Sticking Out Like a Non-dominant Thumb

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Sticking Out Like a Non-Dominant Thumb:
Handedness and Fitts' Throughput for Touch-Based Mobile Interfaces

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Abstract. In this paper we present our study (n=30) to gauge the effect of hand-dominance on Fitts' throughput through four test cases—forefingers and thumbs of dominant and non-dominant hands in tapping tasks for touch-based mobile interfaces. We set out with the expectation that throughput for a dominant digit would exceed that for the corresponding digit of the other hand. We reveal that this was followed in the case of right-handed users for both forefingers and thumbs, and in case of forefingers for all users. Right-handed users had higher throughput for dominant digits (mean=5.608) than non-dominant digits (mean=4.736). All users had higher throughput for dominant forefingers (mean=6.081) than non-dominant forefingers (mean=5.436). However, surprisingly, left-handed users showed a higher throughput for non-dominant thumbs (mean=6.078) than dominant thumbs (mean=5.721). Throughputs of forefingers and thumbs were not significantly different for any groups.

Keywords: Handedness, Fitts' Law, Touch Input.

1 Introduction

While left-handed individuals are a minority (reported numbers ranging from 8-15%) and being left-handed is not exactly a handicap, it is often for this reason that the specific needs of this user group are overlooked and they find themselves at a disadvantage while using daily objects designed with the majority in mind, such as cutting with scissors, unscrewing lids, sharpening pencils and so on. In the case of digital devices, too, it is commonly assumed that left-handed usage would just mirror that of the vast majority i.e., the right-handed population. With handheld mobile devices becoming our way of connecting with the world, it becomes necessary to question this assumption and to make our designs more inclusive to handedness. The first step to this would be to identify the difference, if any, in user performance.

Fitts [10] proposed a relation between amplitude, duration and variability of motor response, which is better known today as Fitts' Law. Different forms of Fitts' equation have been accepted as well as discussed [7] since. There exists no benchmark data nor standard prescribed method readily available to compare the performance of left- and right-handed individuals in touch-based Fitts' tasks. Similarly, there seemed to be no means to comment on whether there exists a sizable difference between the performance of a digit of the dominant hand and that of the corresponding one of the non-dominant hand.

The purpose of this paper is to explore Fitts' Law as applicable for touch-based interfaces through the lens of laterality and hand-dominance. We take Fitts' Law as a given and adopt the form prescribed by MacKenzie [21] to calculate Fitts' Throughput (measured in bits/s) for a series of simple point-and-touch tasks which are then compared and analyzed from the perspective of handedness of the subjects. These are studied bearing in mind two common input configurations based on the primary interacting digit - forefingers and thumbs.

Through this paper, we make three specific contributions. Firstly, we compare and provide benchmark data about relative performances of right- and left-handed people with their dominant and non-dominant forefingers and thumbs for common tapping tasks. Secondly, we reveal that on the whole right-handed users are more accurate and precise than left-handed users and yet the left-handed users have higher throughput than right-handed users. Thirdly, we reveal a surprising finding about the better performance of the non-dominant thumb of left-handed users. This exploratory study could form the basis of argument for better personalization for left- and right-handed users, especially with the consideration that the performance effects are asymmetric. It can set the stage for further work wherever there arises a question of whether left-handed users are at any major disadvantage or need separate consideration. While several studies [17, 21, 24, 25, 29] have been carried out in the domain of tapping tasks on mobile touch devices, these have exclusively recruited right-handed participants, often with an apparently inherent assumption that a laterally flipped interface would exhibit similar results for left-handed users. So also, studies on Back of Device (BoD) interactions [16], handedness detection [20] have recruited only right-handed participants. Our study argues in favor of more inclusive recruitment and perhaps revisiting some of these studies through the lens of handedness.

2 Background

2.1 Hand usage in touch input

In mobile phones designed for portable handheld usage, a single-handed/monomanual grip (see **Fig. 1**) is used fairly commonly when tapping the screen [14, 15]. When using a single hand, front of screen input on a mobile device is generally limited to thumb tapping, where the motor performance of the thumb has been found to vary across configurations and target positions on the screen for a Fitts' based task [29]. The other common configuration for phone usage is bimanual, where one hand supports the phone and a digit of the other hand (usually the forefinger) is used for touch-based input (see **Fig. 1**).

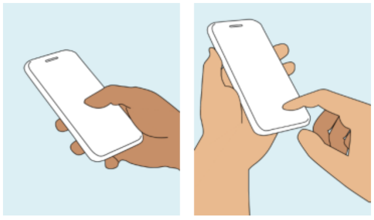

Fig. 1. Single-handed grip with thumb used for input, and two-handed grip with forefinger used for input

2.2 Fitts' law and throughput

The law originally proposed by Fitts [10] may be framed as follows, given time (T) to complete the movement to a target is a linear function of the Index of Difficulty (ID):

$$T = a + b\,ID \quad (1)$$

Here, a and b are arrived upon through empirical measurement, while the Index of Difficulty is a function of target distance (D) and target width (W):

$$ID = \log_2\left(\frac{2D}{W}\right) \quad (2)$$

This has been discussed and modified since [28] to the form:

$$ID = \log_2\left(\frac{D}{W} + 1\right) \quad (3)$$

This [21] formulation for Fitts' throughput for touch-based target selection accounts for amplitude of movement, movement time and accuracy in a single term. This form describes Fitts' throughput (TP) as the ratio of effective index of difficulty (ID_e) measured in bits, to movement time (MT) measured in seconds:

$$TP = \frac{ID_e}{MT} \quad (4)$$

Here, MT is measured empirically while ID_e expands as follows, given that A_e corresponds to the effective movement amplitude and W_e corresponds to effective target width:

$$ID_e = \log_2\left(\frac{A_e}{W_e} + 1\right) \quad (5)$$

The value of Fitts' Throughput varied based on the kind of hardware setup and interaction used. However, for a particular device, input technique, and a given set of tasks, throughput may be compared through direct subtraction.

Fitts law has been researched extensively by various people, and especially in the context of touchscreens. For example, FFitts law [2] proposes a dual distribution hypothesis to interpret the distribution of endpoints considering fat-finger input. The authors suggest a relative component controlled by the speed-accuracy trade-off of the performer, and an absolute component independent of the performer's desire of following the specified task precision which cannot be controlled by the speed-accuracy trade-off. While this [2] formulation could be used as an alternative, the work does not make explicit the method to calculate throughput. To the best of our knowledge, the most recent paper specifying method to calculate Fitts' throughput is MacKenzie [21]. As our goal was not to investigate which model gives the most reliable throughput, but rather how do different digits of differently handed people affect the throughput, for this limited scope we adopted this [21] formulation for our study.

