Mobile Touch Screen User Interfaces: Bridging the Gap between Motor-Impaired and Able-Bodied Users

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Purpose: Touch screen mobile devices are highly customizable, allowing designers to create inclusive user interfaces that are accessible to a broader audience. However, the knowledge to provide this new generation of user interfaces is yet to be uncovered.

Methods: Our goal was to thoroughly study mobile touch interfaces and provide guidelines for informed design. We present an evaluation performed with 15 tetraplegic and 18 able-bodied users that allowed us to identify their main similarities and differences within a set of interaction techniques (*Tapping*, *Crossing,* and *Directional Gesturing*) and parameterizations.

Results: Results show that *Tapping* and *Crossing* are the most similar and easy to use techniques for both motor impaired and able-bodied users. Regarding *Tapping*, error rates start to converge at 12mm, showing to be a good compromise for target size. As for *Crossing*, it offered a similar level of accuracy; however larger targets (17mm) are significantly easier to cross for motor impaired users. *Directional Gesturing* was the least inclusive technique. Regarding position, edges showed to be troublesome. For instance, they have shown to increase *Tapping* precision for disabled users, while decreasing able-bodied users' accuracy when targets are too small (7mm).

Conclusions: We found that despite the expected error rate disparity, there are clear resemblances between user groups, thus enabling the development of inclusive touch interfaces. *Tapping,* a traditional interaction technique, was among the most effective for both target populations, along with *Crossing*. The main difference concerns *Directional Gesturing* that in spite of its unconstrained nature shows to be inaccurate for motor impaired users.

Keywords: Mobile, Touch, Tetraplegic, Motor Impaired, Able-bodied, Interaction Techniques

Introduction

The spectrum of motor abilities is wide and diverse. In the last decades, efforts have been made to compensate this diversity and provide an inclusive access to technology, above all, to desktop computers. The same does not apply to mobile device accessibility, which is still in its infancy. Their small size, less processing capabilities, along with the context it is designed to be used in, may have been the main reasons for this lack of accessibility and overall limited understanding. Meanwhile, mobile phone touchscreens are increasingly replacing their traditional keypad counterparts. These interfaces present challenges for mobile accessibility: they lack both the tactile feedback and physical stability guaranteed by keypads, making it harder to accurately select targets. This becomes especially relevant for people who suffer from lack of precision, such as tetraplegic users. However, these interfaces offer several advantages over their button-based *equivalents*. The ability to directly touch and manipulate data on the screen without any mediator provides a natural and engaging experience. Additionally, the use of PDAs is a viable alternative to traditional input devices (i.e. mouse and keyboard), allowing the same interface to be used in different places and contexts. Furthermore, touch screens' high customization degree makes them amenable to custom-tailored or adaptive solutions that better fit each user's needs [6]. This may as well be a determinant factor for inclusive design as devices used by motor impaired people can be the same as the ones used by the able-bodied population, with slender interface tuning [3], [17], [18].However, there is no comprehensible knowledge of the values and flaws of each touch interaction technique in what concerns users' motor ability. To be able to provide flexible and customizable touch user interfaces, we first need to understand how users with dissimilar motor aptitudes cope with the different demands imposed by interaction techniques and interface parameterizations.

In this paper, we present an evaluation with 15 tetraplegic and 18 able-bodied people aimed at understanding the differences and similarities between populations. We studied a set of interaction techniques (*Tapping, Crossing,* and *Directional Gesturing*) and parameterizations (*Size* and *Position*). Results show that despite the expected error rate disparity, there are clear resemblances, thus giving space for inclusive adaptive user interfaces. *Directional Gesturing* was the least accurate technique for motor-impaired users, while *Tapping* and *Crossing* were the most effective and preferred between both target populations. We conclude the paper by presenting guidelines for inclusive design as well as avenues for future work.

Related Work

Previous work has tried to improve access to mobile touchscreen interfaces by motor-impaired people. Wobbrock et al. [19] proposed a stylus-based approach that uses edges and corners of a reduced touchscreen to enable text-entry tasks on a PDA. Results showed that *EdgeWrite* provides high accuracy and motion stability for users with motor impairments.

Similarly, Barrier Pointing [2] uses screen edges and corners to improve pointing accuracy. By stroking towards the screen barriers and allowing the stylus to press against them, users can select targets with greater physical stability.

Although these works insightfully explore the device physical properties to aid impaired people interacting with touchscreens, there is still little empirical knowledge about their performance with other interaction techniques. On the other hand, a great deal of research has been carried out to understand and maximize performance of able-bodied people using these devices [1, 4, 7, 9, 10, 12, 13, 14, 8].

Target size is one of the main issues when studying touch interfaces. The anthropomorphic average width of the index finger and the thumb for adult men are 18.2 mm and 22.9 mm, respectively, and women 15.5 mm and 19.1 mm, respectively [1]. HCI literature suggests that for soft buttons to work well with finger interaction, the button width needs to be larger than 22 mm [3, 7]. However, while this size is possible to implement in wide screens (e.g. kiosks), they are bigger than what mobile devices are able to accommodate.

Parhi et al. [12] conducted a study to determine optimal target sizes for one-handed thumb use of handheld devices. Results showed that sizes between 9.2 mm and 9.6 mm can be used without degrading performance and preference. Similarly, Park et al. [13] analyzed three different virtual key sizes. Results showed that the larger key size (10 mm) presented higher performance rate and subjective satisfaction. Lee and Zhai [7] obtained similar results, as targets smaller than 10 mm in width showed to strongly reduced performance.

Regarding on-screen target location, users prefer targets near the center of the screen, because it is easier and more comfortable to tap. Additionally, the highest accuracy rate occurs for targets on the edge of the screen [13].

