Touch Pointing Performance for Uncertain Touchable Sizes of 1D Targets

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ABSTRACT

When users operate smartphones and desktop interfaces with their fingers, there are differences between the motor and visual widths. For example, when a user selects an item from a vertical menu, the area that is physically touched by the user is often larger than the visual width (e.g., of the label for the item selected). Therefore, the user aims for the label assuming that the label width (the visual width) means the motor width. Consequently, the user performs operations more carefully than necessary. We conducted an experiment to investigate the effect of the motor and visual widths on finger pointing. After asking participants to explore the motor width, they performed an experimental task. Our experiment shows that the users' movement time depends on the motor width and can be predicted. We also analyze existing interfaces and discuss the implications.

CCS CONCEPTS

• **Human-centered computing** → *HCI theory, concepts and models.*

KEYWORDS

Effects of motor and visual widths, finger pointing, Fitts' law, GUIs

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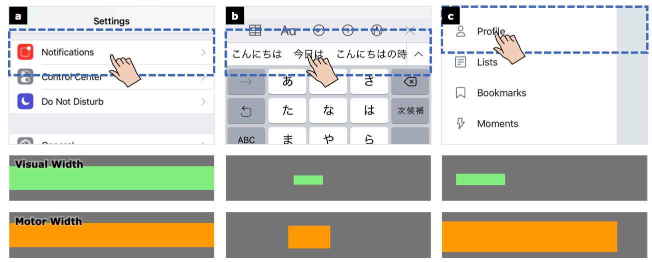

Figure 1: Examples of touch interfaces with a difference between visual and motor widths (top row). Visualizing the visual width (middle row) and motor width (bottom row).

1 INTRODUCTION

In finger pointing, because users occlude targets with their fingers, and because typical capacitive touchscreens detect the center of the finger contact area as the touch point, there is a gap between the user's intended touch position and the touch position recognized by the system [9]. Therefore, when a user types on a software keyboard, for example, sometimes keys other than the target key are pressed. This phenomenon is called the "fat finger problem." Researchers have proposed new interaction techniques to solve the fat finger problem by reducing occlusion [14, 17] and supporting small target acquisition [19]. In addition, because a finger is less accurate than a mouse [3], in touch interfaces such as those of smartphone applications, objects are larger than those on desktop interfaces. As shown in Figure 1, objects are sometimes arranged in one dimension; thus, they can have a large *actual* width along the x-axis. In this paper, we define the actual width, where users can touch the screen and the system senses it, as the *motor width*. Further, we define the size of objects that users see as the *visual width*.

Figure 1a shows that the target has the same motor and visual widths, and Figure 1b and c show that the motor width is larger than the visual width. According to some models, such as Fitts' law[5] and FFitts law[2], when the target width is small, the time taken for users to acquire the target is long. In Figure 1b, where the user types on the keyboard and tries to touch one word among the suggested words, it is expected that the user will perform operations more carefully than necessary because the user believes that the text length (the visual width) means the motor width. In addition, because many laptops are now equipped with touchscreens, users operate not only smartphones and tablets but also computers with their fingers. When users select a column in a spreadsheet, for example, they must touch a target whose motor width is smaller than the visual width (Figure 1c in [15]). In short, targets can have the same motor and visual width or different motor and visual widths, and users must tap the motor width accurately with their fingers.

In this study, we investigate the effect of the motor and visual widths on finger pointing. Usuba et al. previously investigated this effect [15, 16]. However, the input device in their experiments was a mouse, rather than fingers. They found that users performed pointing operations while watching the change of cursor color[1]. In finger pointing, by contrast, users touch the target directly, so some operations performed using a mouse are impossible on touchscreens. In addition, in their experiments, participants were notified of the motor width by sound and text [16] or by highlighting it [15]. However, when using touchscreens, users are not notified of the motor width; they memorize it when using the applications and adjust their tap positions based on it. Therefore, in our experiment, we provided time for the participants to explore the motor width, rather than merely informing them of it. Only thereafter did the participants perform the experimental task. We believe we can understand the effect of the motor and visual widths on finger pointing in a more practical way. Our key contributions are as follows:

- In our experiment, in contrast to researches by Usuba et al. [15, 16], we did not notify participants of the motor width. Instead, we provided time to explore it. Users memorized it when using the applications; thus, our experiment was more suitable for testing touch operations.
- Because the input device was a mouse in the experiments conducted by Usuba et al., their results cannot be directly applied to finger pointing. Therefore, our results form a novel contribution to understanding finger pointing and the design of touch interfaces.
- We found that the participants aimed for the memorized motor width, and that the users' movement (e.g., the movement time and the error rate) strongly depended on the motor width. The effect of the visual width was observed to be slight. This is consistent with the effect on mouse operations [15, 16].
- Even if there is the difference between the motor and visual widths, Fitts' law, using the motor width, can predict the movement time when participants receive enough visual feedback.

