Effects of Aging on Small Target Selection with Touch Input

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Age-related declines in physical and cognitive function can result in target selection difficulties that hinder device operation. Previous studies have detailed the different types of target selection errors encountered, as well as how they vary with age and with input device for mouse and pen interaction. We extend this work to describe the types of age-related selection errors encountered with small touch-screen devices. Consistent with prior results, we found that older adults had longer target selection times, generated higher error rates, and encountered a broader range of selection difficulties (e.g., miss errors, and slip errors) relative to a younger comparison group. However, in contrast to the patterns previously found with pen interaction, we found that miss error (i.e., both landing and lifting outside the target bounds) was a more common source of errors for older adults than slip error (i.e., landing on the target but slipping outside the target bounds before lifting). Moreover, aging influenced both miss and slip errors in our study of touch interaction, whereas for pen interaction, age has only been found to influence slip errors. These differences highlight the need to consider pen and touch interaction separately despite both being forms of direct input. Based on our findings, we discuss possible approaches for improving the accessibility of touch interaction for older adults.[1]

CCS Concepts: • **Human-centered computing** → Touch screens; • **Human-centered computing** → Pointing; • **Human-centered computing** → Empirical studies in accessibility

KEYWORDS

Older adults; target selection difficulties; finger touch input; touch-screen technologies; accessibility; mobile devices.

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1 INTRODUCTION

Adults aged 65 and older are more interested today in using technology than their counterparts from even a few years ago. A survey of U.S. older adults conducted in 2017 by the Pew Research Centre found that 42% of adults, aged 65 and older, reported owning a smartphone, and 32%, a tablet, up from just 18% each in 2013 [Pew 2017]. Respondents were also actively engaged with their devices, with roughly three-quarters reporting daily internet use. However, despite this

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growing adoption, physical and cognitive declines continue to pose barriers to the usage of such technologies. Twenty-eight percent of older adult respondents in the Pew study reported having a health problem, disability, or handicap. Those who reported a disability, were less likely to report using the internet or owning a smart touchscreen device than those who did not [Pew 2017].

Previous work on the effects of aging on interaction have shown that older adults typically demonstrate significantly higher error rates and longer task completion times relative to younger adults when selecting targets (e.g., buttons or links), and that these effects hold for both direct and indirect input devices [Keates and Trewin 2005; Moffatt and McGrenere 2007; Motti, Vigouroux and Gorce 2013; Smith, Sharit and Czaja 1999]. In-depth analyses of target selection errors for mouse [Keates and Trewin 2005] and pen [Moffatt and McGrenere 2007] interaction have documented two main categories of selection errors: (1) missing, which is where the selection point (e.g., the mouse cursor or pen tip) remains fully outside the target bounds during the selection (e.g., the mouse click or pen tap), and (2) slipping, which is where the selection point is initially activated over the target, but slips off before release (e.g., of the mouse button or by lifting the pen).[2] For mouse and pen interaction, both slips and misses were observed, but their relative proportions differed, with misses forming the dominant selection error type for the mouse [Keates and Trewin 2005], and slips for the pen [Moffatt and McGrenere 2007]. This difference suggests that input device may influence the kinds of target selection errors encountered by older adults. As design implications for accessible interfaces may also vary according to the kinds of target selection errors encountered [Moffatt and McGrenere 2010; Trewin, Keates and Moffatt 2006], it is, therefore, important to understand the age-related selection errors specific to touch[3] interaction. However, to the best of our knowledge, no such study has been conducted to date.

This paper addresses this gap in the literature by extending the aforementioned mouse and pen studies to touch input. To gain an in-depth understanding of the touch selection behavior of older adults, we measured movement times, error rates, and the types of selection errors encountered by older and younger adults during a two-dimensional target selection task while varying target size, distance, and location. Younger adults were included as a comparison group to examine the influence of aging on performance. Considering the aforementioned prevalence of smartphone adoption, we focused specifically on target selection on small screen (around 150 mm diagonally) devices, where the targets on the screen are generally very small (the smallest selectable items are about 5 mm). Moreover, the accessibility of small devices may be especially limited, as some studies have suggested that selection difficulties impede use even for younger individuals without any disabilities [Bi, Li and Zhai 2013; Holz and Baudisch 2010; Vogel and Baudisch 2007].

Consistent with previous studies [Hourcade and Berkel 2008; Keates and Trewin 2005; Moffatt and McGrenere 2007; Smith et al. 1999], we found that, relative to younger adults, older adults required more selection time, encountered higher error rates accompanied with a broader range of selection errors, and demonstrated higher endpoint selection variability. However, in terms of the types of selection errors encountered, notable differences emerged. In contrast to the findings of Moffatt and McGrenere [2007] for pen input, we found that for touch input, miss errors were more prevalent. Furthermore, we found that both slip and miss errors increased with age for touch input, whereas in Moffatt and McGrenere [2007], this relationship was only found for slip errors. These differences are notable given that both touch and pen input are

[2] It is worth noting that target selection generally happens when a user releases the mouse button or lifts up the pen, and not when the mouse button is clicked or the pen touches down on the screen.

[3] Here, we use the term touch interaction to specifically refer to touch interaction using the tip of the finger and pen interaction where an intermediary device such as a pen or stylus is used.

direct forms of interaction and suggest that input method is an important factor influencing age-related target selection difficulty in nuanced ways that go beyond simple categorical groupings such as direct versus indirect input. They also highlight a potential tradeoff between pen and touch: while one explanation for the lower miss errors with pen input is that it offers a more precise selection point, touch input may result in fewer slip errors due to the increased friction provided by the finger.

The contributions of this research are two-fold. First, we extend past research on selection difficulties with a detailed account of the kinds of errors older adults encounter with small touch-based interfaces. Second, our results, and in particular the ways in which they differ from past findings on mouse- and pen-based interaction, motivate the need for additional research to (1) establish specific design recommendations for touch-based interaction that account for the capabilities of older individuals and (2) develop new interaction techniques to address the selection difficulties we report here. In Section 5, we outline a few potential directions such research might take.

2 LITERATURE REVIEW

In this section, we first discuss the age-specific target selection difficulties encountered by older adults with indirect and direct input devices. Then, we discuss the range of age-related selection errors that are predominant with mouse and pen input.

2.1 Effect of Aging on Target Selection

Aging significantly affects motor, cognitive, and sensory capabilities relevant to interaction with computers and handheld devices. Motor changes include reduced range of wrist-motion [Chaparro et al. 2000], reduced muscle mass [Ketcham and Stelmach 2004], and an increased noise-to-force ratio [Walker, Philbin and Fisk 1997; Welford 1981] that may lead to loss of fine motor control. In addition, age-related cognitive declines can result in slower information processing [Bashore, Osman and Heffley 1989; Salthouse 1988; Welford 1988] and slower reaction time [Ketcham and Stelmach 2004; Walker et al. 1997]. Aging can also cause sensory declines that may hinder efficient hand-eye coordination and visual feedback processing [Schaie 2004; Schieber 2003].

