As each target condition appeared 5 times in a row, participants selected 300 targets with each hand resulting in 600 selections in total.

Results

First, we checked if fatigue affects the results. We rejected fatigue as the score of the NASA TLX filled after half of the experiment and at the end did not significantly change ($F_{1,19}$=1.549, p=.228).

Error rate

We considered target selections as an error if the target was not successfully selected by the first attempt. In total 12.000 correct target selections were possible (20 participants * 600 selections). Most selection errors occurred for the smallest target size for both, left hand (LH) and right hand (RH) (7mm: LH=27.25%, RH=27.6%), while the larger targets were less error prone (14mm: LH=6.5%, RH=6.2%; 28mm: LH=1.85%, RH=1.6%). Errors rates differed less for orientation (0°: LH=11.16%, RH=12.58%; 45°: LH=12.16%, RH=11.33%; 90°: LH=14.75%, RH=10.41%; 135°: LH=11.66%, RH=11.08%; 180°: LH=9.58%, RH=113.58%) and distance (20mm: LH=10.6%, RH=11.33%; 40mm:

LH=10.6%, RH=11.8%; 60mm: LH=12.06%, RH=10.4%; 80mm: LH=14.2%, RH=13.66%), while a larger distance generally caused more errors. Overall, 1.420 targets were not selected with the first attempt. Thus, we had 10.580 error-free trials. A 4-way ANOVA showed that hand and orientation did not effect the amount of errors (hand: $F_{1,19}$=.007, *p*=.939, orientation: $F_{4,16}$=.247, *p*=.907), while distance and width did (distance: $F_{3,17}$=4.539, *p*=.016, width: $F_{2,18}$=88.8, $p<.001$). Bonferroni corrected pair-wise t-tests revealed that error rate significantly increased by decreasing width size ($p<.001$). Regarding the distance, the 80mm caused significantly more errors then 60mm (*p*=.011) and then 40mm (*p*=.039), but not then 20mm (*p*=.101). The other distance comparisons did also not cause significantly different error rates ($p>.05$).

Task completion time
For analyzing the task completion time (TCT), we only considered the 10.580 trials that where successfully completed with the first attempt. Furthermore, we used the average time of the 5 times a participants selected a target of a certain size and at a particular position. This reduced our data to 2.392 records (of expected 2.400) as some targets were not selected within the 5 trials. Finally, we removed 22 of the 2.392 records that were more than three standard deviations (0.1498) from the mean (0.3889) [24].

We conducted a 4-way ANOVA to examine the effect of thumb orientation on TCT. The analysis yielded a significant difference for orientation ($F_{4,40}$=9.937, $p<.001$) but not for hand ($F_{1,10}$=.442, *p*=.521). We also found a significant effect for target width and distance (width: $F_{2,20}$=69.376, $p<.001$, distance: $F_{3,30}$=314.3, $p<.001$). In line with Fitts' Law, Bonferroni corrected pair-wise t-tests revealed a significant increase of selection time with increasing distance ($p<.001$) and with decreasing target width ($p<.001$). Regarding the thumb orientation evoked by orientation, post-hoc tests showed that selecting targets in 45° took significantly longer than 0° (*p*=.005), 90° ($p<.001$), and 135° ($p<.001$), but not longer than targets in 180° (*p*=.336) (see Figure 2 center). Finally, we found interaction effects between width and distance ($F_{6,60}$=11.541, $p<.001$) and between distance and orientation ($F_{12,120}$=2.002, $p<.030$).

Fitting Fitts' Law models to the data (see Figure 2 right) revealed a fit of $R^2=.93$ to $R^2=.98$ for the five orientations having the following means: 0°: 0.38s (SD: 0.14), 45°: 0.41s (SD: 0.14), 90°: 0.38s (SD: 0.13), 135°: 0.36s (SD: 0.13), and 180°: 0.38s (SD: 0.15) (see Figure 2 center).

Discussion
Previous work suggested that target selection with grasping hands takes longer for short distances, where the joints are flexed until their biomechanic maximum, while targets that are a bit further away, where the thumb has a relaxed pose, are hit quicker [18, 23, 27]. This phenomenon would contradict Fitts' Law which assumes that selection time steadily increases with distance (for equal target width). In line with Fitts Law', however, selection time (like error rate) indeed steadily increased with increasing distance (20mm=0.20s, 40mm=0.35s, 60mm=0.42s, and 80mm=0.51s). However, we used only 4 distances between 20 and 80mm in our study to end up with a typical number of index of difficulties (IDs) which is the common approach when conducting Fitts' Law studies. There is a chance that the valley in selection times found by others [18, 23, 27] is located in between two of our distances. If this is the case, we could not measure this phenomenon with our experiment design. A slight hint that looking deeper into Fitts' Law for one handed interaction is given by the found interaction effect between width and amplitude. This is not in line with Fitts' Law as the com-

binations of distance and width should result in the same ID.