2.3 Laterality and Handedness in HCI

While the human exterior appears to be bilaterally symmetrical, the left and the right sides are differentiated through laterality or sidedness. Laterality manifests in terms of preferential usage or relatively better performance of one of the bilateral counterparts. Despite its seemingly binary nature, there are arguments in favor of a continuous distribution that takes into account the degree of laterality and not just directionality [22]. Attempts have been made to measure different manifestations such as handedness, footedness, earedness, eyedness [5], etc. Of these, handedness is a widely studied manifestation and of our specific interest. It is commonly gauged through self-reporting on the basis of questionnaires consisting commonly carried out day to day activities [1, 23], the merits of which have subsequently been discussed [4, 30].

We found the Edinburgh Handedness Inventory (EHI) [23] to be the most interesting method to determine handedness as it comments on the degree of laterality and not just directionality. It takes into account hand dominance for activities such as writing, drawing, throwing things, and so on. It scores individuals in a range of -100 to 100. Individuals with scores below -28 are considered to be left-handed, while those with scores above 40 are considered to be right-handed. Individuals with scores between -28 and 40 form the 'middle decile' and cannot be conclusively said to have a preferred hand. Formulated in 1971, the EHI includes several daily activities but does not cover touch screens or mice. However, it continues to be used commonly as a means to establish handedness and is thereby relevant to our study. We could also argue that because EHI is independent of most current-day computing tasks, in some sense it provides an assessment of a person's handedness that is independent of the influences of technology use. This argument gathers importance given our results, as we discuss below.

Existing work takes into account the effect of handedness in HCI, such as comparing touchscreens and touchpads in flight-control interfaces [18], or attempts to design specifically left-hand controlled configurations, such as for games [6]. Cursorless pointing has been studied from the perspective of laterality in terms of handedness as well as ocular dominance [26].

A study carried out from the perspective of finger movement pointed out that there are differences in the way motor areas of the brain are functionally organized in right- and left-handed people [27]. Performance on touchscreen mobile phones has been studied 'in the wild' [13] as well as in controlled conditions [19]. Work on one-handed thumb tapping on mobile devices [25] mentions the lack of a study on handedness.

Despite the popularity of touchscreen mobile devices, we did not find extensive studies that compare handedness on touchscreens. Effect of hand use has been studied for one-handed BoD interactions [9]. The closest investigation into handedness on touchscreens that we came across [3] was carried out with only four participants. This work attempted to compare the index of difficulty between left- and right-handed individuals through a Flutter-based prototype. However, we did not come across studies that specifically consider differential performance caused by handedness in terms of Fitts' throughput for tapping tasks on touch-based mobile interfaces.

3 Study

We looked at two commonly used configurations for touch-based interaction in particular: double-handed forefinger (index finger) and one-handed thumb. The study is exploratory and designed to be within-subject, where dominant hand performance of an individual would be compared with their own non-dominant hand performance for corresponding configurations. Users were recruited on the basis of self-reporting (later verified via EHI) and were treated the same for the purpose of data collection i.e., they were not separated into groups. Once collected, readings were separated on the basis of hand dominance for the purpose of analysis, which formed the between-subject aspect of the study.

3.1 Experiment

Study Design. We conducted a mixed design study, with hand-dominance as a between-subject independent variable, and counterbalanced finger configuration—dominant hand forefinger (DF), non-dominant hand forefinger (NF), dominant hand thumb (DT), and non-dominant hand thumb (NT), (see **Fig. 2**), as the within-subject independent variable. In the cases involving input using the thumb, a single-handed grip was used, while for input using the forefinger, a double-handed grip was used (see **Fig. 1**).

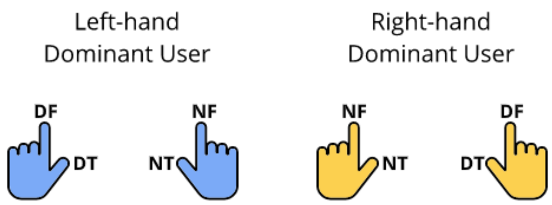

Fig. 2. Dominant hand forefinger (DF), non-dominant hand forefinger (NF), dominant hand thumb (DT), and non-dominant hand thumb (NT) for left- and right-handed users respectively

Our primary dependent variable was Fitts' throughput, while we also measured errors and speed as additional dependent variables. The handedness was initially determined based on self-reporting, but we did use the EHI to verify the self-reports. We did not consider the users who turned out to be ambidextrous i.e., those in the middle decile with EHI scores between -28 and 40.

Apparatus. The study was conducted using an Android application (developed in-house) running on a single touch-screen smartphone device1. There was no screen guard or external cover on the phone which could add to bulk or reduce sensitivity of the screen. The app logged metrics such as the cartesian coordinates of subsequent touches, the time elapsed between them, and the location at which the touch target spawned. The data exported from the app was processed and analyzed using a Python3 script and spreadsheet tools.

The touch targets were high contrast (black on white background) to avoid visual difficulty/unwanted confounding effects, and circular, to prevent any external influence of directionality (see **Fig. 3**). The center of each target was marked by crosshairs to promote accuracy.

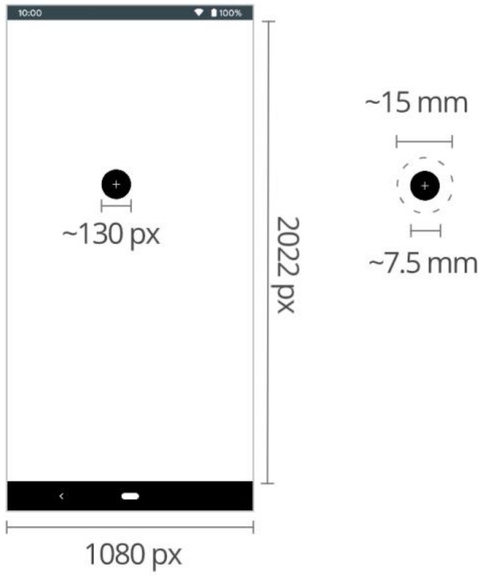

Fig. 3. A sample screenshot of a tapping task in the application used to evaluate throughputs. Dimensions have been provided for reference, including visible and acceptable target sizes