While previous studies derive recommendations on target sizes and locations for mobile touch screen interfaces, Mizobuchi et al. [10] conducted a study to determine how text input, using a stylus, would be affected by walking versus standing. They suggest a virtual keyboard with a minimum width of 3 mm per key, which guarantees an error rate inferior to 2%. However, more demanding walking situations may require larger targets [9]. Users walking in an obstacle course are reported to be able to tap on a 6.4 mm target with 90% accuracy. Although these studies were performed with able-bodied people, with induced impairments [15] and using a stylus, they can reveal useful insights in the design of touch interfaces for motor-impaired users. Indeed, these users may experience similar problems, as tremor and lack of physical stability. However, the apparent similarities are not enough to assume the results as veritable and the basis for the design of more effective touch-based interfaces for motor-impaired people.

As can be seen, there is a severe lack of results pertaining motor-impaired users when interacting touchscreen devices. The experiment reported in this paper tries to bridge this gap by dissecting interaction techniques, their characteristics and parameterizations, thus providing broader empirical knowledge to support informed touch interface design.

Evaluating Touch Techniques

Touch screen devices pose both challenges and opportunities for researchers. Recently, significant efforts have been applied to make these interfaces accessible to motor-impaired people [19, 2]; however there is still little empirical knowledge about their performance with different interaction techniques and how it is related to the performance of able-bodied users.

Our primary goal with this research was to evaluate diverse motor ability-wise participants with different interaction techniques, towards an adaptive/customizable inclusive touch design space. By understanding the limitations and needs of each population, along with the advantages and flaws of each technique and parameterization, we will be able to understand how to design

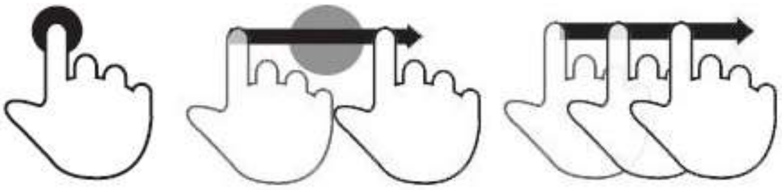

Figure 1. *Interaction Techniques* (from left to right): *Tapping, Crossing, Directional Gesturing*.

interfaces that maximize user's performance. Further, we will be able to build more inclusive interfaces.

Interaction Techniques and Variations

In this experiment, we selected a set of interaction methods representative of the different ways to manipulate a touch interface. This set includes insights from previous work and their assumptions [2, 19]. We then studied and compared both tetraplegic and able-bodied people using those techniques with mobile touchscreens.

We considered two basic interaction paradigms: tapping the screen or performing a gesture. When performing a gesture, users could cross a target or just use directional gestures (Figure 1).

Tapping the screen consisted in selecting a target by touching it (i.e. land on target). This is the most used interaction technique in current touchscreen devices, possibly due to its ease of use or naturalness. In this technique, targets were presented in 3 different sizes (7, 12, and 17 mm), derived from previous studies for able-bodied users [7, 13], and in all screen positions: edges or middle, thus covering the entire surface.

Crossing, unlike *Tapping*, did not involve positioning one's finger inside an area. Instead, a target was selected by crossing it. Previous work, on desktop interaction, has shown that this technique offers better performance for motor-impaired users than traditional pointing methods [20]. In our experiment, targets were shown in the middle screen positions (Figure 2) in 3 different sizes.

Directional Gesturing was the only technique that did not require a target selection. Users could perform directional gestures anywhere on the device's surface. This technique was chosen both due to its unconstrained nature and, as well as *Tapping*, because it is a common interaction technique in current touch-based devices. Table 1 summarizes all interaction techniques and their variations.

Table 1. Interaction techniques and variations.

Technique	**Sizes**	**Positions**
Tapping	7, 12, 17 mm	Middle, Edges
Crossing	7, 12, 17 mm	Middle
Directional Gesturing	N/A	Middle, Edges

Participants

Fifteen tetraplegic people were recruited from a physical rehabilitation center. The target group was composed by 13 male and 2 female with ages between 28 and 64 years with cervical lesions between C4 and C6. Prior to the experiment subjects performed a capability (grasp) assessment test. This functional evaluation aimed to produce an objective capability identification in opposition to lesion level. However, no correlations between participants' functional abilities and task performance were found [5]. All participants had residual arm movement but no hand function. Regarding technologic experience, all had a mobile phone and used it on a daily basis. However, none of them had a touchscreen mobile phone. Regarding able-bodied participants, eighteen people (5 females) with ages comprehended between 20 and 45 years old were recruited word-of-mouth in the local university. All of them had previous contact with mobile touch phones.

Apparatus

In this experiment we used a QTEK 9000 PDA (Figure 2) running Windows Mobile 5.0. The device screen had 640x480 (73x55 mm) pixels wide, with noticeable physical edges. The evaluation software was developed in C# using .NET Compact Framework 3.5 and Windows Mobile 5.0 SDK. Trials were video recorded and all interactions with the device were logged for posterior analysis.

Figure 2. QTEK 9000. Screen positions (left): white – middle; gray and black: edges. Vertical distances (right).

Procedure

At the beginning of the experiment participants were told that the overall purpose of the study was to investigate and compare different touch interaction techniques and their adequacy for both tetraplegic and able-bodied users. We then conducted a questionnaire to assess participants' profile and all techniques (*Tapping*, *Crossing*, and *Directional Gesturing*) were explained and demonstrated.