Previous studies have well documented the interaction difficulties encountered by older adults with indirect input devices, especially for the mouse. Research has shown that older adults have difficulty applying the correct amount of force on the mouse, leading to increased selection errors [Keates and Trewin 2005; Ketcham and Stelmach 2004; Walker et al. 1997; Welford 1981]. Error rates disproportionately increase as target widths decrease for older adults [Keates and Trewin 2005]. Loss of motor functionality has also been shown to hinder the ability to control the mouse, which can result in losing track of the cursor, difficulty positioning the cursor within the target bounds—often resulting in lower precision and higher endpoint selection variability [Chaparro, Bohan, Fernandez, Choi and Kattel 1999; Keates and Trewin 2005; Ketcham and Stelmach 2004; Paradies, Trewin and Keates 2005; Riviere and Thakor 1996; Smith et al. 1999; Walker et al. 1997]. Older adults have also been found to encounter difficulties with more complex interaction tasks such as double clicking [Smith et al. 1999], clicking and dragging [Chaparro et al. 1999], and steering [Findlater, Froehlich, Fattal, Wobbrock and Dastyar 2013]. The combination of slower reaction time and loss of fine motor control can increase target selection time [Keates and Trewin 2005; Smith et al. 1999; Walker et al. 1997; Welford 1988]. Task completion time disproportionately increases with age as the complexity of the task increases [Walker et al. 1997]. The tendency among older adults to adopt a more conservative and error-averse target selection strategy results in more time spent on target verification prior to selection [Keates and Trewin 2005; Salthouse 1988; Smith et al. 1999;

Walker et al. 1997; Welford et al. 1969]. Emphasis on accuracy over speed also influences the movement profiles of older adults, which have lower peak velocities [Keates and Trewin 2005; Ketcham and Stelmach 2004], longer deceleration phases [Ketcham and Stelmach 2004], and consist of smaller sub-movements punctuated with small verification pauses in place of the primary ballistic movement typical of younger adults [Keates and Trewin 2005; Keates, Trewin and Paradise 2005; Ketcham and Stelmach 2004; Smith et al. 1999]. Older adults also tend to initiate more corrective sub-movements than younger adults following a selection error [Keates and Trewin 2005; Walker et al. 1997]. Use of indirect input devices has also been found to cause fatigue and pain in the shoulder, neck, and wrist [Keates and Trewin 2005; Paradise et al. 2005].

Despite not being as well-explored as indirect input devices, studies on age-related interaction difficulties with direct input devices (both pen and touch) have reached similar conclusions, with older adults demonstrating slower selection times [Findlater et al. 2013; Gao and Sun 2015; Hourcade and Berkel 2008; Ketcham, Seidler, Seidler and Stelmach 2002; Moffatt and McGrenere 2007; Rogers, Fisk, McLaughlin and Pak 2005] and higher error rates [Gao and Sun 2015; Hourcade and Berkel 2008; Moffatt and McGrenere 2007]. Older adults have also been found to be more likely to encounter difficulties with complex tasks such as dragging [Findlater et al. 2013], steering [Findlater et al. 2013], and sliding [Rogers et al. 2005] with touch input. Target width has been shown to significantly influence error rates for pen input with aging–leading to disproportionately higher error rates with smaller targets [Hourcade and Berkel 2008; Moffatt and McGrenere 2007]. Movement profiles of older adults with pen input are also consistent with that of mouse input having a combination of smaller sub-movements rather than a primary ballistic movement [Ketcham et al. 2002; Yan 2000]. Direct input devices are thought to have better support for hand-eye coordination than indirect input devices, which may explain the findings that direct input can reduce the performance gap (in terms of speed and accuracy) between older and younger adults [Atsuo and Iwase 2002; Charness et al. 2004; Findlater et al. 2013; Murata and Iwase 2005; Rogers et al. 2005; Schneider, Wilkes, Grandt and Schlick 2008; Taveira and Choi 2009].

2.2 Types of Age-related Selection Errors

Both mouse and pen interactions from older adults have shown a wider range of selection errors than younger adults. Keates and Trewin [2005] demonstrated that with a mouse, older adults encounter two main categories of selection errors: (1) Miss errors, where the mouse button is both clicked and released (while aiming for a target) outside the target bounds. (2) Slip errors, where the mouse button is clicked for selection inside the target boundary, but is released outside the target area during a selection. Because successful selection is typically defined by the location of the mouse cursor at the moment of the release of the mouse button, both slips and misses result in errors. Their study showed that older adults encountered higher errors rates than younger adults for both miss and slip errors. However, the proportions of miss errors were significantly higher than the slip errors with older adults. Keates and Trewin [2005] further sub-categorized the miss errors as follows:

Near Miss Errors. Mouse button clicks within 50% of the target radius away from the target boundary.

Not-so-near Miss Errors. Mouse button clicks between 50% and 100% of the target radius away from the target boundary.

Accidental Clicks. Mouse clicks greater than 200% of the target radius away from the target boundary, possibly unintentional click.

Among these sub-categories, the near miss errors are the most common one among older adults with mouse input.

Moffatt and McGrenere [2007] extended Keates and Trewin's work [2005] for pen input with older adults. They defined miss errors as when a pen is both landed and lifted up outside the target boundary, and slip error as when a pen is landed inside the target boundary but is lifted up outside the target area. In contrast to the mouse interaction study [Keates and Trewin 2005], this study concluded that slip errors are more predominant than miss errors with pen interaction. Ninety percent of all selection errors encountered by older adults were either slip errors or near miss errors. Furthermore, with other sub-categories of miss errors, each contributed no more than 5% of selection errors. Slip errors were also found to increase with age, while miss errors remained similar across different age groups. The difference in the dominating error types with mouse and pen input is particularly important because these results indicate that input devices may also influence the type of selection errors. However, because of the absence of any such studies with touch interaction from older adults, it is not clear if the nature of interaction (i.e., direct vs. indirect) is the reason for such differences in the proportion of miss and slip errors, or if it is the input device (regardless direct or indirect) that influences the type of errors.

3 EXPERIMENTAL METHODOLOGY

To gain a deeper understanding of age-related touch selection difficulty, we designed a laboratory experiment using a two-dimensional Fitts' task [Fitts 1954; MacKenzie 1992]. We recorded movement times, error rates, number of corrective attempts, finger pressure, target selection end-point coordinates, and the types of selection errors encountered, respectively. Older adults' performance was compared to a younger adult control group.

3.1 Participants

We recruited 20 older (14 female and 6 male, aged 67–81, mean: 73.3, SD: 4.89) and 16 younger (12 female and 4 male, aged 22–35, mean: 28.9, SD: 3.73) adults, all of whom self-reported as right-handed, with no motor impairments to their right hands, and as having normal or corrected-to-normal vision.

All participants reported holding at least a high-school diploma (older adults) or a bachelor's degree (younger adults). Older adults reported using touch-screen devices for an average of 3.78 hours per week (SD: 4.66) and desk or laptop computers for an average of 17 hours per week (SD: 16.32). Younger adults reported spending an average of 19.46 hours per week on touch-screen devices (SD: 11.35) and 46.66 hours per week on desk or laptop computers (SD: 12.29). Four older adults reported no prior touch-screen experience, but basic to expert knowledge of desk or laptop computers. The remaining older adults rated their knowledge of touch-screen devices as basic to moderate and all younger adults rated their knowledge as moderate to expert.