Target position was randomized with some constraints i.e., ensuring that a target would not appear at the very edge of the screen, with a minimum distance of 130 px (≈ one target size) separating any two consecutive targets (see **Fig. 4**). The minimum distance between spawned targets was ~1.49 cm (260 px), the maximum was ~11.41 cm (1981 px), while the mean distance between targets was ~4.64 cm (806 px) with sd=2.113 cm

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[1] Google Pixel 3a - weight: 147g, dimensions: 151.3 x 70.1 x 8.2 mm (5.96 x 2.76 x 0.32 inches), display size (measured diagonally): 142.2 mm (5.6 inches), display resolution: 1080 x 2220 pixels, pixel density: 441 PPI

(367 px). Target size was kept constant as a controlled variable, with visible diameter fixed at 12% of display width (~7.5mm). Targets smaller than that have been found to have higher error rates [21]. Our choice of target width was driven by the need for it to be ergonomically large enough to touch (7-10 mm) [11], with the visible area being small enough to encourage precision. We considered the touches within a concentric circle of diameter of 36% of the display width (~390px ≈22.5mm) as intentional, and ignored any touches outside of this region, regarding these as unintended touches, probably caused by some other part of the hand coming in contact with the screen, such as the base of the palm touching the screen while extending thumb, etc. (see **Fig. 5**)

0	0	0	0	0	0	0	0	0	0	0	0
0	49	52	52	56	50	51	63	55	46	41	0
0	52	41	68	51	61	42	53	60	52	51	0
0	75	64	62	58	49	47	53	52	58	60	0
0	46	57	49	60	60	47	53	48	60	68	0
0	53	49	48	52	46	49	55	55	68	37	0
0	61	49	50	64	53	59	46	57	50	55	0
0	58	50	47	70	56	62	66	60	63	53	0
0	54	57	55	46	53	56	43	49	75	66	0
0	41	50	53	65	46	67	60	58	62	36	0
0	53	63	47	48	44	49	52	61	61	57	0
0	53	57	51	50	50	65	61	62	59	42	0
0	41	51	63	52	44	43	50	66	58	43	0
0	50	63	63	42	52	50	62	51	48	42	0
0	55	47	62	40	65	58	48	62	49	44	0
0	59	62	47	55	49	49	58	74	44	52	0
0	47	41	58	61	49	56	49	65	60	58	0
0	60	60	55	60	39	39	55	50	56	44	0
0	52	58	44	45	64	56	55	52	59	57	0
0	55	68	49	56	62	62	57	53	50	48	0
0	63	49	58	53	45	63	48	52	52	50	0
0	0	0	0	0	0	0	0	0	0	0	0

Fig. 4. Distribution of target count (total: 10,800) if phone screen were bucketed into even cells

We note that the targets were randomly spawned, and they turned out with a reasonably even distribution, except at the very edges of the screen.

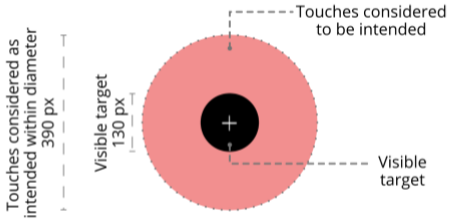

Fig. 5. Target visible to user (130px ≈ 7.5mm), region where touches are considered to be intentional (enclosed by dotted line, 390px ≈ 22.5mm), and the touches on the rest of the screen ignored as unintentional (outside the bounds of the dotted line)

Participants. Participants were recruited locally in the Thane-Mumbai region, India (aged 18-60 years). The stipulation was that participants were regular users of a touchscreen phone, and had been for at least a month. During recruitment, participants were asked to self-identify as left- or right-handed. While self-reporting handedness, potential participants were also asked in particular which hand they preferred for input on mobile touchscreens, being clearly told that preference was a matter of their choice (see **Table 1**). It was decided not to take a representative sample of the population in terms of handedness distribution, as the proportion of left-handed participants would be lower. Instead, there was balanced recruitment (equal number) of self-reported left- and right-handed participants to ensure enough data could be gathered for both groups, although they were not treated any differently during data collection. Participants with severe or uncorrected visual or hand-eye coordination issues were excluded from the study. While carrying out the study, it was ensured that the participants were not injured or inconvenienced in a way which could affect or bias their motor movement.

Table 1. Breakdown of participants as per self-reported preference of hand usage (A—Left hand preferred, B—Mostly prefer left hand, but at times use right, C—No particular preference, D—Mostly prefer right hand, but at times use left, E— Right hand preferred) and gender

	A	B	C	D	E	Total
Female	5	3	0	3	3	13
Male	6	2	1	2	7	19
Total	11	5	1	5	10	32

Upon being recruited for the study, participants were initially asked to respond to the Edinburgh Handedness Inventory (EHI) Laterality Test as available on brainmapping.org [8]. If in doubt, they were asked to enact the activity in question in order to help them answer. Of the participants, the handedness index for right-handed ones varied from 50 to 95 with a median of 80 and for the left-handed ones varied from -30 to -95 with a median of -65. Initially, 32 participants were administered the EHI Test, of which 2 had to be excluded from the study as the results of their EHI Test were inconclusive as to handedness, placing them in the middle decile (-28 to 40). The 2 participants (1 female, 1 male) excluded from the final study had reported "mostly prefer left hand but at times use right" and "no particular preference" respectively. The remaining 30 participants (see **Table 2**), mean age 33.5 years (SD = 11.23), were included in the final study and their EHI Indices conformed with their self-reported handedness.

Table 2. Breakdown of participants as per handedness and gender after excluding the two participants whose EHI results placed them in the middle decile

	Left-handed	Right-handed	Total
Female	7	5	12
Male	8	10	18
Total	15	15	30

Procedure. Each participant was asked to sit comfortably on a chair for the duration of the experiment, with no direct glare on the mobile screen. The task was explained to the participants, and they were told the order in which they would be carrying out the four cases (DF, NF, DT, NT) which was ordered across participants such that no consecutive test cases would require the use of the same hand for tapping, to prevent any fatigue effects. The conditions were order-balanced through Latin square for each group of users. For each test case a participant would undergo 3 consecutive sequences of 30 touch targets (appearing one after the other on the screen) across which we later calculated mean throughput. Successive sequences were separated by a minimum of 45s rest period. This gave a total of 3 sequences x 30 touch targets x 4 test cases i.e., 360 targeted touches for each user, and 360 x 30 users i.e., 10,800 total touch tasks in the study.