To attenuate learning effects, participants were given warm-up trials before the evaluation of each technique. During these trials they were able to move the mobile device to a comfortable position. All sessions were performed in a quiet environment (the university, their homes or rehabilitation centre facilities). Motor impaired participants carried out the trials sitting on their wheelchairs with a table or armrest in front of them. Able-bodied participants completed the trials sitting in a chair in front of a table and were free to choose how to hold the device. The interactions with the touch screen were stylus-free; however participants were free to issue selections with any part of their hands/fingers.

Each subject was asked to perform target selections with each technique (*Tapping* and *Crossing*). For the *Directional Gesturing* condition, there were no targets and participants only had to perform a gesture in a particular direction (e.g. north). There were sixteen possible directions, including diagonals and repeated directions with edge support (e.g. north using the right edge as a guideline). For the *Tapping* condition participants were asked to select targets in all screen positions, as shown in Figure 2, one at a time. For the *Crossing* condition we only used the middle area (9 positions).

Participants had one attempt to complete the current trial and were not informed on whether the selection was successful or not. However, they received feedback that an action was performed. The next target appeared following a two second delay after each action. We selected each technique in a random order to avoid bias associated with experience. Within each technique condition, target positions were also prompted randomly to counteract order effects.

In the end of the study, participants were debriefed and asked to rate each technique *Ease of Use*, using a 5-point Likert scale (*1 – very hard to use; 3 – neutral; 5 – very easy to use*), and their preferred technique.

Measures

The measures used in this experiment were obtained through our logging application, which captured all user interactions with the mobile device. The dependent variables were *Error Rate*, *Precision*, *Movement Error*, and *Movement Time* [16].

For target selection techniques (*Tapping*, *Crossing*), *Precision* was calculated as the minimum distance to the center of the target. For the gesturing condition, *Precision* corresponded to the average distance to the requested direction axis.

For gestural approaches (*Crossing* and *Directional Gesturing*) both *Movement Time* and *Error* [16] were captured. *Movement Time* corresponded to the time participants spent touching the screen while performing the gesture. *Movement Error* consisted in the average absolute deviation from the gesture axis. The difference between *Movement Error* and *Precision* is that the former relates to the stability of the movement while the latter relates to the task goal (correct direction or proximity to target).

In addition to objective measures, we also assessed each technique perceived *Ease of Use* and overall *Preference*.

Experimental Design and Analysis

The experiment varied interaction technique, target size and screen position. Our goal here is not to assess differences in overall performance between motor-impaired and able-bodied people. Hence, we will not statistically compare both groups, instead we will analyze each group separately and how they behave with different interfaces and parameters. This will enable us to draw conclusions on resemblances and differences between both domains but always acknowledging that they are different and performances are likely to vary. For each group, we used a within-subjects design, where each participant tested all conditions. For the position analysis, we created one extra factor: *Vertical Distance* (Figure 2), which reflects the target position in relation to the users' support (level 1 refers to the closest screen position while level 5 refers to the most distant ones).

For dependent variables that showed to fit a normal distribution, we used a repeated-measures ANOVA and Bonferroni post-hoc multiple comparisons test in further analysis. On the other hand, for observed values that did not fit a normal distribution, a Friedman test was used. Post-hoc tests were performed using Wilcoxon signed rank pair-wise comparisons with a Bonferroni correction.

Results

Our goal is to understand and relate the capabilities of both user populations (i.e. motor-impaired and able-bodied) when using different touch techniques. We present the results highlighting their main similarities and differences considering each technique, target size and interaction area. This knowledge will enable designers to predict how both motor-impaired and able-bodied users will perform using their touch interfaces and employed techniques. Table 2 summarizes results for each interaction technique.

Table 2. Mean values (standard deviations) of each interaction technique and size for error rate, precision, movement error, and movement time.

	Measure	***Error Rate (%)***			***Precision (px)***			***Mov. Error (px)***			***Mov. Time (s)***		
	Size (mm)	***7***	***12***	***17***	***7***	***12***	***17***	***7***	***12***	***17***	***7***	***12***	***17***
Motor-Impaired	Tapping	42.7 (24)	24.3 (20)	20.5 (17)	330 (24)	327 (22)	327 (21)						
	Crossing	37.0 (25)	26.7 (23)	23.7 (20)	44.8 (33)	55.9 (41)	63.3 (51)	12.9 (18)	16.1 (15)	15 (22)	659 (345)	661 (391)	662 (422.9)
	Gesturing	36.7 (24.4)			36.1 (36.3)			8.49 (7.62)			327.3 (144.2)		
Able-Bodied	Tapping	13.8 (14)	1.8 (4)	0 (0)	21.1 (6)	26.3 (8)	30.5 (5)						
	Crossing	6.2 (10)	6.2 (12)	1.9 (4)	16.2 (10)	21.6 (15)	15.4 (8)	4.7 (2)	6.1 (3)	5.6 (2)	560 (269)	557 (228)	617 (235)
	Gesturing	1.4 (2.7)			11.23 (6.85)			3.92 (1.38)			339.6 (136)		

Looking into Each Technique

The techniques analyzed in this user study have different essences and each has its own advantages and disadvantages. In this section, we present the results obtained for each technique and analyze differences strictly within them.

Tapping

Tapping consisted in selecting a target by land-on it. The results obtained were analyzed in respect to *Error Rate* and *Precision*.