[1]The cursor color changed when the cursor entered the motor width [15, 16].

2 RELATED WORK

Models for Pointing

Equation 1 shows Fitts' law [5], which can predict the movement time of pointing MT with the distance to the target D (or A in some studies), target width W, and two linear regression constants (a and b):

$$MT = a + bID, \text{ where } ID = \log_2\left(\frac{D}{W} + 1\right) \tag{1}$$

In user studies on pointing, an experimenter typically asks participants to aim for the target as quickly and accurately as possible. It is known that there is a speed–accuracy tradeoff: if participants perform pointing quickly, the error rate is higher, and vice versa [20]. If the speed and accuracy are reasonably balanced, and if devices such as mice and styli are used, the error rate will be close to 4%[11, 13]. However, with a narrower target, the error rate is higher [7]. If the error rate deviates from 4%, Fitts' law is modified by using ID_e (Equation 2) instead of ID [4, 11]. ID_e is calculated by using the standard deviation of tap positions (σ):

$$ID_e = \log_2\left(\frac{D}{\sqrt{2\pi e}\sigma} + 1\right) \tag{2}$$

It is known that there is a gap between the users' intended tap point and the position where a touch is sensed on the screen [9]. Therefore, a model taking the absolute precision of finger touching into account has been proposed, called FFitts law [2] (Equation 3). In our experiment, the input probe was the participant's finger; thus, we also verified the fitness of FFitts law for our results.

$$ID_f = \log_2\left(\frac{D}{\sqrt{2\pi e\left(\sigma^2 - \sigma_a^2\right)}} + 1\right) \tag{3}$$

Effect of Motor and Visual Widths

Usuba et al. investigated the effect of motor and visual widths on the acquisition of small targets (e.g., window frames) [16] and larger targets [15]. To the best of our knowledge, only these two studies have investigated this effect. The studies included conditions where the motor width is (a) smaller than, (b) equal to, and (c) larger than the visual width. They found that user movements depend strongly on the motor width, but not the visual width. That is, the average speed does not change as a result of changes to the visual width. They also showed that the distribution of click coordinates depends on the motor width; hence, using an effective width provides a good fit given differences between the motor and visual widths. However, it is still unclear whether their results can be directly applied to different input devices such

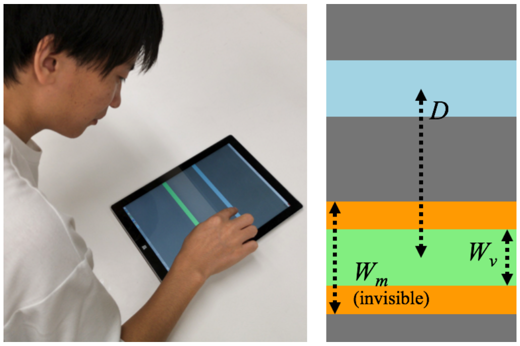

Figure 2: Experimental task outline.

as touchscreens. Additionally, in their experiments, they notified the participants of the motor width; the effect without this prior notification is unknown. We believe that replicating Usuba et al.'s experiments under different conditions (e.g., using finger touches, and not notifying the participants of the motor width) provides a novel contribution to the design of touch interfaces and a better understanding of finger pointing overall.

3 EXPERIMENT

Figure 2 shows an outline of the experimental task. Participants performed discrete 1D pointing tasks vertically (from top to bottom).

Apparatus

We used a Microsoft Surface Pro 3 tablet (Intel Core i7, 2.29 GHz, 2 cores, Intel HD Graphics 5000, 8 GB RAM, Windows 8.1 Pro). We rotated the screen vertically; thus, the display scaling resolution was 1440 × 2160 pixels (the actual size was 12 inches, 169.07 × 253.61 mm, with 0.12 mm/pixel resolution). The participants tapped the surface with their right index finger. We turned off Windows' default touch feedback. The full-screen experimental system was developed using JavaScript.