A screenshot of the target was shown while explaining the task, and the display brightness was adjusted to the participant's comfort. By default, this was kept at ~75% of maximum. Of the 30 participants, 4 chose to increase it slightly while 2 chose to decrease it. They were asked to tap as close to the center of the tapping target using the finger corresponding to the test case. When a touch was registered, the next target would appear elsewhere on the screen without any programmed delay. The participants were asked to touch the targets as quickly and accurately as possible. They were told that if their finger were slightly off a target, it was OK, and that they should try to keep going as quickly and accurately as possible. We calculated throughput over a sequence of targets i.e. 'serial target clicking' where each trial begins at the selection point of the previous trial. Thereby for a sequence of 30 consecutive targets (serial target clicking [21] tasks), we have 29 data points contributing to the overall throughput. As we were not studying discrete tasks, there was no assigned 'home' position for the input finger.

For the test cases requiring the use of a thumb (DT, NT) for tapping, the participants were asked to hold the phone in the corresponding hand, while the trials with the forefinger (DF, NF) needed the phone to be held in the other hand. We asked the users not to use any other part of their body/any external support for the phone, and to adjust to a comfortable grip before starting a trial sequence.

3.2 Results

We took the mean of 3 sequences of each test case to get corresponding throughput. As discussed earlier, we had to exclude two of the thirty-two initial participants, giving us overall n=30. (see **Table 3**, **Table 4**, **Table 5**).

Table 3. Overall throughputs (bits/s) for the different cases (DF—Dominant Forefinger, NF—Non-Dominant Forefinger, DT—Dominant Thumb, NT—Non-Dominant Thumb)

	Mean	N	SD	95% CI from	95% CI to
Overall DF	6.081	30	1.365	5.592	6.569
Overall NF	5.436	30	1.479	4.907	5.965
Overall DT	5.572	30	1.458	5.050	6.093
Overall NT	5.328	30	1.624	4.747	5.909
Overall D (DF, DT)	5.826	30	1.312	5.357	6.296
Overall N (NF, NT)	5.382	30	1.457	4.861	5.903
Overall F (DF, NF)	5.758	30	1.376	5.266	6.251
Overall T (DT, NT)	5.450	30	1.434	4.937	5.963

	Mean	N	SD	95% CI from	95% CI to
Overall (DF, NF, DT, NT)	5.604	30	1.328	5.129	6.079

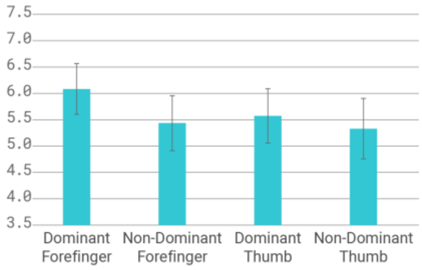

Fig. 6. Overall comparison between throughputs (error bars for 95% CI)

Table 4. Throughputs (bits/s) for the different cases (DF—Dominant Forefinger, NF—Non-Dominant Forefinger, DT—Dominant Thumb, NT—Non-Dominant Thumb) for right-handed participants

	Mean	N	SD	95% CI from	95% CI to
Right-handed DF	5.792	15	1.390	5.089	6.496
Right-handed NF	4.894	15	1.146	4.314	5.474
Right-handed DT	5.423	15	1.561	4.633	6.213
Right-handed NT	4.577	15	1.381	3.879	5.276
Right-handed D (DF, DT)	5.608	15	1.365	4.917	6.298
Right-handed N (NF, NT)	4.736	15	1.101	4.178	5.293
Right-handed F (DF, NF)	5.343	15	1.219	4.726	5.960
Right-handed T (DT, NT)	5.000	15	1.378	4.303	5.697
Right-handed Overall (DF, NF, DT, NT)	5.172	15	1.173	4.578	5.765

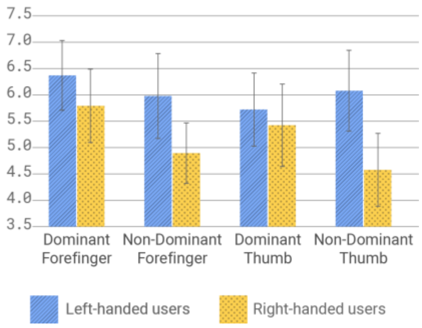

Fig. 7. Comparing throughputs across left and right-handed individuals (error bars for 95% CI)

Table 5. Throughputs (bits/s) for the different cases (DF—Dominant Forefinger, NF—Non-Dominant Forefinger, DT—Dominant Thumb, NT—Non-Dominant Thumb) for left-handed participants

	Mean	N	SD	95% CI from	95% CI to
Left-handed DF	6.369	15	1.324	5.700	7.039
Left-handed NF	5.978	15	1.608	5.164	6.792
Left-handed DT	5.721	15	1.384	5.020	6.421
Left-handed NT	6.078	15	1.532	5.303	6.854
Left-handed D (DF, DT)	6.045	15	1.265	5.405	6.685
Left-handed N (NF, NT)	6.028	15	1.512	5.263	6.794
Left-handed F (DF, NF)	6.174	15	1.439	5.446	6.902
Left-handed T (DT, NT)	5.900	15	1.387	5.197	6.602
Left-handed Overall (DF, NF, DT, NT)	6.037	15	1.369	5.344	6.730

We validated our data by graphing for Fitts' Law (MT v/s ID_e) and found that it follows (see **Fig. 8**) with a performance front [12].

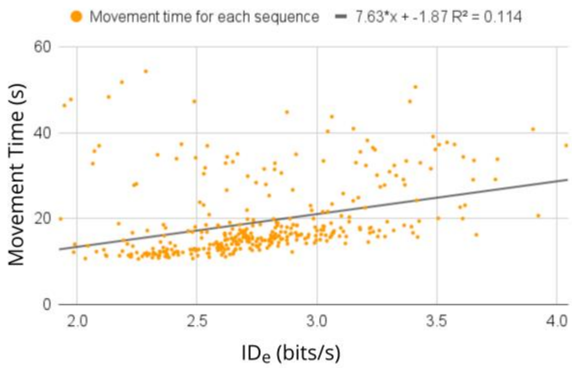

Fig. 8. Plotting movement time v/s index of difficulty for each sequence

We performed a 4x2 mixed ANOVA with Finger as a within-subject factor with four levels (dominant forefinger, non-dominant forefinger, dominant thumb and non-dominant thumb), Handedness as the between subject factor with two levels (left-handed and right-handed), and with Age as a covariate (as we suspect that the dexterity, and throughput varies with age).