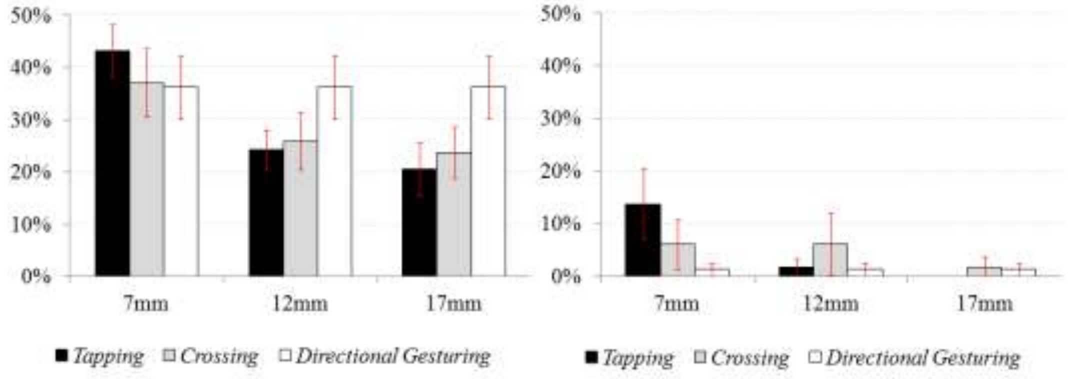

Figure 3. *Error Rate* for each *Technique* and *Target Size* (left: motor impaired, right: able-bodied). Error bars denote 95% confidence intervals.

Motor impaired. There was a significant effect of *Target Size* on *Error Rate* ($F_{1,42}=25.10$, $p<.001$). A multiple comparisons post-hoc test found significant differences between small and medium sizes, as well as between small and large sizes (Figure 3). These results suggest 12 mm as an approximate suitable value for targets to be acquired by motor-impaired users. Regarding *Precision*, no significant difference was found between target sizes (mean distance: 7mm - 330px, 12mm – 327px, 17mm – 327px). Also, we found no significant effect of *Target Position* (edge or not) on *Error Rate* for *Tapping*, regardless of target size. However, there was a significant effect of *Target Position* on *Precision* (Figure 5) for the smallest ($F_{1,28}=14.41$, $p<.01$), medium ($F_{1,28}=6.85$, $p<.005$) and large ($F_{1,28}=27.67$, $p<.001$) sizes, showing higher precision in the *Edges* (mean distance: 7mm – 331px, 12mm – 327px, 17mm – 321px) than elsewhere (mean distance: 7mm – 328px, 12mm – 325px, 17mm – 332px). This indicates that *Edges* offer higher stability although this is not reflected in higher accuracy. Regarding *Vertical Distance,* it has shown to have a significant effect on *Error Rate* for *Tapping* both on medium ($F_{1,42}=3.59$, $p<.05$) and largest ($F_{1,42}=5.19$, $p<.05$) sizes. Post-hoc tests showed that targets closer to the users' operating arm are easier to tap. As to *Precision*, a minor effect was found in the medium and largest sizes, also pointing to differences between top and bottom areas (higher precision in bottom areas). This strongly suggests that the users are more accurate and precise acquiring targets closer to their arm support point (Figure 4-left).

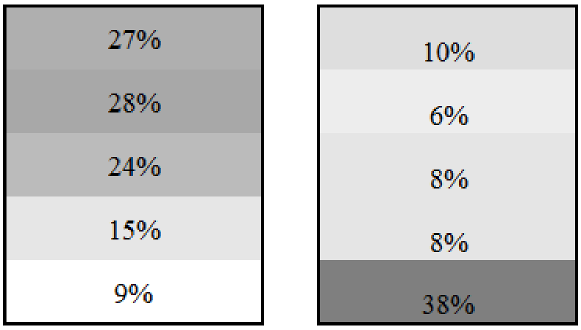

Figure 4. *Error Rate* by *Vertical Distance*: left - motor impaired (large size); right - able-bodied (small size)

Able-bodied. There was a statistically significant difference in *Error Rate* depending of *Target Size* for *Tapping* ($\chi^2_{(2)}$=26.261, *p<.001*). Post-hoc analysis revealed significant differences between the smallest and both medium and largest sizes (Figure 3). As with motor impaired participants, results suggest that *Error Rate* starts to converge at 12 mm. Moreover, we also found an effect of *Precision* between *Target Sizes* ($\chi^2_{(2)}$=32.444, *p<.001*). Results show that participants had lower precision on larger targets (mean distance: 7mm – 21px, 12mm – 26px, 17mm – 31px); in other words participants decreased their aiming precision as target size increased in size, however they did not decrease their accuracy. Considering *Target Position (edges vs. middle)*, we found a significant effect on *Error Rate* (Z=-2.987, *p<.05*). Results showed that, for small sizes, targets are easier to acquire in the middle of the screen. Moreover, participants had higher *Precision* in the middle of the screen for small (mean distance=16px, Z=-3.724, *p<.001*), medium (mean distance=18px, Z=-3.724, *p<.001*) and large targets (mean distance=22px, Z=-3.724, *p<.001*).
Regarding *Vertical Distance,* there was a significant effect for *Tapping* in the smallest size ($\chi^2_{(4)}$=24.172, *p<.001*). As shown in Figure 4-right, targets near the bottom edge are significantly harder to acquire. Also, participants were less precise on the bottom edge for all sizes ($\chi^2_{(4)}$=31.442, *p<.001*).

Differences and similarities. Traditional *Tapping* technique revealed to be very similar regarding *Target Size*. Both tetraplegic and able-bodied participants performed worse with small target sizes (7 mm), and *Error Rate* begins to converge at 12mm. Nevertheless, we suspect that able-bodied users can achieve similar accuracy results with smaller targets [7, 8]. Regarding *Position*, *Edges* can benefit motor-impaired users allowing them to tap targets with higher *Precision*.