Participants

Twelve volunteers participated in this study (four females, with a mean age of 22.08, *SD* = 2.27 years). All participants were right-handed and usually operated touch displays with their right hand. Each participant received US$18 for the study.

Task

As shown in Figure 2 (left), the visual width W_v indicates the target size displayed on the screen. The motor width W_m is the invisible area that needs to be tapped to succeed in a trial. When the participants touched the start area (blue), a sound was played to inform them that the trial was beginning, and measurements began. The participants aimed for the end area (the green target). Then, if the touched position was within the motor width, a sound was played to indicate success. However, if the position was outside the motor width, a different sound was played to indicate failure, and the trial was regarded as having failed. Thus, although we did not visualize the touch position, we informed the user whether the touch was successful using sound.

These conditions regarding how to inform the participants of the result were determined based on realistic user interface designs. For example, when users would like to select a menu item, if they touch an undesired item next to the intended item, they are led to an incorrect page. Then, they understand that the touch point was outside the intended target. In addition, if the touch point falls within the margin between two items, nothing happens, and the user remains on the current page. Likewise, they will understand that the touch failed. In summary, users understand whether the touch is successful, but they do not know the actual touch position. Therefore, we decided to inform the participants whether the trial was successful exclusively using sound.

Design

The distance to the target D was 600 or 800 pixels (70.45 or 93.93 mm, respectively). Both the motor target width W_m and visual target width W_v were 20, 40, 70, or 120 pixels (2.35, 4.70, 8.22, or 14.09 mm, respectively). We referred to Bi et al.'s [2] and Usuba et al.'s [15] studies for these variables.

Procedure

First, the participants performed a *finger calibration task* [2]. The participants touched a 1-pixel horizontal line that appeared at a random position 50 times. We measured the signed gap between the line and the tap position and calculated the standard deviation of the gap values as σ_a for FFitts law. In the finger calibration task, we asked the participants to perform the task as accurately as possible.

When users use a new application, although they do not know the motor width at first, they roughly grasp the motor width by getting used to the application. In the experiment, we simulated this process. To do so, we generated two blocks for producing experimental data: an *exploring block* and a *data-collection block*. The participants performed the main experimental task with a condition randomly selected from $2D \times 4W_m \times 4W_v = 32$ combinations. In the exploring block, to explore the motor width, participants were asked to complete ten trials without considering errors and the operation time. Before starting the experiment, we informed the participants that there could be a condition where the motor width differed from the visual width. If we did not inform them of that, they would always aim at the visual width and could not explore the motor width. We also informed them that the motor width was not especially large (e.g., W_m was not half of the size of the screen) or small (e.g., it was not 1 pixel) and that the motor width extended/shrank equally from the center of the visual width. After the exploring block, in the data-collection block, we asked the participants to perform ten trials as quickly and accurately as possible. That is, in the data-collection block, the participants repeated ten trials in the same condition, such that the target position was not random. The participants repeated the above tasks under 32 conditions in random order. In total, 3,840 trials (i.e., $2D \times 4W_m \times 4W_v \times 10$ trials $\times$ 12 participants) were carried out, and the total time needed was approximately 30 minutes per participant.

Measurements

The dependent variables were the movement time MT (the time from touching the start area to touching the target, excluding erroneous trials), the spread of hits along the y-axis SD_y (the standard deviation of the y-coordinate of the tap position, including erroneous trials), and the error rate. To investigate whether our results are consistent with those of the previous studies [15, 16], our data was processed in the same manner as previous studies.

Results

From 3,826 trials (having eliminated 14 outliers[2]), 582 errors occurred (15.21 %). This error rate was slightly lower than that in Bi et al. [2]. We believe the reason for this is that the range of the target width (2.35–14.09 mm) was larger than Bi et al.'s condition (2.40–7.20 mm). We analyzed the data using repeated measures of ANOVA and the Bonferroni post hoc test. The independent variables were D, W_m, and W_v. The dependent variables were the same as the measurements. In our graphs, the error bars represent the standard error, and ***, **, and * indicate $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively.