Tests of between-subjects effects showed that there were significant effects of Age ($F = 15.625$, $p = 0.001$), but Handedness did not have a significant effect ($F = 2.747$, $p = 0.109$). We checked the studentized residuals, and found that one left-handed user was an outlier in each of the four fingers ($t = -2.66$ to -3.24 for the different fingers, critical t for 14 degrees of freedom = 2.145). Hence, we removed this outlier and ran the above ANOVA again.

After removal of the outlier, tests of between-subjects effects showed that there were significant effects of both Age (F = 12.526, p = 0.002) and Handedness (F = 7.568, p = 0.011). After accounting for age, left-handed users had significantly higher Fitts' Throughput (mean 6.193, N = 14, standard error = 0.234, 95% CI lower bound = 5.712, higher bound = 6.673) than the right-handed users (mean = 5.289, N = 15, standard error = 0.226, 95% CI lower bound =4.825, higher bound =5.753) evaluated at Age = 33. The 95% CI for the difference varies from 0.229 to 1.579 in favor of the left-handed users. Thus, the left-handed users gave higher Fitts' throughput than right-handed users.

Tests of within-subjects effects showed that there was a significant interaction between Finger and Handedness (F = 3.731, p = 0.015). This is perhaps explained by the fact that the non-dominant thumb of left-handed users (i.e. their right thumb) showed higher mean Fitts' throughput than all the other three thumb conditions (their own dominant thumb, and both left and right thumbs of right-handed users).

Overall, Finger was not a significant factor by itself in the omnibus ANOVA, though post-hoc tests using the Bonferroni correction revealed that the dominant forefinger gave slightly higher throughput (mean = 6.204, N = 29, standard error = 0.196, 95% CI lower bound =5.801, higher bound =6.606) than the non-dominant forefinger (mean = 5.588, N = 29, standard error = 0.179, 95% CI lower bound =5.220, higher bound =5.955) and the non-dominant thumb (mean = 5.458, N = 29, standard error = 0.222, 95% CI lower bound =5.001, higher bound =5.915). The throughput of the dominant thumb (mean = 5.714, N = 29, standard error = 0.205, 95% CI lower bound =5.293, higher bound =6.135) did not differ from any of the other conditions.

There was no significant interaction between Finger and Age.

However, another important result from the perspective of our study was the within-subject comparison between corresponding fingers. As throughput comparison might be carried out through direct differences [21], we subtracted the throughput of the non-dominant finger (NF, NT) from that of the corresponding dominant finger (DF, DT) for each participant. These differences were then categorized on the basis of handedness as 'left' (blue, lined) or 'right' (yellow, dotted), and plotted (see **Fig. 9**).

The graphs are indicative of the difference between throughputs of DF and NF and DT and NT respectively. The results have been arranged in an increasing order as per DT-NT. The DF-NF graph follows the same order of participants. It was found that DF-NF was primarily positive, as expected, but DT-NT was segmented largely across left and right-handed users. We did not record the physical dimensions of fingers, as our argument here was that taking a within-subject difference in readings would nullify anthropometric effects.

As mentioned above, the visible diameter of the target was fixed at 12% of display width (~7.5mm) while the touches within a concentric circle of diameter 36% of the display width (~390px) were considered as intentional. Those within 24% of the display width (~260px, ~15mm) were accepted as correct touches. Touches within a concentric circle of diameter of 36% of the display width (~390px) were considered to be erroneous as they were intended to land on the target but were clearly off. Any touches outside of this region were ignored as unintended touches.

By this definition, we found that the errors (clearly missed intentional touches) were generally quite low. Overall, 285 of the 10,800 touches, or 2.64% (adjusted Wald 95%

confidence interval from 2.34% to 2.94%), were erroneous. The non-dominant forefingers of the right-handed users were the most accurate (10 errors out of 1,350, 0.74%, CI 0.24% to 1.24%), followed by the dominant forefingers of the right-handed users (12 errors out of 1,350, 0.89%, CI 0.35% to 1.43%). The non-dominant forefingers of the left-handed users and the non-dominant thumb of the right-handed users were the least accurate (54 errors each out of 1,350, 4.00%, CI 2.94% to 5.06%) (see **Table 6**, **Table 7**, **Table 8** for the descriptive statistics of other combinations).

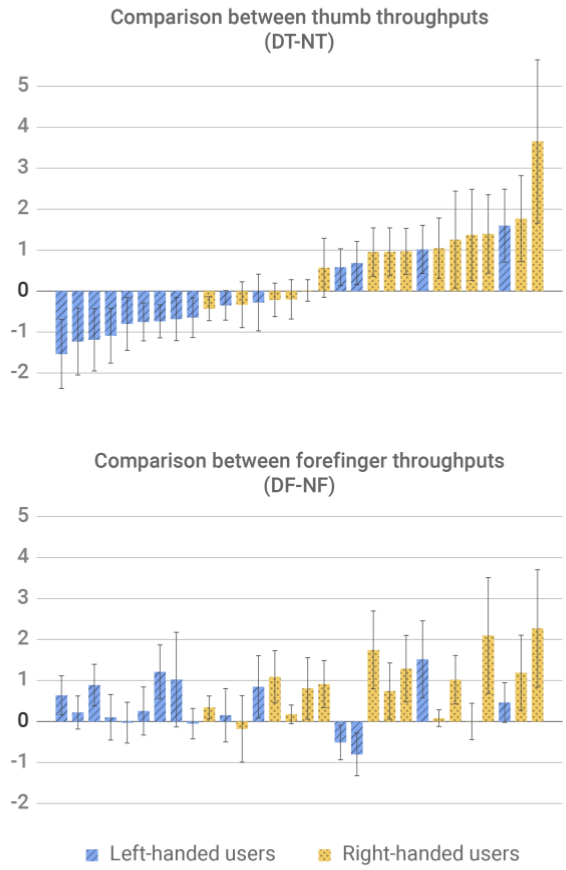

Fig. 9. Comparison of (dominant to non-dominant) thumb throughputs and forefinger throughputs for corresponding participants, where yellow (dotted) indicates right-handed and blue (lined) indicates left-handed users with error bars denoting ±1SD.The results have been arranged in an increasing order as per DT-NT.