We applied standardized tests to assess participants' sensory-perceptual and motor skills. Across the tests, we did not find any in-group differences, nor any outliers. The Digit Symbol Substitute Test (DSST) [Strauss, Sherman and Spreen 2006] measures perceptual speed. As expected, older adult participants had lower scores, indicating lower perceptual speed: out of total 84 points, mean DSST score for older and younger adults were 54.2 (SD: 14.85) and 72.5 (SD: 16.30), respectively. The Letter Set Test (LST) [Strauss, Sherman and Spreen 2006] was used to confirm fluid intelligence. Although the older group did score lower on this test than the younger group (as expected) the difference was not as large as we anticipated with both age groups performing poorly (older: mean = 12.71, SD = 6.18; younger: mean = 17.31, SD = 4.67, out of 30). Our observations suggest that the younger group may not have been properly motivated: whereas the older group struggled to solve the problems (and none finished on time), the younger participants seemed to rush through them, focusing more on speed than accuracy. The

LST enforces negative marking for wrong answers, which penalized the behavior of the younger group. We additionally confirmed the ability to follow English instructions with the first 15 words of North American Adult Reading Test (NAART) [Strauss, Sherman and Spreen 2006]. All participants demonstrated high NAART score (older: mean = 13.9, SD = 1.29; younger: mean = 11.69, SD = 3.36, out of 15), indicating that both age groups had sufficient familiarity with the English language to correctly follow the experiment's instructions.

3.2 Apparatus

We used a Motorola Nexus 6 smartphone running the Android Lollipop 5.0.1 operating system for this study. The screen resolution of the device was 1440 × 2560 pixels and the screen size was 74.19 × 131.89 mm, resulting in 1 mm = 19.41 pixels (PPI = 493). The experiment was carried out in portrait orientation of the device, with the auto-rotate to landscape feature disabled. The experimental software was developed with Android Studio plugins for the Eclipse development environment.

3.3 Task

Participants completed a two dimensional Fitts' task (see Fig. 1), following a similar procedure to prior work [Ren and Moriya 2000]. At the beginning of each trial, a 7 mm wide circular start button appeared at the center of the screen. Upon successful selection of the start button, a red circular target appeared on the screen at one of the two predefined target amplitudes (20 mm and 30 mm), three predefined target widths (4.88 mm, 7.22 mm, and 9.22 mm), and eight predefined movement angles (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) from the center of the start button. Target widths were chosen based on the widths used in Bi et al. [2013]; however, we eliminated the smallest size (2.88 mm) used in that study. We considered it to be too small for touch-screen interaction (even for the able-bodied younger adults) and added a larger 9.22 mm width, which is roughly the size of an icon of an Android phone. The combination of target amplitude (distance), width (size), and angular direction was determined randomly for each trial such that each unique combination appeared exactly once per block of 48 trials.

Participants were instructed to hold the device with their left hand and select targets with their right index finger as quickly and as accurately as possible. If they missed a target, they continued with the trial until the target was selected successfully. We asked for the corrective attempts until successfully acquiring the target for ecological validity and to enable us to estimate the cost of errors in terms of time and effort for recovery. Knowing the error recovery cost is important in understanding target selection, because a high error recovery cost can lead to frustration and further poor selection performance.

Before participants started the experiment, they were asked to complete a practice block consisting of six trials. Participants moved to the experiment task once they were comfortable with the practice trials. None of them required more than one block of practice trials (i.e., six trials). The two-dimensional selection task was carried out in four blocks, each containing 48 trials. Short breaks were given between the blocks as needed. All breaks were one minute or less. Participants were allowed to ask questions prior to and between trials. A timer was displayed at the top of the screen, and a scoreboard was displayed at the bottom of the screen, during each trial, to give feedback to the participants about their movement time and accuracy.

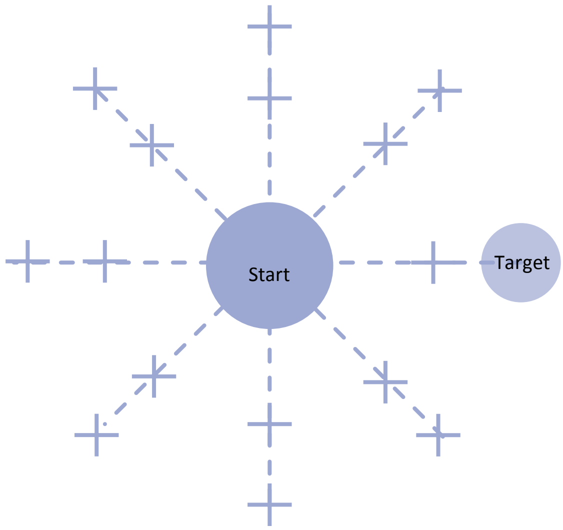


Fig. 1. A two dimensional Fitts' task having the *Start* button at the center of the screen and targets located at the given amplitudes (20 mm and 30 mm) and directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°). The crosshairs indicate all sixteen possible locations (8 angles × 2 amplitudes) of the center of the targets. Target widths were chosen from three predefined sizes (4.88 mm, 7.22 mm and 9.22 mm). The circle labeled as *Target* shows a sample target at the 0° and 30 mm amplitude.

3.4 Measures

We recorded the following measures from all participants across both age groups:

Movement Time (ms). Movement time, measured in milliseconds (ms), was defined as the elapsed time from when the participant's finger lifted up off of the start button to the first lift up event following selection of the start button, regardless of whether or not this touch event successfully selected the target.

Error Rate (%). Errors were defined as trials in which more than one attempt was needed to successfully select the target. Error rate was thus the percentage of erroneous trials relative to all trials under consideration (e.g., all trials for an individual participant or at a particular target width or amplitude).

Finger Pressure. The Android pressure sensing API reports pressure on a scale from 0 to 1, where 0 is no pressure and 1 is the maximum pressure the device can measure. The Android device we used in this experiment, measures finger pressure from the finger surface that is in contact with the touchscreen, where more finger surface in contact means more pressure is applied on the screen. This measure is useful for comparing relative pressure differences as we report here, but cannot be converted into a real-world measure of force[4].

Selection Error Type (slips, misses). Based on the works of Keates and Trewin [2005] and Moffatt and McGrenere [2007] for mouse and pen interaction, respectively, we focused primarily on two sources of selection errors: slips, and misses. Considering the higher proportion of slips relative to misses in older adults with pen interaction Moffatt and

[4] Documentation on the Android pressure-sensing API can be found in: https://developer.android.com/reference/android/view/MotionEvent

McGrenere [2007], we further subcategorized slip errors based on the distance slipped beyond the target bounds.

Table 1 defines each of the error categories used in our analyses, comparing them to those reported in previous work.