However, targets should not be placed far from the users' arm support due to restrictions of reach. On the other hand, the physical constraint of *Edges* seems to hinder able-bodied users' *Accuracy* and *Precision* (also reported in [13]). In fact, when these were placed near edges, particularly the lower edge, *Tapping* accuracy was 3 times lower for small targets (18% *Error Rate*).

Crossing

This experiment featured targets in the nine central positions, thus avoiding targets close to the edge or corner. *Crossing* included, besides *Error Rate* and *Precision*, analysis to *Time* and *Movement Error*.

Motor impaired. There was a significant effect of *Target Size* on *Error Rate* ($F_{1,42}$=6.56, p<.01). Significant differences were found between the smallest and largest sizes (Figure 3). No effect was found in *Precision* (mean distance: 7mm – 45px, 12mm – 56px, 17mm – 63px), *Time* (mean time: 7mm – 659ms, 12mm – 661ms, 17mm – 662ms) or *Movement Error* (mean distance: 7mm – 13px, 12mm – 16px, 17mm – 15px). The absence of significant effects suggests that *Target Size* does not have an influence on the way the users cross the targets (the type of movement and time dispended to accomplish the task).
Similarly, no significant effect was found for *Target Position* (*Vertical Distance*) on *Error Rate, Precision, Time or Movement Error.* This comes as no surprise as all targets were placed in a center position, minimizing the vertical differences.

Able-bodied. No significant differences were found between *Target Size* or *Vertical Distance* regarding *Error Rate* (Figure 3), *Precision* (mean distance: 7mm – 16px, 12mm – 22px, 17mm – 15px) *or Movement Time* (mean time: 7mm – 560ms, 12mm – 557ms, 17mm – 617ms). This suggests that performance with Crossing is independent of both *Target Size* and *Position*. Nevertheless, a significant effect of *Movement Error* was found between target sizes ($\chi^2_{(2)}$=14.778, $p<.001$). Post-hoc analysis revealed that gestures are more erroneous with larger targets (mean distance=6px) when compared to the smallest ones (mean distance=4px, Z=-2.809, $p<.005$). This suggests that participants decreased their movement stability when larger targets were presented.

Differences and similarities. *Crossing* is the most consistent interaction technique both *intra* and *inter* user population. Particularly, it seems to be independent of *Target Position,* since no effects of *Error Rate, Precision, Time or Movement Error* were found. Regarding *Target Size*, 17mm targets (larger) are easier to cross for motor impaired users.

Directional Gesturing

Concerning *Directional Gesturing*, there are no particular on-screen targets or sizes, just directions. This method included analysis of *Error Rate*, *Precision*, *Time* and *Movement Error*.

Motor impaired. No significant effect was found between *Target Position* (gestures supported by the edges or anywhere else on-screen) in *Error Rate* (mean ER: edge – 35%, middle – 37.5%), *Precision* (mean distance: edge – 31px, middle – 41px) *and Movement Error* (mean distance: edge – 7px, middle – 10px). Regarding *Time*, a significant effect was found with edge-supported gestures (mean time=288 ms) being faster than the middle ones (mean time= 367ms, $F_{1,70}$=2.52, p<.05). This was probably due to the length of gestures (see Figure 5-left). Additionally, no significant effect was found between Gesture *Direction* in *Error Rate*, *Precision*, *Time* and *Movement Error.* Several errors when performing *Directional Gestures* were due to undesired taps but with no relation with particular directions. Visual inspection suggested that some directions are more problematic than others, for individual participants, but these differences were not significant.

Able-bodied. When considering *Directional Gesturing*, no significant differences were found between gestures on the edge or elsewhere onscreen regarding *Error Rate* (mean ER: edge – 1.39%, middle – 1.39%), *Time* (mean time: edge – 326ms, middle – 353ms), and *Movement Error* (mean distance: edge – 4px, middle – 4px). Nevertheless, a significant effect was found for *Precision* (Z=-3.724, $p<.001$). A post-hoc analysis showed that participants were less precise without the aid of edges (mean distance: edge – 5px, middle – 17px). Also, we found that horizontal and vertical gestures are significantly more precise (mean

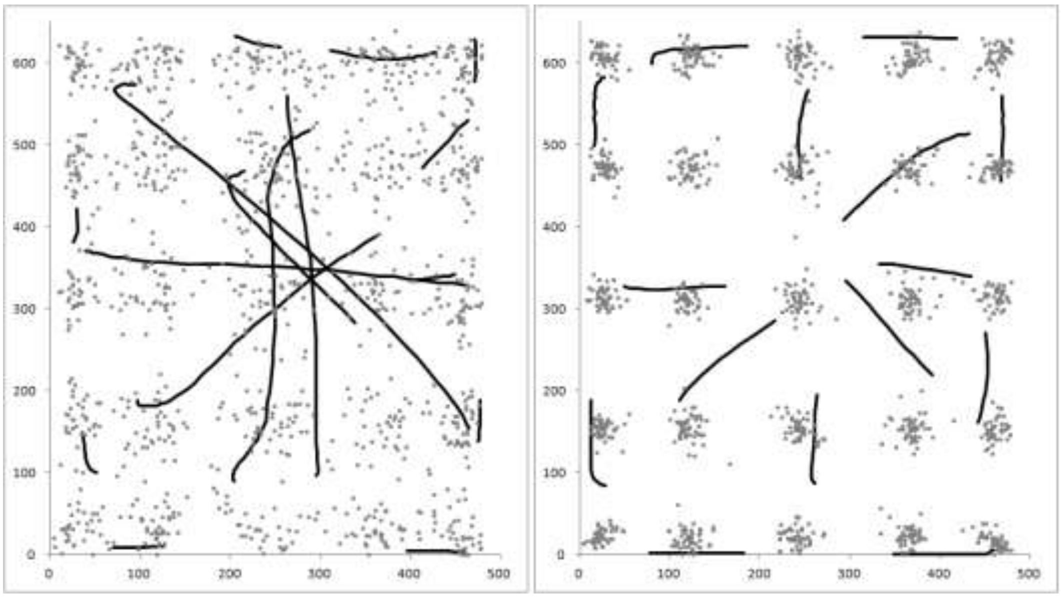

Figure 5. Overall Taps and *Directional Gestures* - left: motor impaired participant, right: able-bodied participant. *Tapping* dispersion is much higher for the disabled participants and *Gestures* are longer and more erroneous.

distance=6px) than diagonals (mean distance=17px, Z=-3724, *p*<0.001), yet error rates are similar.