Movement Time. We observed the main effects for D ($F_{1,11} = 29.43, p < 0.001, \eta_p = 0.73$), W_m ($F_{3,33} = 31.47, p < 0.001, \eta_p = 0.74$), and W_v ($F_{3,33} = 4.24, p < 0.05, \eta_p = 0.28$). Figure 3 shows the post hoc test. No interaction was found ($p > 0.05$).

Standard Deviation of y-coordinates. We observed the main effects for D ($F_{1,11} = 6.23, p < 0.05, \eta_p = 0.36$) and W_m ($F_{3,33} = 10.76, p < 0.001, \eta_p = 0.49$). Regarding W_v, there were no significant differences ($F_{3,33} = 2.42, p = 0.084, \eta_p = 0.18$). Figure 4 shows the post hoc test. No interaction was found ($p > 0.05$).

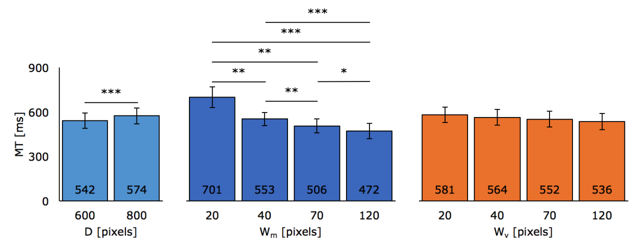

Figure 3: Main effects for MT.

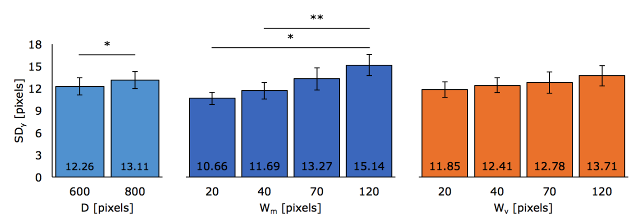

Figure 4: Main effects for SD_y.

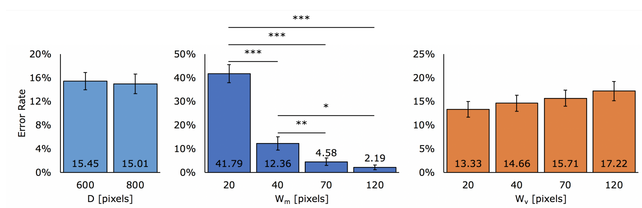

Figure 5: Main effects for the error rate.

Error Rate. We observed the main effects for W_m ($F_{3,33} = 60.43, p < 0.001, \eta_p = 0.85$). Regarding W_v, there were no significant differences ($F_{3,33} = 2.47, p = 0.080, \eta_p = 0.18$). Figure 5 shows the post hoc test. No interaction was found ($p > 0.05$).

Model Fitting. In accordance with related studies [15, 16], we verified the fitness with ID_m (Equation 4), ID_v (Equation 5), and ID_e (Equation 2). In our experiment, because the input probe was a finger, we also verified FFitts law (ID_f, Equation 3). MT in ID_m and ID_v is the mean time excluding the erroneous trials [15, 16], and MT in ID_e and ID_f includes the erroneous trials [2, 4, 11]. Figure 6 shows the fitness of each model for the 32 data points ($2D \times 4W_v \times 4W_m$). All fitness values are lower than the typical threshold ($R^2 > 0.90$) [8, 13]. In addition, when only $W_m = W_v$ (this is a normal task with Fitts' law), it is a good fit (Figure 7).

$$ID_m = \log_2 \left(\frac{D}{W_m} + 1 \right) \tag{4}$$

[2]When the movement distances were less than $\frac{D}{2}$, the trial was regarded as an outlier [13]. We did not use the criterion that "the clicked position is far from $2W$ from the target center" because of the large difference between W_m and W_v. In addition, when the participants tapped the screen, if the system did not sense the tap, they tapped again. In that case, the movement time was very long; thus, we removed such cases as outliers.