Table 1. Comparison of Error Categories

Definition	Keates & Trewin [2005]	Moffatt & McGrenere [2007]	Current Study
Input (i.e., mouse, pen, or finger) lands on the target, but…			
Lifts at a distance less than 50% of the target radius away from the target boundary	Slip Error	Slip Error	Narrow Slip Error
Lifts between 50% and 100% of the target radius away from the target boundary			Moderate Slip Error
Lifts between 100% and 200% of the target radius away from the target boundary			Large Slip Error
Lifts at a distance greater than 200% of the target radius away from the target boundary			Very Large Slip Error
Input lands outside the target bounds, but…			
Lifts at a distance less than 50% of the target radius away from the target boundary	Near Miss Error	Near Miss Error	Near Miss Error
Lifts between 50% and 100% of the target radius away from the target boundary	Not So Near Miss Error	Not So Near Miss Error	Not So Near Miss Error
Lifts between 100% and 200% of the target radius away from the target boundary	[Not Reported]	Other Error	Other Error
Lifts more than 200% of the target radius away from the target boundary	Accidental Click	Accidental Tap	Accidental Tap

3.5 Design

We used a 2 (age groups) × 4 (blocks) × 3 (target widths) × 2 (movement amplitudes) × 8 (movement angles) mixed design with all factors except for age as within-subjects factors. Each block consisted of 48 trials containing each unique combination of width × amplitude × angle exactly once, presented in a random order. Across the entire experiment, each participant completed 192 trials, resulting in a total of 3840 trials from 20 older participants and 3072 trials from 16 younger participants. We excluded trials with a movement time of more than three standard deviations away from the age group's mean movement time, as prior work [Findlater and McGrenere 2010] has suggested. We thus removed 44 trials from the older adult group and

31 trials from the younger adult group, resulting in 3796 and 3041 trials for each group, respectively.

3.6 Procedure

We designed the experiment to fit within a single session of no more than 90 minutes for older participants and 60 minutes for younger participants based on pilot testing. All participants finished within these target times. Older and younger participants received an honorarium of $15 and $10, respectively.

Each study session started with a brief introduction to the study along with a review of the consent process. Participants then completed a background questionnaire covering demographic data and computer experience. Next, participants completed a finger calibration task as outlined in Bi et al. [2013][5], followed by the Digit Symbol Substitute Test (DSST). They then completed the two-dimensional Fitts' task, while the researcher conducting the session took observational notes on their target selection behavior. After the Fitts' task, participants completed a questionnaire about their overall experience. They were then asked to read the first 15 words from the North American Adult Reading Test (NAART), as a rough indicator of their familiarity with the English language. They finished the session with the Letter Set Test (LST), followed by a short debrief and wrap-up session. All procedures were reviewed and approved by our institution's Research Ethics Board prior to commencement of the study.

3.7 Analysis

We present the study results in terms of descriptive and inferential statistics. We applied repeated measure ANOVAs (as defined in Section 3.5) to evaluate the main and interaction effects of our primary performance measures (i.e., movement time, error rates, finger pressure, and types of selection errors). All pairwise comparisons in the repeated measure ANOVAs were corrected with a Bonferroni correction. We also conducted Mauchly's test to identify sphericity violations, and corrected such violations with Greenhouse-Geisser corrections; where degrees of freedom (*df*) are non-integer, a correction has been applied. Along with statistical significance, we report partial eta-squared (η_p^2), a measure of effect size.

4 Results

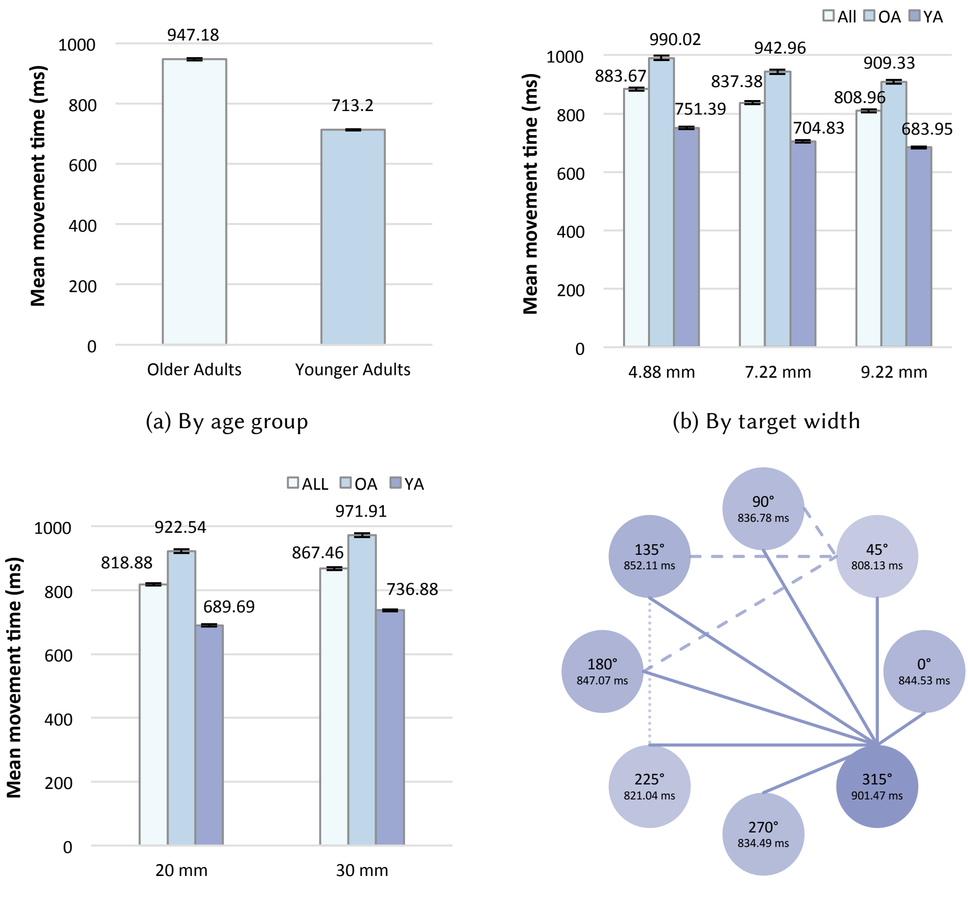
We first examine the overall performance effects of movement time and error rate, comparing our results to prior findings on aging and touch interaction. We then dedicate the bulk of our attention to an analysis of age-related touch selection errors. Throughout the presentation of the results, we focus on our primary factors of interest and other significant main and interaction effects. Tables providing the full statistical results of all analyses are included in Appendix A. In presenting our results, we focus on comparisons of group means. We do not present individual participant data as no outliers were found in the data; i.e., no individual participant data were three standard deviations away from the group mean for any of the performance measures reported. A sub-group analysis comparing the 65–74 year-olds (n = 10) to those 75 and over (n = 10) did not reveal any differences.

[5] The finger calibration task was included in the hopes it would provide additional insight; however, it did not and thus, we do not report on them further.