Differences and similarities. *Directional Gesturing* was the least inclusive technique. Particularly, the difference in the magnitude of errors between user populations is the greatest among all interaction techniques (Figure 3), illustrating the capability gap between able-bodied and disabled users. Therefore, when designing interfaces for motor impaired users *Directional Gestures* should only be considered if targets are small, and even then, users may not be able to perform specific directional gestures. Regarding similarities, one could argue that *Gestures* performed with edge support would be more accurate to both able-bodied and disabled users. However, results have shown that both user populations have similar error rates performing a *Gesture* on the edge or anywhere else on the screen.

Comparing Techniques

The analysis performed for each technique reinforces the idea that user effectiveness and efficiency is affected by target characteristics like size or on-screen position. This effect has different proportions for the different proposed approaches. We have already addressed each method in this regard. We will now focus on comparing techniques and understanding which is best suited for particular target size/position combinations. Moreover, we will perform this comparison for each user population and again highlight their main differences and similarities.

Target Size

Motor impaired. There was a significant effect of *Interaction Technique* on *Error Rate* in the medium ($F_{1,56}$=8.04, $p<.001$) and largest ($F_{1,56}$=3.83, $p<.05$) sizes, in which *Directional Gesturing* performed worst than *Tapping* and *Crossing*. This suggests that *Directional Gestures* are only worth considering when target size is small. *Tapping* and *Crossing* performed equally for all target sizes.

Able-bodied. We found a significant effect of *Interaction Technique* in the smallest size ($\chi^2_{(2)}$=13.765, $p<.001$). Further analysis revealed that *Directional Gestures* is significantly more accurate than *Tapping* (Z=-3.237, $p<.001$). This result suggests that when interface targets are small, *Gestures* are a more adequate technique.

Differences and Similarities. Regarding each interaction technique, *Tapping* and *Crossing* seem to be the most similar between target populations, particularly both techniques perform equally across all target sizes. The main difference between these two types of users lies in the magnitude of errors. Regarding *Directional Gesturing*, motor-impaired users have great difficulty performing gestures in specific directions, while able-bodied users have no difficulty using this technique. Indeed, results suggest that *Directional Gesturing* can be a suitable alternative when the interface only has small targets.

Interacting in the Middle of the Screen

The “middle of the screen” refers to all areas away from edges. This represents a major percentage of the interaction surface and it is worthy to comprehend how a user can interact therein. In this experiment, the participants could tap or cross a target and perform directional gestures in the middle of the screen.

Motor impaired. There was no significant effect of *Interaction Technique* on *Error Rate*, suggesting that users have similar accuracy while interacting in the middle of the screen with *Tapping, Crossing* and *Directional Gesturing*.

Able-bodied. As disabled users, regardless of target size, we found no significant differences between *Tapping, Crossing* and *Directional Gesturing* techniques on *Error Rate*.

Differences and Similarities. When considering interaction on the middle of the screen, both target populations perform equally with *Tapping, Crossing*, and *Directional Gestures*, suggesting that the main differences between techniques are in the remaining of the screen (i.e. edges).

Interacting with Edge Support

One can argue that screen edges offer a positive support for interaction. In the techniques considered, the users were asked to tap targets near an edge (*Tapping*) and to perform gestures with edge support (*Directional Gesturing*).

Motor impaired. No significant effect of *Interaction Technique (Tapping in the edge vs. Gesturing in the edge)* was found on *Error Rate* in the smallest or medium sizes. A minor effect was found in the largest size suggesting better accuracy in edge-supported taps ($F_{1,28}$=3.15, p<.1). This is understandable as the edge forces the user to perform the movement in a particular direction, one that may or may not be possible/easy for him to perform. *Tapping* is less restrictive as the user may approach the target as he is more comfortable to do so.

Able-bodied. *Directional Gesturing* have shown to be more accurate than *Tapping* on screen *Edges* (Z=-3.066, $p<.05$) for small sizes. No significant effect of *Interaction Technique* was found on *Error Rate* in the medium and largest sizes, indicating that accuracy is similar.

Differences and Similarities. Unlike disabled users, able-bodied are able to take advantage of screen *Edges*, particularly when faced with small target sizes;

performing *Directional Gestures* on edges is significantly easier than *Tapping* small targets.

User Opinions

In the end of each session we asked the participants about each technique *Ease of Use*, using a 5-point Likert scale. Additionally, they were asked about their preferred method.

Motor impaired. The median [quartiles] attributed by participants was for *Tapping* 4[4, 4.5], for *Crossing* 4[4, 4] and for *Directional Gesturing* 4[4, 4], showing a slight preference for *Tapping*. This idea was reinforced when they were asked about their preferred method (9/15 selected *Tapping*, 3/15 selected *Crossing*, and 3/15 selected *Directional Gesturing*)

Able-bodied. The median [quartiles] attributed by able-bodied participants was for *Tapping* 4[4, 5], for *Crossing* 5[4, 5] and for *Directional Gesturing* 4[4, 4]. Unlike disabled participants, able-bodied had a slight preference for *Crossing*, which was confirmed when directly asked about their preferred method (5/18 answered *Tapping*, 9/18 answered *Crossing*, and 4/18 answered *Directional Gestures*).