Table 6. Overall percentage erroneous touches and their adjusted Wald 95% confidence intervals

	Error%	Adjusted Wald 95% CI from	Adjusted Wald 95% CI to
Overall DF	2.26	1.69	2.83

	Error%	Adjusted Wald 95% CI from	Adjusted Wald 95% CI to
Overall NF	2.37	1.79	2.95
Overall DT	2.30	1.72	2.87
Overall NT	3.63	2.92	4.34
Overall D (DF, DT)	2.28	1.88	2.68
Overall N (NF, NT)	3.00	2.54	3.46
Overall F (DF, NF)	2.31	1.91	2.72
Overall T (DT, NT)	2.96	2.51	3.42
Overall (DF, NF, DT, NT)	2.64	2.34	2.94

Table 7. Percentage erroneous touches and their adjusted Wald 95% confidence intervals for right-handed participants

	Error%	Adjusted Wald 95% CI from	Adjusted Wald 95% CI to
Right-handed DF	0.89	0.35	1.43
Right-handed NF	0.74	0.24	1.24
Right-handed DT	1.63	0.93	2.33
Right-handed NT	4.00	2.94	5.06
Right-handed D (DF, DT)	1.26	0.83	1.69
Right-handed N (NF, NT)	2.37	1.79	2.95
Right-handed F (DF, NF)	0.81	0.46	1.17
Right-handed T (DT, NT)	2.81	2.18	3.45
Right-handed Overall (DF, NF, DT, NT)	1.81	1.46	2.47

Table 8. Percentage erroneous touches and their adjusted Wald 95% confidence intervals for left-handed participants

	Error%	Adjusted Wald 95% CI from	Adjusted Wald 95% CI to
Left-handed DF	3.63	2.62	4.64
Left-handed NF	4.00	2.94	5.06
Left-handed DT	2.96	2.04	3.89
Left-handed NT	3.26	2.29	4.22
Left-handed D (DF, DT)	3.30	2.62	3.98
Left-handed N (NF, NT)	3.63	2.92	4.34
Left-handed F (DF, NF)	3.81	3.09	4.54
Left-handed T (DT, NT)	3.11	2.45	3.77
Left-handed Overall(DF, NF, DT, NT)	3.46	2.97	3.95

We also plotted scatter plots of the touches that were considered accurate by the above definition. On the whole, the right handers seem to be more accurate and precise than the left handers (see **Fig. 10**).

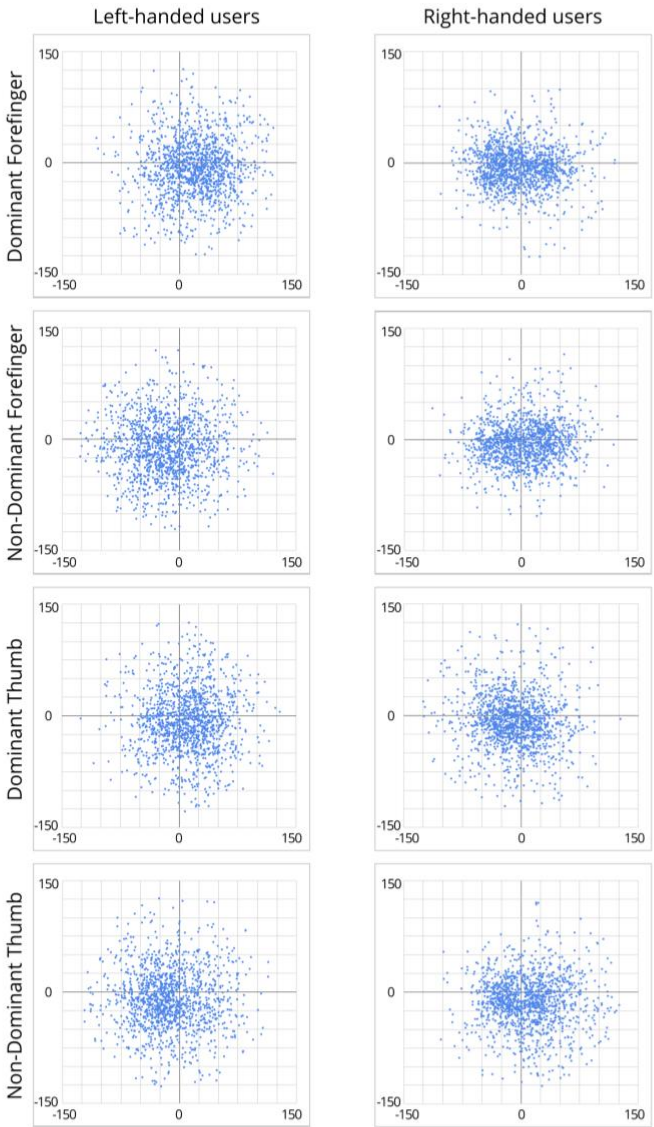

Fig. 10. Scatter plots of touches for different combinations

We summarized these distributions numerically with mean difference in the X and Y axes and their standard deviations (see **Table 9**). We can see that all mean differences in the Y axis are negative, indicating that most people hit just below the intended point. On the other hand, all mean differences of the digits of the right hands tend to overshoot slightly to the left of the intended target, and conversely for the fingers of the left hand.

Table 9. Distribution of touches for the different cases (DF—Dominant Forefinger, NF—Non-Dominant Forefinger, DT—Dominant Thumb, NT—Non-Dominant Thumb) for right-handed and left-handed participants respectively

	Mean diff x	SD diff x	Mean diff y	SD diff y
Right-handed DF	-1.7	37.1	-5.4	27.9
Right-handed NF	4.0	37.2	-5.2	28.0
Right-handed DT	-8.4	36.7	-8.5	35.5
Right-handed NT	9.6	39.2	-12.9	34.8
Left-handed DF	19.8	37.2	-7.0	39.1
Left-handed NF	-16.1	41.6	-11.6	40.1
Left-handed DT	11.0	36.8	-7.3	41.8
Left-handed NT	-12.3	40.1	-9.5	40.4
Right-handed DF	-1.7	37.1	-5.4	27.9

4 Discussion

The hypothesis in our study was that the throughput of the dominant finger would be higher than the corresponding non-dominant finger for both thumb and forefinger for all users. The forefinger throughputs conformed to this for both right- and left-handed participants. It was also followed in the case of thumbs for the right-handed participants. Surprisingly, though, left-handed participants had higher throughput with their non-dominant thumb compared to their dominant thumb.