4.1 Overall Performance Effects

4.1.1 Movement Time

Consistent with previous findings [Moffatt and McGrenere 2007], older adults were slower than younger adults and more variable in their performance (see Fig. 2(a)). Main effects were significant for all factors (age: $F_{1,\,33} = 19.01$, $p < .0005$, $\eta_p^2 = .37$; width: $F_{1.17,\,38.59} = 37.46$, $p < .00001$, $\eta_p^2 = .53$; amplitude: $F_{1,\,33} = 119.40$, $p < .00001$, $\eta_p^2 = .78$; and angle: $F_{4.73,\,156.07} = 17.13$, $p < .00001$, $\eta_p^2 = .34$). Pairwise comparisons confirmed that consistent with Fitts' law [Fitts 1954], movement time increased as width decreased ($p < .00001$ for all pairs; Fig. 2(b)), and as amplitude increased ($p < .00001$; Fig. 2(c)). Targets located in the lower-right corner (315°) were significantly slower to select than those in all other locations (all $p < .00001$) and targets in the upper-left corner (135°) were significantly slower to select than those in the lower-left corner (225°, $p < .05$). In addition, targets in the upper-right corner (45°) were the fastest to select, and



(a) By age group

(b) By target width

(c) By movement amplitude

(d) By movement angle

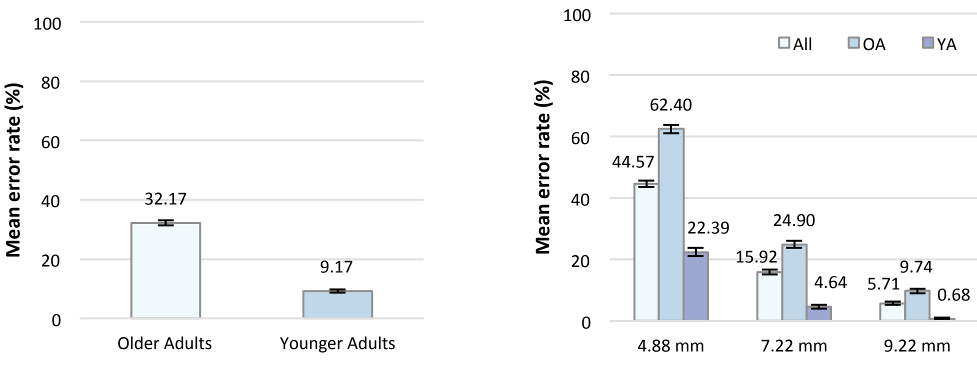
Fig. 2. Mean movement times per trial by (a) age group, (b) target width, (c) movement amplitude, and (d) movement angle (N = 36; OA = older adults, n = 20; YA = younger adults, n = 16). For graphs (a)–(c), error bars show the standard errors. For movement angle (d), darker shades indicate longer movement times and connecting lines indicate significant pairwise differences. The pairwise differences with targets located at 315°, 45° and 135° angles are represented with solid, dashed and dotted lines, respectively.

significantly faster than those in the upper-left quadrant (90°: $p < .5$, 135°: $p < .001$, 180°: $p < .0005$), as shown in Fig. 2(d). These findings are consistent with prior work on angular movement and pen input, and reflect the effects of human physiology for right-handed individuals (radial movements to the upper-right are fastest) as well as right hand occlusion (targets to the lower-right are most likely to be occluded) [Hancock and Booth 2004].

There was a significant interaction between width × amplitude ($F_{2, 66} = 3.14$, $p = .05$, $\eta_p^2 = .09$). Pairwise comparison confirmed significant differences in movement time for all width-amplitude pairs (all $p < .00001$), but the impact of amplitude on movement time was somewhat less pronounced at larger target widths. No other interaction effects were significant, and in particular, there were no interaction effects with age, suggesting that older adults were not disproportionately slowed by decreasing target size, increasing movement amplitude, or by the particular angle of approach.

4.1.2 Error Rates

In contrast to prior work on age-related differences in touch interaction [Findlater et al. 2013], we observed significantly higher error rates for older adults relative to younger adults ($F_{1, 33} = 42.23$, $p < .0001, \eta_p^2 = .56$, see Fig. 3(a)). This difference is likely due to the different target widths used in the two studies: our largest target width (9.22 mm) was the smallest target width used by Findlater et al. [2013]. Indeed, target width had a significant effect on error rate ($F_{1.35, 44.68} = 153.60$, $p < .0001, \eta_p^2 = .82$, see Fig. 3(b)), and there was also a significant age × width interaction ($F_{1.35, 44.68} = 27.68$, $p < .0001, \eta_p^2 = .46$, see Fig. 4). Pairwise comparisons confirmed that error rates significantly increased as target width decreased (all $p < .0001$). While this pattern was true for both older and younger adults, errors rates disproportionately increased for older adults at smaller target sizes, as shown in Fig. 4 and reflected by the significant age × width interaction. Pairwise comparisons on this interaction effect confirmed that older adults had significantly higher error rates than younger adults for all target widths (for 4.88 mm: $p < .0001$; for 7.22 mm: $p < .00005$; for 9.22 mm: $p < .0005$). No other significant main or interaction effects were observed.



(a) By age group

(b) By target width

Fig. 3. Mean error rate per trial by (a) age group, and (b) target width, across all participants ($N = 36$) and by age group (older adults = OA, $n = 20$; younger adults = YA, $n = 16$). Error bars show the standard errors.

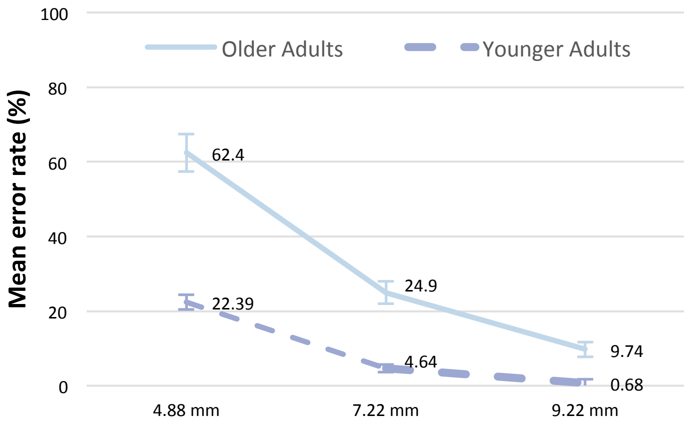
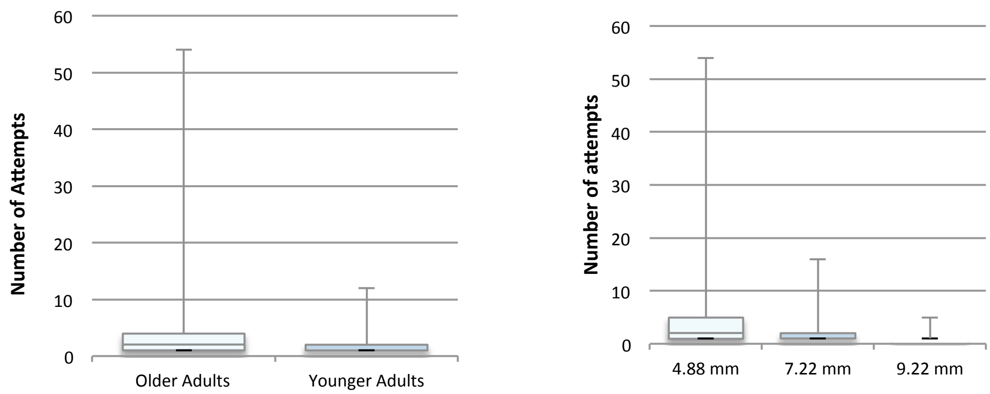


Fig. 4. Mean error rate at each target width, for older adults (*n* = 20), and younger adults (*n* = 16). While older adults made significantly more errors than younger adults for all target widths, the error rate disproportionately increased for older adults as target sized decreased. Error bars show standard errors.