Differences and Similarities. Concerning similarities, *Tapping* and *Crossing* were the best rated *Interaction Techniques*. However, while motor impaired participants chose *Tapping* as their preferred method, able-bodied participants selected *Crossing*. In fact, those techniques obtained similar performances for both user populations during our user study.

Towards Inclusive Touch Interfaces

Use *Tapping* and *Crossing* as inclusive interaction techniques. Taking into account all interaction techniques, *Tapping* and *Crossing* have shown to be the ones with more resemblances between motor impaired and able-bodied users. These techniques presented a low and very similar *Error Rate* within both target populations and, therefore can both be used in touch interfaces.

Moreover, although most of our analysis focus on accuracy results, timing results revealed that motor-impaired participants take on average 148s (*sd*=87s) and 175s (*sd*=74s) to tap and cross a target, respectively. This difference did not show to be statistically significant (Z=-1.726, *p*>.08), suggesting that both techniques are equally efficient and effective.

Avoid *Directional Gesturing* for motor impaired users. *Directional Gestures* have shown to be significantly more inaccurate than both *Crossing* and *Tapping* with 12mm and 17mm targets. Even when considering small targets, *Gestures* do not outperform any of the remaining techniques, thus showing no gain in its usage.

***Error Rate* starts to converge between 7mm and 12mm for *Tapping*.** *Tapping*, the traditional selection method, has shown to be one of the most accurate *Interaction Techniques*. Moreover, 12 mm revealed to be a good compromise for target size as *Error Rate* begin to converge for both user populations. Nevertheless, we suspect that able-bodied users can select smaller targets (between 7mm and 12mm) with similar accuracy [13].

Edges are troublesome. Both user populations can use all interaction techniques on the middle of the screen with similar accuracy. This suggests that it is the remaining of the screen (edges) that can favor or hinder interaction. For instance, *Edges* have shown to increase *Tapping* precision for disabled users, while decreasing able-bodied users' accuracy. On the other hand, when targets are small (7mm) *Tapping* techniques should be avoided near *Edges* and instead make use of *Directional Gestures* (for able-bodied). Overall, when designing new touch interfaces, *Edges* should be handled carefully.

Take reach restrictions into account. One major difference between user domains populations is their ability to reach far-away targets. Motor impaired users have greater difficulties *Tapping* targets far from their arms' support, thus resulting in lower accuracy rate. This may be especially relevant for bigger touchscreen devices, such as tablets. Conversely, able-bodied users do not face this difficulty, however when targets are small they present some difficulties in

Tapping targets near the bottom edge. This may be due to the restrictions imposed by the physical edges, preventing users to fully land their fingers on targets.

***Directional Gestures* are a suitable alternative to small targets (only) for able-bodied users.** *Directional Gesturing* proved to be an accurate interaction technique for able-bodied users. In fact, this technique has shown to be a suitable alternative to *Tapping*, particularly when small targets are placed near the edges. Unlike motor impaired people, who have many difficulties performing specific gestures, able-bodied people can easily take advantage of this technique.

Keep in mind the magnitude of errors. Despite the similarities between motor impaired and able-bodied users with touch interfaces, one of the main differences resides in the magnitude of errors. As expected disabled users have a much lower accuracy rate. Overall, error rates are 5.6%, 6.1%, and 26.1% times higher for *Tapping*, *Crossing* and *Directional Gesturing*, respectively. Therefore, we believe that touch interfaces are still in need for new and more inclusive interaction techniques.

Limitations

Our motor impaired participants only included novice users, which is an essential user group if the goal is to design more accessible and effective interfaces. Nevertheless, all able-bodied participants had previous experience with touch-based interfaces, which may have introduce an effect of experience on obtained results. Since recruiting participants with no experience on touchscreen devices is an extraordinary task these days, we decided to minimize this effect by thoroughly explaining all interaction techniques and providing practice trials to all motor impaired participants. Since techniques were fairly simple, we believe that the effect of experience was indeed minimized. Users' comments and subjective ratings leverage the idea that the main differences between users' performance were mainly due to their physical abilities. Nevertheless, future work will need to confirm whether practice will decrease the gap between able-bodied and motor impaired users.

The conditions studied in this work were always performed with the same device, in a controlled and quiet environment, and featuring target selection tasks. While this decision was necessary to achieve our goals and assure high internal validity, allowing users to interact with new devices and perform realistic tasks (e.g. contact managing, emailing, etc.) is needed. Particularly, future research should explore target selection tasks featuring multiple targets, simultaneously displayed on screen. This would allow researchers to answers questions such as: How much space needs to be left between targets to avoid false positives? What is the maximum density of targets that can be displayed on the screen for a given selection method? Although our work did not focus on these questions, it shed light on interaction issues that motor-impaired people face on current touch-based devices. Also, we believe our findings to be generalizable beyond the set of conditions of our experiment, since most tasks are a composition of the chosen interaction techniques. Still, this hypothesis needs to be fully investigated.

We are currently exploring new environment settings in order to understand how users' performance is affected by mobility. In fact, related work [9] and preliminary results [11] show that motor-impaired and (able-bodied) situational-impaired users' error rates start to converge. These findings open exciting new opportunities in the discipline of universal and inclusive design.