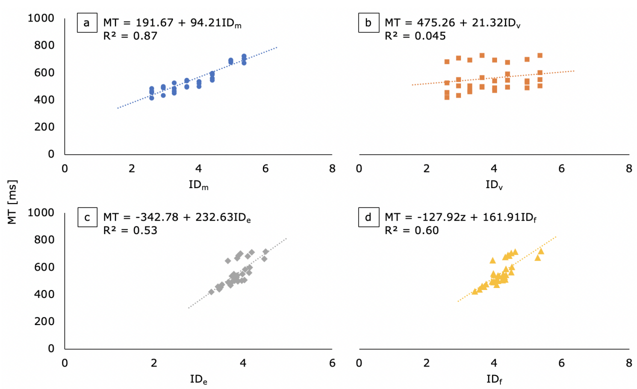

Figure 6: Model fitting with a) ID_m, b) ID_v, c) ID_e, and d) ID_f.

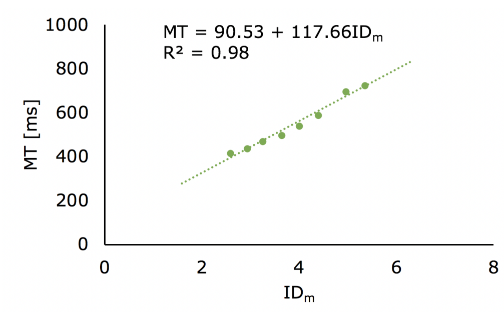

Figure 7: Model fitting with ID_m for $W_m = W_v$.

$$ID_v = \log_2\left(\frac{D}{W_v} + 1\right) \quad (5)$$

According to Figure 3, MT slightly varied by W_v. Thus, we believe that Figure 6a shows that the variation of MT at the same ID_m was caused by W_v. Therefore, we decided to analyze the fitness for the eight data points ($2D \times 4W_m$) separated by W_v. The upper row of Table 1 shows their fitness. Using ID_m resulted in a good fit, except for $W_v = 70$. According to Figure 5, when $ID_m < 3.00$ ($D = 600, W_m = 120$ and $D = 800, W_m = 120$), the error rates are very small. Therefore, when $ID_m < 3.00$, the participants were almost always able to tap successfully. Consequently, we believe that they performed the task as quickly as possible. In short, when $ID_m < 3.00$, we believe that the participants' movement is ballistic and that designers that adjust interfaces based on the movement time are interested in movement that is not ballistic ($ID_m \geq 3.00$). Hence, we analyzed the fitness separated by W_v in $ID_m \geq 3.00$, as shown in the lower row of Table1. According to Table 1, ID_m obtained by each W_v is a good fit ($R^2 > 0.90$).

Table 1: Modeling the fit with each W_v.

	W_v	a	b	R^2
all ID_m	20	246.30	86.06	0.91
	40	236.71	84.06	0.93
	70	171.57	97.74	0.86
	120	112.12	109.01	0.95
$ID_m \geq 3.00$	20	177.40	101.04	0.91
	40	169.61	98.61	0.93
	70	13.71	131.92	0.94
	120	41.46	124.40	0.95

Participant Strategies. After the experiment, we asked the participants how they explored the motor width. To summarize the participants' comments, there were two strategies: adjusting the speed and moving the touch position.

When using the first strategy, (a) the participants operated quickly, and if there were many errors at that speed, they slowed down in the next trial and (b) if there were few errors, they sped up. According to Fitts' law, movements are fast when the target width is large. In addition, it is expected that fast movements result in many errors. The users believe that the motor width is large if they operate quickly and few errors occur. This suggests that users explore the motor width by adjusting their speed.

When using the second strategy, the participants first touched the visual width, and if that touch was successful, they moved the next touch position farther away from the target center. Figure 8a shows that, first, a user aims for the visual width, with a successful touch. Next, the user touches the screen in a position far from the visual width. When this touch fails, the user performs operations that approach the visual width. Figure 8b shows a user performing pointing operations that approach the visual width on account of the first touch failing. In this way, several participants explored the motor width while moving the touch position gradually.

4 DISCUSSION

As with the studies by Usuba et al. [15, 16], the participants' movement depended on the motor width, and the effect of the visual width was slight. In our experiment, instead of notifying the participants of the motor width, we provided time for them to explore it, and our results are nevertheless consistent with those of Usuba et al.