Corrective Attempts

To better understand the impact of age-related differences in error rates, we additionally considered the number of corrective attempts required to successfully select a target. Recall, that errors were defined as trials requiring more than one selection attempts; thus, an error free trial requires exactly one attempt, while an error trial requires two or more (i.e., one initial attempt and one or more corrective attempts). As shown in Fig. 5(a), older adults required more corrective attempts (min: 1, max: 54, median: 2) than younger adults (min: 1, max: 12, median: 1). For both age groups, the majority of errors were addressed with a single corrective attempt (older adults: 41% of 1221 error trials, younger adults: 67% of 279 error trials). However, while younger adults corrected all errors within 12 corrective attempts, older adults required more than 12 corrective attempts in 89 trials, which is more than 7% of the error trials from that age group. All participants (both younger and older) struggled to correct selection errors for the smallest targets, compared to the medium and largest targets (Fig. 5(b)). While, all errors with the largest targets were corrected with at most 5 corrective attempts (for all participants), 8 trials for the medium targets, and 233 trials for the smallest targets, needed more than 5 corrective attempts. Older adults' substantial difficulties with recovering from errors with both medium (min: 1, max: 16, median: 1) and smallest (min: 1, max: 54, median: 3) targets were reflected by the higher number of corrective attempts with the medium and the smallest targets (Fig. 6). In the same figure, we also see that younger adults had a higher number of corrective attempts with the small targets (min: 1, max: 12, median: 1).



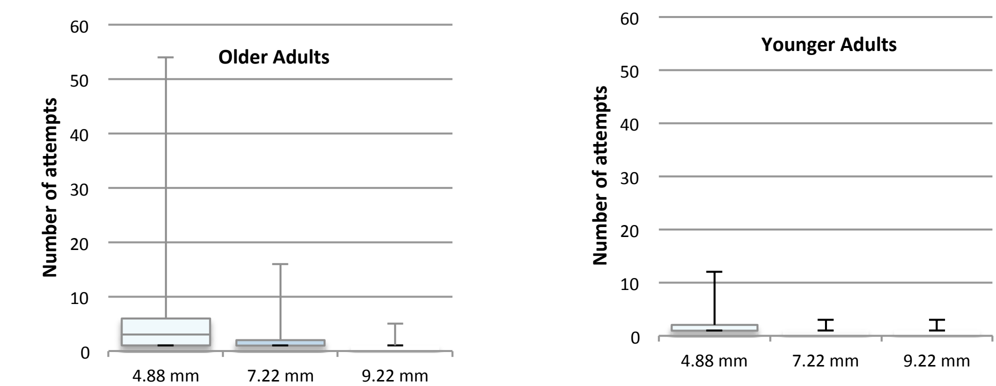
	Older Adults	Younger Adults
Max	54	12
Median	2	1
Min	1	1

(a) By age group

	4.88 mm	7.22 mm	9.22 mm
Max	54	16	5
Median	2	1	1
Min	1	1	1

(b) By target width

Fig. 5. Boxplots showing the number of corrective attempts to recover from an error for all participants (*N* = 36) by (a) age groups, and (b) target widths.



	4.88 mm	7.22 mm	9.22 mm
Max	54	16	3
Median	3	1	1
Min	1	1	1

	4.88 mm	7.22 mm	9.22 mm
Max	12	3	3
Median	1	1	1
Min	1	1	1

Fig. 6. Boxplots showing the number of corrective attempts required for older adults (*n* = 20, left) and younger adults (*n* = 16, right) across all target widths (4.88 mm, 7.22 mm, 9.22 mm) in the trials that generated errors. The higher number of corrective attempts for the older adults, relative to younger adults, for the small and medium targets indicate substantial difficulty recovering from errors on these targets.

Selection Endpoint Variability

As prior work has shown that older adults demonstrate higher selection endpoint variability relative to younger adults for mouse [Keates and Trewin 2005] and pen interaction [Moffatt and McGrenere 2007], we additionally examined the end point variability of the both age groups, by plotting the finger lift-up coordinates from the first selection attempt of each trial. As shown in Fig. 7, which plots the coordinates relative to the center of the target (regardless of where the target is actually located on the screen), the younger adults' selections were tightly clustered around the center of the target (mean distance from the target center = 1.92 mm, SD = 1.33), while the selections of the older adults were noticeably spread out, especially towards the lower-right of the targets (mean distance from the target center = 3.36 mm, SD = 4.40). To better understand the influence of target location, we also plotted this same endpoint data relative to the center of the start button, as shown in Fig. 8. Here we can see 16 distinct clusters, one for each combination of angle and amplitude. The higher spread of pixels in the lower-right quadrant of the left graph suggests a tendency for older adults to overshoot targets located to the lower right of the starting position, possibly in response to hand occlusion.

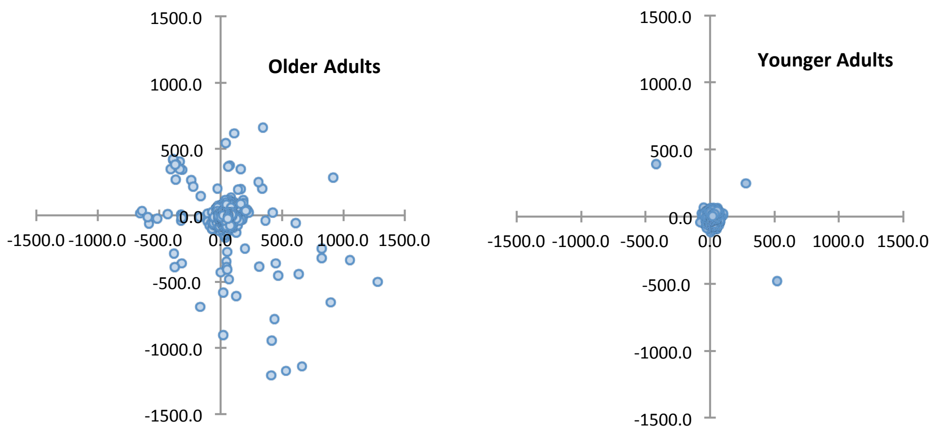


Fig. 7. Selection endpoints relative to the center of the target, for older (left) and younger (right) adults measured in pixels (1 mm = 19.41 pixels). The larger spread of points on the left graph reflects higher endpoint selection variability of older adults relative to younger adults.

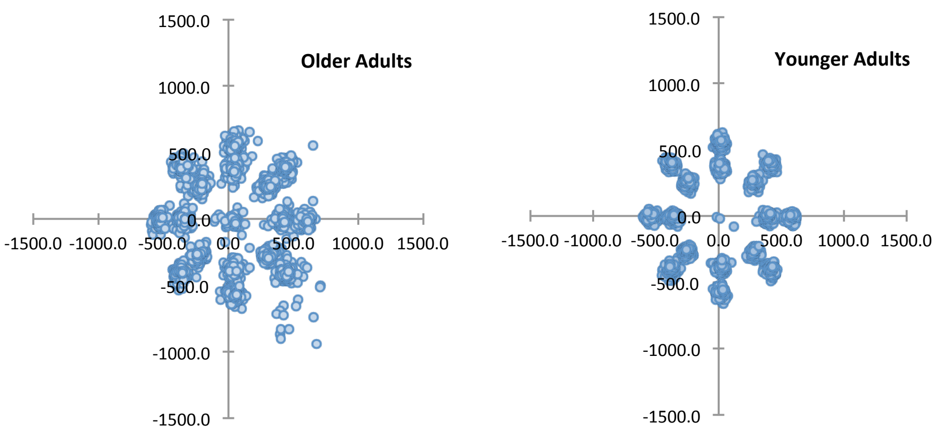


Fig. 8. Selection endpoints relative to the center of the start button, for older (left) and younger (right) adults measured in pixels (1 mm = 19.41 pixels). In addition to the higher variability for older adults that was observed in Fig. 7, this representation also reveals that variability was particularly high for older adults when selecting targets to the lower right of the start button.