4.1 Thumb performance of left-handed participants

One might question if there's also a concept such as 'fingeredness' which transcends beyond mere hand laterality but looks at the preference as well as efficiency of use of each individual digit in light of the digital world. The high throughput for the DF case for all users seems particularly compelling for such an argument. The choice of using forefingers might be said to demonstrate intent, unlike engaging only one hand for phone usage.

The comparison between DT and NT of left-handed users, however, clearly deviated from our expectation of a positive return. A point to be noted here is that 'dominant' and 'non-dominant' labels were assigned on the basis of initial self-reporting of handedness by the subject and verified by the EHI.

In the scenario where both hands are available for use, there is a natural tendency to use the preferred (dominant) hand for touch input. A possible explanation of the surprising better performance of the non-dominant thumb of the left-handed users is that the user interfaces of touch-screen devices are biased in favor of right-handed users for thumb use. This will provide incentive and practice to the left-handed users to use their right i.e. non-dominant thumb more frequently. Another possible explanation could be that the difference in performance is a result of inherent neurobiological differences in left- and right-handed individuals such as functional organization of motor areas in the brain [27].

By and large, the throughput of left-handed users was found to be higher than that of right-handed users, which could be the cumulative result of intrinsic proficiency combined with years of conditioning over a lifetime.

The result of our study leads us to question the notion of handedness from the perspective of handheld touch-based devices. What exactly is "handedness" and do we need to redefine it? As we discussed above, established handedness inventories are old, and do not consider the day-to-day activities of today's age—such as using touchscreen phones, computer trackpads and so on. With writing or drawing no longer being the main activity requiring high levels of hand dexterity, should such inventories take into account the activities from the modern context—such as using touchscreen phones and computer trackpads?

5 Conclusion

Through our paper we studied the Fitts' throughput for 4 test cases – dominant forefinger, non-dominant forefinger, dominant thumb and non-dominant thumb within-subject for 30 participants, and compared these results from the perspective of handedness. We found that the throughput for the dominant finger was higher than that of the corresponding non-dominant finger for a series of tapping tasks on a handheld touchscreen device. However, an exception to this was the performance of left-hand dominant users, for whom the throughput of the non-dominant (right) thumb was found to be better than that of the dominant (left) thumb. We also reveal that right-hand dominant users, when using their non-dominant (left) thumbs for tapping on a handheld touchscreen device perform the poorest (with the least mean Fitts' throughput). We also found that right-handed users were more accurate and precise than left-handed users.

We believe that taking our observations into consideration could potentially strengthen the design of relevant interfaces and improve inclusivity for both left- and right-handed individuals. While there is potential to bring some benefits especially in frequent tasks such as text input or gaming, additional research would be required to assess the benefits and the costs. We acknowledge the difficulties posed by tailoring the interface to multiple intersections of users in real-life projects. Further work will be required to establish standards related to design for handedness on touchscreens.

The major limitation of our study is that the conditions in which it was carried out may not encompass all the contexts in which touchscreen devices may be used in real life. Varying target widths, landscape vs. portrait modes, screen sizes, screen resolutions, display brightness and contrast, device weight, touch sensitivity, screen glare, different visual appearances of touch targets, and urgency of tasks might impact users' performance. We understand that the grips prescribed by us in the study are not exhaustive and there may be other more preferred or familiar configurations for certain users, and further work may be carried out to investigate the effect of grips on Fitts' throughput. In real life, users would not always be seated in ideal lab conditions and work may be carried out to confirm the applicability of our results with greater external validity.

While our choice to spawn targets at random destinations with varying amplitudes provides additional external validity to the study – in real life settings, targets could be anywhere on the screen and at any amplitude – further experiments may be conducted with our motivation incorporating multiple target widths, using a standardised task, or fixing amplitude over a sequence and the results could be compared. The study design choice of using a constant target width may have an effect on the error rate observed, while random spawning positions may explain a small reduction in throughput (among other factors such as age) due to the additional time a user might spend looking for the next target. The study could be repeated using other formulations of Fitts' Law such as FFitts [2], and these results could be compared.

Further, tapping, though common, is only one type of action that a user might be engaged in. Relationship between laterality and dexterity of other tasks, such as sliding, flicking, pinching and expanding need to be investigated in future.

Our study does not take into account factors such as the impact of gender, education, cultural background or ethnicity on performance. The study was carried out in a fairly localized sample group (technologically adept individuals from the Thane-Mumbai region), and repeating the study in a different geolocation with a more diverse sample might yield different results. For the purpose of collecting sufficient data for both left and right-handed participants, we recruited an equal number of these, which is not representative of the population at large. It is not obvious how this choice might have affected the outcomes. Our study does not delve into the anthropometric aspect, and there could be further work where empirical relations may be drawn between the dimensions of the thumb or finger and the performance in the task, or while taking into account the peculiar nature of movement of the human thumb and the limitations of its reach or range of extension. The directionality of movement might also play a role and further work would be required to determine this.

We believe that the clear asymmetry revealed through our work in the interaction by left- and right-hand dominant users warrants for incorporating handedness into future work in HCI. These could include revisiting several existing HCI studies that have been conducted with right-hand dominant participants which have implicitly assumed a laterally symmetric response. Our work points to possible areas of future research that could be explored, viz. intent-driven tasks such as text input or gaming controls, which might also include two-handed operation, specific grip configurations, etc. There might be exploration into questioning handedness indices and revising them to include contemporary activities on digital interfaces. The work could form a background for personalization and optimization of interfaces based on laterality. Our current work does not establish causality or reasoning behind the results observed, and there exist opportunities for further work to be carried out in this area. For this paper, we only took into account the users who have used a touch-based device regularly for at least a month. It could be interesting to study if similar results are observed by repeating the experiment in the case of users completely new to touchscreen usage, and perhaps thereby free of the biases arising thereof.