Standard Deviation of the y-coordinate and Error Rate

We found that the spread of touch positions SD_y depends on D and W_m. Regarding W_v, SD_y slightly increases as W_v increases. Usuba et al. also found that SD_x depends on W_m,

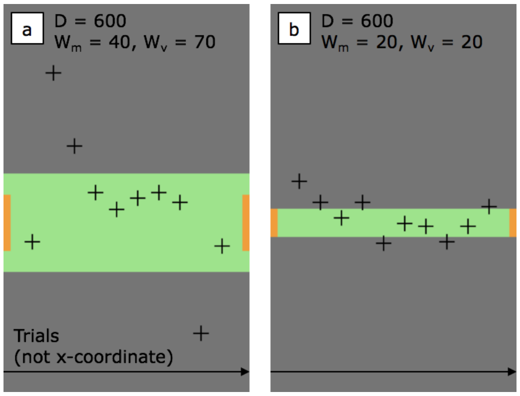

Figure 8: Examples of the touch positions of participants in the exploring block. Note that horizontal axis is not the x-coordinate but rather the trial number.

and W_v has a slight effect on SD_y[15]. In addition, Bi et al. found that σ (i.e., SD_y) depends on D and W. Thus, their results are consistent with ours.

Our experiment showed that the error rate depends on W_m. In tasks for Fitts' law, it is known that the effect of the target width on the error rate is larger than that of the target distance [18]. Compared to Bi et al. [2] and the error model [18], our results are consistent. Although the effect of W_v on the error rate is slight, however, Figure 5 shows that increasing W_v increases the error rate. Considering that increasing W_m decreases the error rate, W_v has the opposite effect to W_m. We believe that the reason for this is the effect of W_v on SD_y. If SD_y increases when W_m increases, because the area that can capture the user's touch extends, the error rate does not increase. However, even when increasing W_v, the area that can capture the user's touch does not extend. Therefore, we believe that a larger W_v increased SD_y (Figure 4), inducing a higher error rate (Figure 5).

In the exploring block, 1,104 errors occurred (28.75%). Compared to the data-collection block (15.21%) and Bi et al.'s work, this error rate is high. As mentioned above (in the subsection "Participant Strategies" in the "Results"), in several trials, the participants deliberately made errors because we told them not to worry about making them. However, considering the participants' interviews and the decrease in the error rate from the exploring block to the data-collection block (and that the error rate in the data-collection block is comparable to that in Bi et al. [2]), we believe that the participants explored the motor width sufficiently well.

Model Fitting

The existing model for pointing did not fit with our overall results. However, ID_m separated by W_v could predict the participants' movement (lower row of Table 1). This shows that even if there is a difference between the motor and visual widths, designers can predict MT for new D and W_m based on MT for experimental data under a specific W_v value. We expect that this will be convenient for designers. For example, when creating a vertical navigation menu such as the one shown in Figure 1c, designers can decide the font size of the menu by considering the font size of the other components first. Typically, the font size will be decided by the design guidelines of the products. That is, in many cases, the visual width (e.g., the font size) is decided in advance. Further, designers decide the margins around the text, and the margins indicate the motor width. Thus, when designers decide the visual width and the movement time, for example, they can know the minimum value of the margins by using our separate model. As such, designers can adjust the interface freely within the range so as not to frustrate users. In this way, we believe that our model can contribute to interface design.

Analysis of Existing Interfaces and Design Recommendations

We reanalyzed Figure 1b and c where the target has different motor and visual widths. According to our results, if users can memorize the motor width, they can appropriately perform pointing, even if W_v is larger than W_m. In addition, the error rate depends on the motor width. Therefore, interfaces such as those shown in Figure 1b and c will not frustrate users when they perform pointing operations. In interfaces such as the one shown in Figure 1c [15], the motor width is smaller than the visual width. According to the standard deviation of the y-coordinate and the error rate discussed above, when the motor width is smaller than the visual width, it is expected that slightly more errors will occur owing to the spread of click positions slightly widened by the visual width. To summarize the above discussion, in touch interfaces, designers should make the motor width larger than the visual width. Alternatively, if they want to make the motor width smaller, they should aim to have the motor width closely approximate the visual width. Johnson [10] suggests something similar by taking a website [3] where the motor width is smaller than the visual width as an example. Obviously, considering existing pointing models [2, 5] and our results, designers should make the motor width sufficiently large. In addition, user performance when there is a difference between the motor and visual widths is predicted by ID_m separated from W_v. Thus, designers can adjust the motor and visual widths by the model.