Analyzing the collected data, we found that the orientation of the thumb indeed has an effect on one handed pointing performance with hand-held tablets. If the thumb moves 45° upwards, the time it takes to select targets increases significantly compared to moving the thumb towards other directions (0°, 90°, and 135°) using the device edge at the inner palm as reference point. The interaction effect of distance and orientation indicates that targets requiring certain thumb orientations are harder for certain distances. A potential reason is that the joints are easier to flex or to stretch for some thumb orientations. Furthermore, for larger distances, the wrist joint could compensate the reachability of locations limited through the thumb's length. This might work well for most orientations, while for others, such as 45°, the wrist rotation is affected by biomechanic constrains as here it has to be negatively over-flexed.

In this experiment, we only considered the thumb's middle (TMCP) and top (TDIP) joint flexing for selecting targets under different bottom joint (TBJ) orientations. Previous works showed that both, high amounts of thumb stretching and flexing negatively effects pointing performance [18, 23, 27]. Thus, to further explore the thumb's pointing performance, we conducted a second experiment to compare the thumb's pointing performance while stretching and flexing as well as when rotating the thumb (at its bottom joint) without stretching and flexing.

Influence of thumb movement direction

Here, we focus on the effect of thumb movement direction on pointing performance, considering stretching and flexing the thumb without rotating the bottom joints and rotating the thumb's bottom joint without stretching and flexing.

Method

Design

The study followed a 2x4x4x3 within-subjects design with the independent variables hand (left and right hand), direction (thumb stretching, thumb flexion, arc up, and arc down) see Figure 3 left, distance (20, 40, 60, and 80mm), and target width (7, 14, and 28mm). Again, the dependent variables were target selection time and error rate. We also measured the perceived task load using the NASA TXL questionnaire after half of the trials and at the end to test for fatigue effect. We recruited 20 participants, 16 males and 4 females, through the mailing list of our university, aged from 19 to 32 (M=23, SD=3.5). All participants were right-handed. We again screened for participants with a thumb length between 60 and 75mm, which resulted in participants having a thumb length between 60 and 75mm (M=68.4, SD=4.8).

Task & procedure

Using the same device and a slightly modified software, the task was again to tap at a start point and then at a target. If the target position should require to stretch the thumb (90°), the starting point had the same position as in the first study. If the selection of the target should require flexing the thumb (-90°), the starting point was places in the vertical center of the screen, 80mm away from the bezel the pointing hand was touching (see Figure 3 left). Half of the participants started selecting targets with their right hand, the other half started with their left hand. Movement direction, distance, and target size were randomized. Each target condition appeared 5 times in a row. In total, participants had to select 480 targets, 240 times per hand.

Results

We found that fatigue did not influence pointing times generated by the hand used in the beginning, as no significant

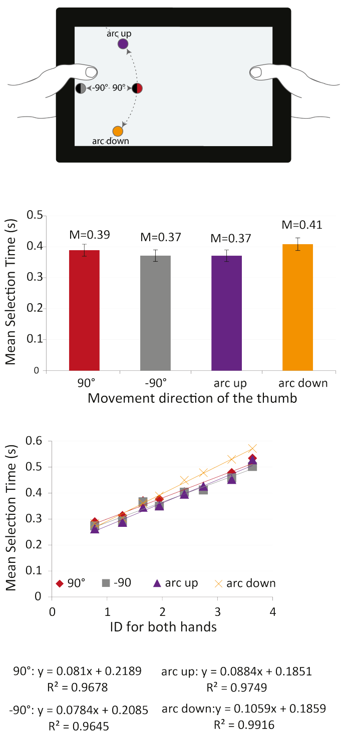

Figure 3: Top: Experimental tasks of pointing from the black start position in 5 different directions. Center: Task completion time over direction. Bottom: Fitts' Low models of task completion time over direction.

difference was found for Task Load Index between the first and the second hand used in the experiment ($F_{1,19}$=.137, p=.716).