4.1.3 Finger Pressure

Consistent with prior findings for pen interaction [Moffatt and McGrenere 2010], older adults applied more pressure during target selections than younger adults (Fig. 9(a). As mentioned in Section 3.4, more finger pressure means more finger surface is in contact with the touchscreen. Older adults resulting in applying more pressure implies that they had more finger surface area in contact with the touchscreen, compared to younger adults–that also aligns with their higher selection endpoint variability as reported in (Section 4.1.2). The main effects of age, width, and angle on finger pressure were also found to be statistically significant (age: $F_{1, 33} = 8.18$, $p < .01$, $\eta_p^2 = .20$; width: $F_{2, 66} = 28.77$, $p < .00001$, $\eta_p^2 = .47$; and angle: $F_{3.42, 231} = 10.67$, $p < .00001$, $\eta_p^2 = .24$). No main effect of amplitude was observed. We also did not find any interaction effects of age with width, amplitude, or angle. Finger pressure increased as target width increased (Fig. 9(b). Pairwise comparison found significant differences between each pair of target widths (small-medium: $p < .005$, small-large: $p < .00001$, medium-large: $p < .0005$). Participants applied more pressure to select targets located at the upper-left quadrant than on the lower-right

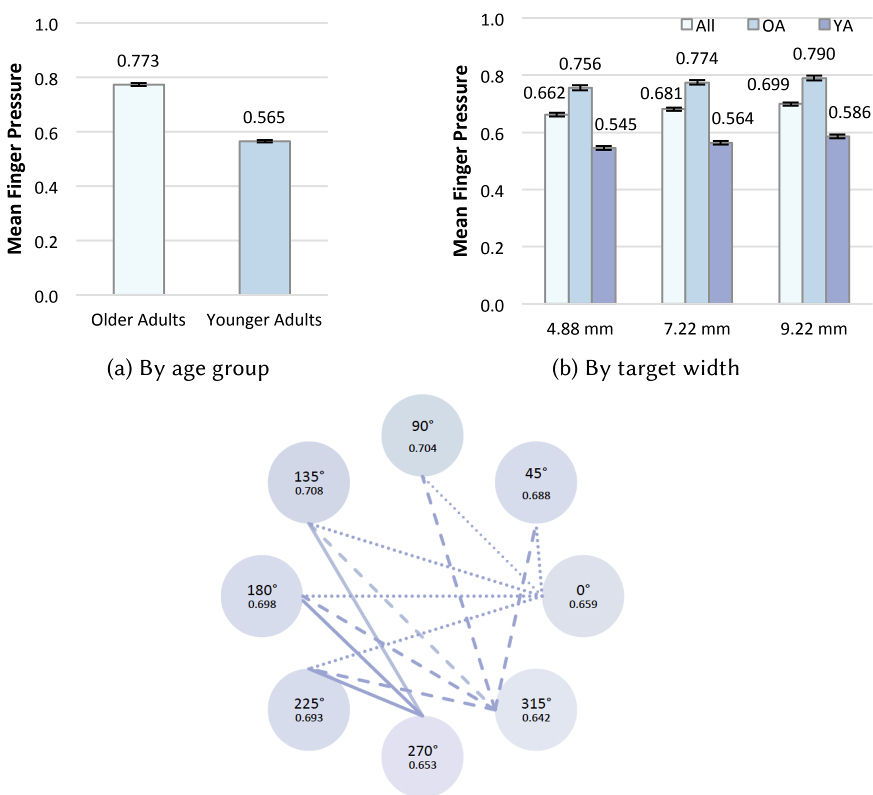


Fig. 9. Mean finger pressure applied per trial by (a) age group, (b) target width, and (c) movement angle, across all participants (N = 36) and for (b) by age (OA = older adults, n = 20; YA = younger adults, n = 16). For graphs (a)–(b), error bars show the standard errors. For movement angle (c), darker shades indicate higher finger pressure applied and connecting lines indicate significant pairwise differences. The pairwise differences with targets located at 0°, 270° and 315° angles are represented with dotted, solid, and dashed lines, respectively.

quadrant (Fig. 9(c)). The lowest mean pressure was applied on the lower-right corner (at 315° angle, mean = 0.642, SD = 0.268) and finger pressure increased gradually counter-clockwise until the target at the upper-left corner (at 135° angle, mean = 0.708, SD = 0.303). Then, finger pressure gradually decreased counter-clockwise until back again to the lower-right corner (315°). As seen in Fig. 9(c), pairwise comparison also found significant differences in applied finger pressure between targets located at the lower-right, and the upper-left quadrants (at 0° angle, 45°: $p < 0.05$, 90°: $p < 0.05$, 135°: $p < 0.0005$, 180°: $p < 0.01$, 225°: $p < 0.005$; at 270° angle, 135°: $p < 0.01$, 180°: $p < 0.01$, 225°: $p < 0.05$; at 315° angle, 45°: $p < 0.05$, 90°: $p < 0.05$, 135°: $p < 0.0001$, 180°: $p < 0.005$, 225°: $p < 0.00005$). Table 2 shows all pairwise significant differences in applied finger pressure across target angles for all participants. Our analysis also found significant interaction effect of amplitude × angle ($F_{4.58,\ 151.06} = 2.48$, $p < .05$, $\eta_p^2 = .07$) on finger pressure. For older adults, we found no correlation between errors and finger pressure (r = 0.021, p = .204), however there was a significant correlation between errors and finger pressure for younger adults (r = 0.140, p < .00001).

Table 2. Pairwise significant differences in applied finger pressure across different target locations for all participants (*N = 36*).

	45°	90°	135°	180°	225°	270°	315°
0°	$p < .05$	$p < .05$	$p < .0005$	$p < .01$	$p < .005$	n. s.	n. s.
45°		n. s.	n. s.	n. s.	n. s.	n. s.	$p < .05$
90°			n. s.	n. s.	n. s.	n. s.	$p < .05$
135°				n. s.	n. s.	$p < .01$	$p < .0001$
180°					n. s.	$p < .01$	$p < .005$
225°						$p < .05$	$p < .00005$
270°							n. s.
315°							

*n. s. = not significant

4.1.4 Subjective Analysis

In our post experiment questionnaire, we asked participants to reflect on their speed, error rate, difficulty level and preference of target width, amplitude and location. Responses generally aligned with the performance results presented in Sections 4.1.1–4.1.3. All older adults reported that the smallest targets were the slowest, most error-prone, and most difficult to select, and thus, were the least preferred. Younger adults also had similar comments about the smallest targets, with 12 out of 16 describing them as most time consuming, error-prone, and difficult, and least preferred. However, there were some differences in the most preferred target size: all older adults (20/20) preferred the largest target size—reporting that it was the fastest, least error-prone, and least difficult to select—while 6/16 younger adults described the largest size as too big and preferred the medium targets.