[3]https://web.archive.org/web/20110308051632/http://www.asaging.org/aia11/

5 LIMITATIONS AND FUTURE WORK

In this study, we studied only 1D finger-pointing tasks. Thus, our study is limited and there are many opportunities for future research.

Although we showed that ID_m separated by W_v can predict the movement time, we believe that a model with variables D, W_m, and W_v will be more convenient. However, we failed to build such a model. This is one of the limitations of our work.

Although it is true that the participants explored the motor width, it is unclear whether their explorations were successful. MT and SD_y significantly depended on the motor width (Figures 3 and 4). After the experiment, we asked the participants how they explored the motor width, and they gave an example of such exploration (Figure 8). In addition, we also asked the participants whether they were able to understand whether the motor width was larger than, equal to, or smaller than the visual width, and almost all participants stated that they could do this. In this way, there is evidence that the participants explored the motor width, although it is unclear whether the exploration was successful. Therefore, if we conduct an experiment where we make participants explore the motor width in a different way, the results may differ from those of this study. In addition, in our task, we instructed the participants to perform pointing operations *as quickly and accurately as possible*. Thus, the participants aimed for a balance of speed and accuracy. It is known that giving different speed–accuracy instructions produces different results [6], e.g., if an experimenter merely asks participants to perform pointing as quickly as possible, there is a higher error rate and faster movement time. Even in a situation with different the motor and visual widths, we believe that different instructions will produce different results. Moreover, the movement time was slightly affected by the visual width. Thus, depending on situation, it is possible that the user performance changes owing to the visual appearance of targets like the placeholder effect [1, 12].

The task in our experiment was 1D pointing. However, as shown in Figure 1, there are 1D and 2D targets in graphical user interfaces. In 2D finger pointing, in addition to deviations to the upper and lower touch positions, users must consider those to the left and right. Figure 1b and c show that there are other items (unintended targets) around the target. Such potential targets are usually aligned in a regular pattern; thus, we assume that this fact enables users to predict the motor width well.

In pointing, it is known that a finger is faster but less accurate than a mouse or stylus [3]. Taking together our research and that of Usuba et al. [15], the effects of the motor and visual widths were verified for fingers and a mouse. As mentioned above, we are interested in, among other things, extending the dimension, the effect of surrounding objects, and the effect on other input devices. Additionally, we currently have no general model for finger pointing in cases where there is a difference between the motor and visual widths. In future research, we will build such a model by verifying or modifying existing models and further experimental results.

6 CONCLUSION

As an extension to research by Usuba et al. [15, 16], we investigated the effect of motor and visual widths on finger pointing. In contrast to their studies, by considering more suitable conditions to test touch operations, we provided time for users to explore the motor width. Although our experimental conditions differed from those of Usuba et al. (e.g., the input probe was a finger), the results were consistent. The participants decided upon movements based on the memorized motor width. We found that the movement time strongly depended on the motor width and could be predicted by ID_m separated by W_v.

This study is a first step toward better understanding the relationship between finger pointing and the difference in the motor and visual widths. There remain various conditions that should be investigated, such as 2D targets and grid-pattern layouts. We hope researchers, us included, will investigate limitations and offer contributions to a better understanding of finger pointing and the design of touch interfaces.

REFERENCES

[1] Jos J. Adam, Robin Mol, Jay Pratt, and Martin H. Fischer. 2006. Moving Farther but Faster: An Exception to Fitts's Law. *Psychological Science* 17, 9 (2006), 794–798. DOI: http://dx.doi.org/10.1111/j.1467-9280.2006.01784.x

[2] Xiaojun Bi, Yang Li, and Shumin Zhai. 2013. FFitts Law: Modeling Finger Touch with Fitts' Law. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 1363–1372. DOI: http://dx.doi.org/10.1145/2470654.2466180

[3] Andy Cockburn, David Ahlström, and Carl Gutwin. 2012. Understanding performance in touch selections: Tap, drag and radial pointing drag with finger, stylus and mouse. *International Journal of Human-Computer Studies* 70, 3 (2012), 218 – 233. DOI: http://dx.doi.org/10.1016/j.ijhcs.2011.11.002

[4] E. R. F. W. Crossman and P. J. Goodeve. 1983. Feedback control of hand-movement and Fitts' law. *The Quarterly Journal of Experimental Psychology Section A* 35, 2 (1983), 251–278. DOI: http://dx.doi.org/10.1080/14640748308402133

[5] Paul M Fitts. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology* 47, 6 (1954), 381.