Error rate
In total, participants selected 9.600 targets (20 participants * 480 selections). 8.521 targets were successfully selected with the first attempt. The small targets again caused more errors than the larger sizes (7mm: LH=30.38%, RH=23.38%; 14mm: LH=6.69%, RH=4.81%; 28mm: LH=1.44%, RH=0.75%). Error rates differed only little between the different movement directions (90°: LH=11.42%, RH=11.08%; -90°: LH=13.5%, RH=8.08%; arc up: LH=12.75%, RH=9.75%; arc down: LH=13.67%, RH=9.67%) and distances (20mm: LH=11.67%, RH=7.58%; 40mm: LH=13.75%, RH=9.08%; 60mm: LH=13.5%, RH=11.0%; 80mm: LH=12.42%, RH=10.92%) A 4-way ANOVA showed that distance and movement direction did not effect the amount of errors (distance: $F_{2,17}$=2.209, p=.124, movement direction: $F_{3,17}$=.462, p=.713), while hand and width did (hand: $F_{1,19}$=10.389, p=.004, width: $F_{2,18}$=165.153, $p<$.001). Bonferroni corrected pair-wise t-tests revealed that error rate significantly increased by decreasing width size ($p<$.001). Regarding the hand, the left hand caused significantly more errors then the right one (p=.004).

Task completion time
For analyzing TCT, we considered 8.521 trials that where successfully completed with the first attempt. We calculated the average time of the (maximum of 5) times a participants selected a target of a certain size and at a particular position. This reduced our data to 1.919 records (of expected 1.920) as some targets were not selected within the 5 trials. Finally, we removed 12 of the 1.919 records that were more than three standard deviations (0.1249) from the mean (0.3884) [24].

A 4-way ANOVA revealed a significant difference for movement direction ($F_{3,33}$=19.474, $p<$.001) but not for hand ($F_{1,11}$=4.424, p=.059). We found also a significant effect for target width and distance (width: $F_{2,22}$=170.572, $p<$.001, distance: $F_{3,33}$=44.804, $p<$.001). Bonferroni corrected pair-wise t-tests revealed again a significant increase of selection time with increasing distance ($p<$.001) and with decreasing target width ($p<$.001). Regarding the thumb movement direction, post-hoc tests showed that selecting targets in direction of 90° took significantly longer than -90° (p=.028) and than arc up (p=.002), but not than arc down (p=.447). Selecting targets in direction of -90° was significantly faster than arc down ($p<$.001), but not than arc up (p=1.000). Pointing at targets arc up-wards is significantly faster then arc down-wards ($p<$.001), see Figure 3 center. Finally, we found interaction effects between width and distance ($F_{6,66}$=125.449, $p<$.001) and between width and movement direction ($F_{6,66}$=2.863, p=.015).

Analyzing our data showed a fit between 96 and 99% with Fitts' Law for all movement directions (R^2=0.96 for -90°, R^2=0.99 for arc down), see Figure 3 right, that have as means: thumb stretching: 0.39s (SD: 0.11), thumb flexion: 0.37s (SD: 0.11), arc up: 0.37 (SD: 0.12), and arc down: 0.41s (SD: 0.12) (see Figure 3 center).

Discussion
This experiment showed that the movement direction of the thumb has an effect on target selection time. We found that moving the thumb upwards and flexing it is faster than moving it downwards or stretching it. In previous research it was stated that pointing at positions, where a thumb is in a relaxed position is faster than where it is flexed or stretched [18, 23, 27]. Previous work did neither state whether stretching or flexing is faster (requiring the thumb's middle (TMCP) and top (TDIP) joint rotation) nor did it consider up- or down-

wards movements (realized through bottom joint (TBJ) rotations). Thus, we can extend the existing body of work on thumb ergonomics in one handed target selection.

Selection times of our second experiment are again in line with Fitts' Law using only 4 distances, which, like in experiment 1, could hide some effects; and future research may consider this lack in data resolution and use more data points within the reach range of the thumb. While error rate again differ for target width, they interestingly and in contradiction to the first experiment differ also between hands, but neither for target distance nor for movement direction. This surprising result may again be a motivation for future research, and considering smaller distance gaps in future studies may provide deeper insight into thumb ergonomics when pointing and grasping a device at the same time.

Conclusion

In this paper, we presented two studies that investigated target selection performance using the thumb when interacting with grasping hands. We show that the relative direction of the target as well as the direction of movement significantly affect users' performance. Selecting targets 45° upwards and 180° downwards is slower compared to other orientations. Moving away from the palm is slower than moving towards the palm. Moving downwards is slower than moving upwards.

While the results extend our knowledge about pointing on hand-held tablet, they also apply to ergonomically optimizing mobile GUIs. Grid menus, used for example to start application, could be organized so that often selected icons are located at easily reachable positions. Moreover, (half) pi-menus could be optimized by not only placing more often used functions at position within easy reach but could also be optimized for action sequences that are easy to perform.

In this paper we did not considered that the thumb occludes the target differently for different orientation and directions of movement. It would therefore be interesting for future work to investigate the effect of occlusion for different orientations and directions of movement.

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