References

1. Annett, M.: A classification of hand preference by association analysis. British Journal of Psychology. 61, 303-321 (1970). doi: 10.1111/j.2044-8295.1970.tb01248.x
2. Bi, X., Li, Y., Zhai, S.: FFitts Law: Modeling Finger Touch with Fitts' Law. In: 2013 CHI conference on Human Factors in Computing Systems. 1363-1372 (2013). doi: 10.1145/2470654.2466180
3. Brush, K., Verma, A., Siddiqui, S., Sheridan, J., Leider, A., Tappert, C.: Index of Difficulty Measurement for Handedness in Human Computer Interaction. In: Proceedings of 2019 Student-Faculty Research Day, CSIS, Pace University. doi: 10.1007/978-3-030-30712-7_51
4. Chapman, L.J., Chapman, J.P.:The measurement of handedness. Brain and cognition 6, no. 2, pp. 175-183 (1987). doi: 10.1016/0278-2626(87)90118-7
5. Coren, S.: The lateral preference inventory for measurement of handedness, footedness, eyedness, and earedness: Norms for young adults. Bulletin of the Psychonomic Society 31, no. 1 (1993), pp. 1-3. doi: 10.3758/BF03334122
6. Crotte, A.M., Hepting, D.H., Roshchina, A.: Left-Handed Control Configuration for Side-Scrolling Games. In: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems, pp. LBW1622. ACM, 2019. doi: 10.1145/3290607.3312777
7. Drewes, H.: Only one Fitts' law formula please!. In: CHI'10 Extended Abstracts on Human Factors in Computing Systems, pp. 2813-2822. ACM, 2010. doi: 10.1145/1753846.1753867
8. Edinburgh Handedness Inventory. Retrieved 2020. http://www.brainmapping.org/shared/Edinburgh.php
9. Fan, Z., Coutrix, C.: Impact of Hand Used on One-Handed Back-of-Device Performance. In: Proceedings of the ACM on Human-Computer Interaction 4. ISS (2020), pp. 1-19. doi: 10.1145/3427316
10. Fitts, P.M.: The information capacity of the human motor system in controlling the amplitude of movement. In: Journal of experimental psychology 47, no. 6 (1954), pp. 381. doi: 10.1037//0096-3445.121.3.262
11. Google Material Design Guidelines. Retrieved 2020. https://material.io/design/usability/accessibility.html#layout-typography
12. Gori, J., Rioul, O., Guiard, Y., Beaudouin-Lafon, M.: 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, pp. 1-10. ACM, 2018. doi: 10.1145/3173574.3173770f
13. Henze, N., Boll, S.: It does not Fitts my data! Analysing large amounts of mobile touch data. IFIP Conference on Human-Computer Interaction, pp. 564-567. Springer, Berlin, Heidelberg, 2011.
14. Hoober, S.: How Do Users Really Hold Mobile Devices? Retrieved 2020. https://www.uxmatters.com/mt/archives/2013/02/how-do-users-really-hold-mobile-devices.php
15. Kim, I., Hyeon, J.J.: Performance comparisons between thumb-based and finger-based input on a small touch-screen under realistic variability. International Journal of Human-Computer Interaction, 31(11), pp. 746-760. doi: 10.1080/10447318.2015.1045241
16. Le, H.V., Mayer, S., Wolf, K., Henze, N.: Finger placement and hand grasp during smartphone interaction. In: Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing systems, pp. 2576-2584. doi: 10.1145/2851581.2892462
17. Lehmann, F., Kipp, M.: How to hold your phone when tapping: A comparative study of performance, precision, and errors. In: Proceedings of the 2018 ACM International

Conference on Interactive Surfaces and Spaces, pp. 115-127. ACM, 2018. doi: 10.1145/3279778.3279791
18. Lewis, R.: The Effect of Handedness on use of Touch Screen versus Touch Pad. In: Proceedings of the 5th International Conference on Application and Theory of Automation in Command and Control Systems, pp. 115-120. ACM, 2015. doi: 10.1145/2899361.2899373
19. Ljubic, S., Glavinic, V., Kukec, M.: Finger-based pointing performance on mobile touchscreen devices: Fitts' law fits. In: International Conference on Universal Access in Human-Computer Interaction, pp. 318-329. Springer, Cham, 2015. doi: 10.1007/978-3-319-20678-3_31
20. Löchtefeld, M., Schardt, P., Krüger, A., Boring, S.: Detecting users handedness for ergonomic adaptation of mobile user inrfaces. In Pro-ceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia, pp. 245-249. 2015. doi: 10.1145/2836041.2836066
21. MacKenzie, I.S.: Fitts' throughput and the remarkable case of touch-based target selection. International Conference on Human-Computer Interaction, pp. 238-249. Springer, Cham, 2015. doi: 10.1007/978-3-319-20916-6_23
22. McManus, I.C.: The interpretation of laterality. Cortex 19, no. 2 (1983), pp. 187-214.
23. Oldfield, R.C.: The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9, no. 1 (1971): 97-113. doi: 10.1016/0028-3932(71)90067-4
24. Parhi, P., Karlson, A.K., Bederson, B.B.: Target size study for one-handed thumb use on small touchscreen devices. In: Proceedings of the 8th conference on Human-computer interaction with mobile devices and services, pp. 203-210. ACM, 2006. doi: 10.1145/1152215.1152260
25. Perry, K.B., Hourcade, J.P.: Evaluating one handed thumb tapping on mobile touchscreen devices. In: Proceedings of graphics interface 2008, pp. 57-64. Canadian Information Processing Society, 2008. doi:10.5555/1375714.1375725
26. Plaumann, K., Weing, M., Winkler, C., Müller, M., Rukzio, E.: Towards accurate cursorless pointing: the effects of ocular dominance and handedness. Personal and Ubiquitous Computing 22, no. 4 (2018), pp. 633-646. doi: 10.1007/s00779-017-1100-7
27. Solodkin, A., Hlustik, P., Noll, D.C., Small, S.L.: Lateralization of motor circuits and handedness during finger movements. In: European Journal of Neurology 8, no. 5 (2001), pp. 425-434. doi: 10.1046/j.1468-1331.2001.00242.x
28. Soukoreff, R.W., MacKenzie, I.S.: Towards a standard for pointing device evaluation, on perspectives on 27 years of Fitts' law research in HCI. In: International journal of human-computer studies 61, no. 6 (2004), pp. 751-789.
29. Trudeau, M. B., Young, J.G., Jindrich, D.L., Dennerlein, J.T.: Thumb motor performance varies with thumb and wrist posture during single-handed mobile phone use. In: Journal of biomechanics 45, no. 14 (2012), pp. 2349-2354. doi: 10.1016/j.jbiomech.2012.07.012
30. Williams, S.M.: Handedness inventories: Edinburgh versus Annett. Neuropsychology 5, no. 1 (1991), pp. 43.doi: 10.1037/0894-4105.5.1.43