[6] Paul M Fitts and Barbara K Radford. 1966. Information capacity of discrete motor responses under different cognitive sets. *Journal of Experimental Psychology* 71, 4 (1966), 475.

[7] Julien Gori, Olivier Rioul, and Yves Guiard. 2018. Speed-Accuracy Tradeoff: A Formal Information-Theoretic Transmission Scheme (FITTS). *ACM Trans. Comput.-Hum. Interact.* 25, 5, Article 27 (Sept.

2018), 33 pages. DOI: http://dx.doi.org/10.1145/3231595

[8] Julien Gori, Olivier Rioul, Yves Guiard, and Michel Beaudouin-Lafon. 2018. The Perils of Confounding Factors: How Fitts' Law Experiments Can Lead to False Conclusions. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 196, 10 pages. DOI: http://dx.doi.org/10.1145/3173574.3173770

[9] Christian Holz and Patrick Baudisch. 2011. Understanding Touch. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2501–2510. DOI: http://dx.doi.org/10.1145/1978942.1979308

[10] Jeff Johnson. 2014. *Designing with the Mind in Mind: Simple Guide to Understanding User Interface Design Guidelines* (2 ed.). Morgan Kaufmann.

[11] I. Scott MacKenzie. 1992. Fitts' Law as a Research and Design Tool in Human-Computer Interaction. *HumanâĂŞComputer Interaction* 7, 1 (1992), 91–139. DOI: http://dx.doi.org/10.1207/s15327051hci0701_3

[12] Jay Pratt, Jos J. Adam, and Martin H. Fischer. 2007. Visual layout modulates Fitts's law: The importance of first and last positions. *Psychonomic Bulletin & Review* 14, 2 (01 Apr 2007), 350–355. DOI: http://dx.doi.org/10.3758/BF03194076

[13] R William Soukoreff and I Scott MacKenzie. 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of FittsâĂŹ law research in HCI. *International journal of human-computer studies* 61, 6 (2004), 751–789.

[14] Chao-Huai Su, Liwei Chan, Chien-Ting Weng, Rong-Hao Liang, Kai-Yin Cheng, and Bing-Yu Chen. 2013. NailDisplay: Bringing an Always Available Visual Display to Fingertips. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 1461–1464. DOI: http://dx.doi.org/10.1145/2470654.2466193

[15] Hiroki Usuba, Shota Yamanaka, and Homei Miyashita. 2018. Pointing to Targets with Difference Between Motor and Visual Widths. In *Proceedings of the 30th Australian Conference on Computer-Human Interaction (OzCHI '18)*. ACM, New York, NY, USA, 374–383. DOI: http://dx.doi.org/10.1145/3292147.3292150

[16] Hiroki Usuba, Shota Yamanaka, and Homei Miyashita. 2018. User Performance by the Difference Between Motor and Visual Widths for Small Target Pointing. In *Proceedings of the 10th Nordic Conference on Human-Computer Interaction (NordiCHI '18)*. ACM, New York, NY, USA, 161–169. DOI: http://dx.doi.org/10.1145/3240167.3240171

[17] Daniel Vogel and Patrick Baudisch. 2007. Shift: A Technique for Operating Pen-based Interfaces Using Touch. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 657–666. DOI: http://dx.doi.org/10.1145/1240624.1240727

[18] Jacob O. Wobbrock, Edward Cutrell, Susumu Harada, and I. Scott MacKenzie. 2008. An Error Model for Pointing Based on Fitts' Law. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 1613–1622. DOI: http://dx.doi.org/10.1145/1357054.1357306

[19] Haijun Xia, Tovi Grossman, and George Fitzmaurice. 2015. NanoStylus: Enhancing Input on Ultra-Small Displays with a Finger-Mounted Stylus. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 447–456. DOI: http://dx.doi.org/10.1145/2807442.2807500

[20] Shumin Zhai, Jing Kong, and Xiangshi Ren. 2004. Speed-accuracy tradeoff in Fitts' law tasks: on the equivalency of actual and nominal pointing precision. *International Journal of Human-Computer Studies* 61, 6 (2004), 823–856. DOI: http://dx.doi.org/10.1016/j.ijhcs.2004.09.007