Conclusions and Future Work

Touch screen mobile devices are able to exhibit different interfaces in the same display, allowing designers to create more suitable interfaces to their users' needs. These devices carry with them the promise of a new kind of user interfaces; one that is accessible to a broader user population. To fulfill this vision we undertook an extensive evaluation with 15 tetraplegic and 18 able-bodied users in order to provide empirical knowledge to be used in the design of future touch interfaces. Our goal was to indentify the main resemblances and differences between these two populations, while comparing different interaction techniques, target sizes and positions.

Results showed that traditional interaction techniques, such as *Tapping,* can be used by motor impaired users, however with higher *Error Rate* than those obtained by able-bodied users. On the other hand, *Directional Gesturing* while extremely easy to perform by those with no impairments, proved to be inadequate to the remaining. *Crossing* targets has also shown to be a suitable alternative to motor impaired people, since performance was very similar to *Tapping*.

Indeed, future touch interfaces have to take into account their users' capabilities and provide the most adequate techniques to ensure an efficient and effective experience.

Following this work, we intend to instantiate our findings and develop a touch interface that can be adaptable to its users' capabilities, regarding *Interaction Technique*, *Target Size* and *Position*.

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References

[1] DREYFUSS, H., ALVIN, R., ET AL. The measure of man and woman. Whitney Library of Design, 1993.

[2] FROEHLICH, J., WOBBROCK, J. O., AND KANE, S. K. Barrier pointing: using physical edges to assist target acquisition on mobile device touch screens. In *Proceedings of the 9th international ACM SIGACCESS conference on Computers and accessibility* (New York, NY, USA, 2007), Assets '07, ACM, pp. 19–26.

[3] GAJOS, K. Z., WOBBROCK, J. O., AND WELD, D. S. Automatically generating user interfaces adapted to users' motor and vision capabilities. In *UIST '07: Proceedings of the 20th annual ACM symposium on User interface software and technology* (New York, NY, USA, 2007), ACM, pp. 231–240.

[4] GREENSTEIN, J. Pointing devices. *Handbook of human-computer interaction* (1997), 1317–1348.

[5] GUERREIRO, T., NICOLAU, H., JORGE, J., AND GONÇALVES, D. Towards accessible touch interfaces. In *Proceedings of the 12th international ACM SIGACCESS conference on Computers and accessibility* (New York, NY, USA, 2010), ASSETS '10, ACM, pp. 19–26.

[6] KANE, S. K., WOBBROCK, J. O., AND SMITH, I. E. Getting off the treadmill: evaluating walking user interfaces for mobile devices in public spaces. In *MobileHCI '08: Proceedings of the 10th international conference on Human computer interaction with mobile devices and services* (New York, NY, USA, 2008), ACM, pp. 109–118.

[7] LEE, S., AND ZHAI, S. The performance of touch screen soft buttons. In *CHI '09: Proceedings of the 27th international conference on Human factors in computing systems* (New York, NY, USA, 2009), ACM, pp. 309–318.

[8] LEWIS, J. Literature review of touch-screen research from 1980 to 1992. *Design* (1993).

[9] LIN, M., GOLDMAN, R., PRICE, K., SEARS, A., AND JACKO, J. How do people tap when walking? An empirical investigation of nomadic data entry. *International Journal of Human-Computer Studies 65*, 9 (2007), 759–769.

[10] MIZOBUCHI, S., CHIGNELL, M., AND NEWTON, D. Mobile text entry: relationship between walking speed and text input task difficulty. In *Proceedings of the 7th international conference on Human computer interaction with mobile devices & services* (2005), ACM, p. 128.

[11] NICOLAU, H., AND JORGE, J. Touch typing using thumbs: understanding the effect of mobility and hand posture. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems* (New York, NY, USA, 2012), CHI '12, ACM, pp. 2683–2686.

[12] PARHI, P., KARLSON, A. K., AND 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* (New York, NY, USA, 2006), MobileHCI '06, ACM, pp. 203–210.

[13] PARK, Y., HAN, S., PARK, J., AND CHO, Y. Touch key design for target selection on a mobile phone. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services* (2008), ACM, pp. 423–426.

[14] PERRY, K., AND HOURCADE, J. Evaluating one handed thumb tapping on mobile touchscreen devices. In *Proceedings of graphics interface 2008* (2008), Canadian Information Processing Society, pp. 57–64.

[15] SEARS, A., AND YOUNG, M. Physical disabilities and computing technology: An analysis of impairments. *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications. Lawrence Erlbaum, New Jersey, USA* (2003), 482–503.

[16] SOUKOREFF, R., AND MACKENZIE, I. Towards a standard for pointing device evaluation, perspectives on 27 years of fitts' law research in hci. *International Journal of Human-Computer Studies 61*, 6 (2004), 751–789.

[17] TREWIN, S. Automating accessibility: the dynamic keyboard. *ACM SIGACCESS Accessibility and Computing*, 77-78 (2003), 71–78.

[18] WOBBROCK, J., KANE, S., GAJOS, K., HARADA, S., AND FROEHLICH, J. Ability-based design: Concept, principles and examples. *ACM Transactions on Accessible Computing (TACCESS) 3*, 3 (2011), 9.

[19] WOBBROCK, J., MYERS, B., AND KEMBEL, J. EdgeWrite: a stylus-based text entry method designed for high accuracy and stability of motion. In *Proceedings of the 16th annual ACM symposium on User interface software and technology* (2003), ACM, p. 70.

[20] WOBBROCK, J. O., AND GAJOS, K. Z. Goal crossing with mice and trackballs for people with motor impairments: Performance, submovements, and design directions. *ACM Trans. Access. Comput. 1* (May 2008), 4:1–4:37.