Both older and younger adults faced difficulty with selecting the targets located at the lower-right and at the left side of the screen. Four older adults reported particular difficulty with the smallest target when it was located at the lower-right corner as the right hand blocks the view of the target; 3 noted difficulty with the horizontal-left and lower-left side positions due to the longer travel distance. Two younger adults reported that the smallest targets at the left side of the screen were more difficult to select: one preferred targets on the vertical (top and bottom of the screen) positions, while the other preferred targets in the horizontal-right position. Some (3/16) younger participants reported that smallest targets located diagonally were the most difficult ones to select.

Finger size, position and pressure also had impact on selection difficulty in both age groups. Some participants from both age groups (older: 5/20, younger: 1/16) commented that their finger was bigger than the smallest targets, making it difficult to see whether they were within the target bounds. One older adult mentioned that placing the finger vertically on the target before selection reduced their error rate and one noticed that putting less pressure on the screen helped reduce selection errors.

4.2 Distribution of Target Selection Errors

We now turn our attention to the different types of selection errors encountered. For both older and younger adults, miss errors dominated over slip errors, with older adults making over six times, and younger adults making over ten times as many miss errors than slip errors, respectively, as shown in Table 3. In Fig. 10, we further provide the distribution of major error types across each target width. The stacked bars show that the general pattern holds across widths: at every width, misses outnumbered slips by at least a factor of four.

Table 3. Total Miss and Slip Errors for Older and Younger Adults

	Total	Miss Errors			Slip Errors		
	Trials (#)	**Total (#)**	**Rate (%)**	***SD***	**Total (#)**	**Rate (%)**	***SD***
Older Adults	3796	1058	27.87%	44.84	163	4.29%	20.27
Younger Adults	3041	255	8.39%	27.72	24	0.79%	8.85

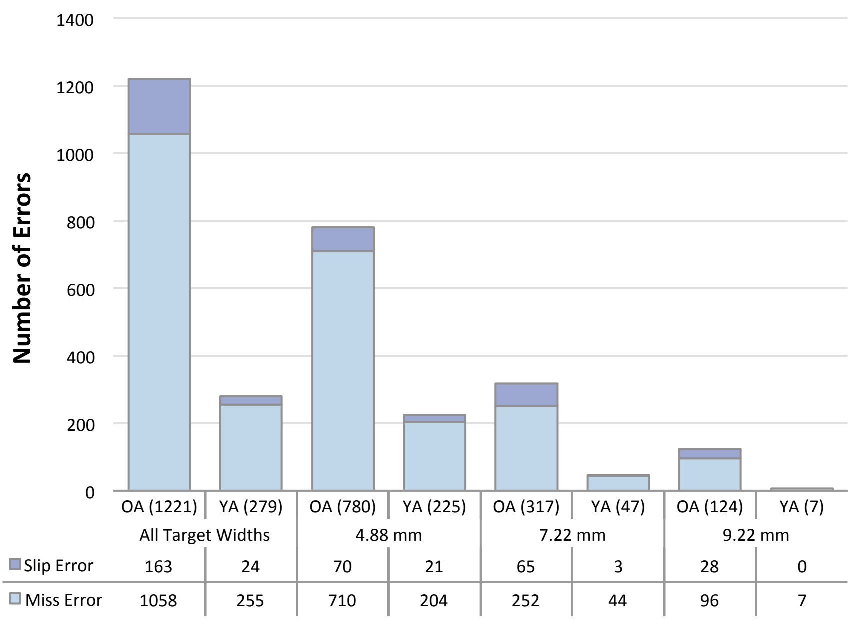


Fig. 10. Distribution of slip and miss errors for all trials, and across each target width for older (n = 20) and younger (n = 16) adults.

4.2.1 Miss Errors

Older adults encountered over three times as many miss errors as younger adults (see Table 3), a difference that was statistically significant ($F_{1, 33}$ = 36.27, $p < .0001$, $\eta_p^2 = .52$). There was also a significant effect of target width on miss errors ($F_{1.27, 41.96}$ = 141.36, $p < .0001$, $\eta_p^2 = .81$) with pairwise comparisons revealing that miss errors increased as width decreased (for all pairs: $p < .00001$). A significant age × width interaction effect ($F_{1.27, 41.96}$ = 27.71, $p < .00001$, $\eta_p^2 = .46$) shows that miss errors disproportionately increased for older adults relative to younger adults as width decreased (see Fig. 11). Pairwise analysis confirmed that for all widths, older adults had significantly higher miss error rates than younger adults (small targets: $p < .00001$, medium targets: $p < .0001$, large targets: $p < .001$). Moreover, older adults had disproportionately higher miss error rates as target width decreased (all pairwise target widths: $p < .0001$). Younger adults had significantly higher miss error rates with the smallest target width ($p < .00005$ for the small-medium, and for the small-large width pairs), but no difference was observed between the medium and largest widths ($p = 0.49$). No other significant main or interaction effects were observed.

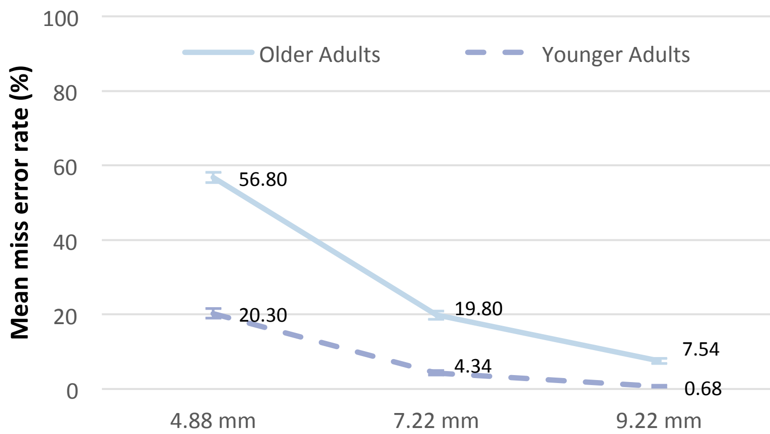
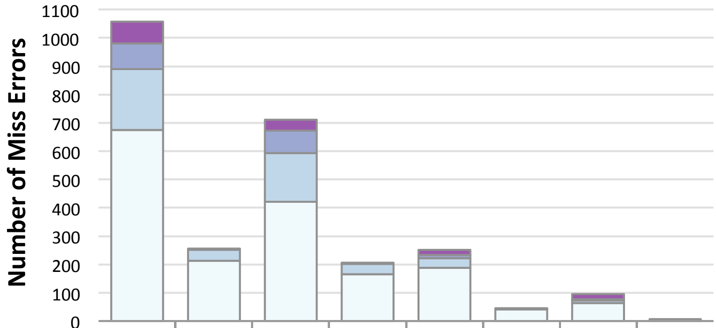


Fig. 11. Mean miss error rates at each target width, for older (n = 20), and younger (n = 16) adults. The steeper slope for older adults (upper line) reflects the significant age × target width interaction and shows that, relative to younger adults, miss errors disproportionately increased for older adults as target sized decreased. Error bars show standard errors.

Similar to prior work [Keates and Trewin 2005; Moffatt and McGrenere 2007] on mouse and pen interaction, the majority of miss errors were near miss errors, occurring within 50% distance of the target radius away from the target boundary. Near miss errors accounted for 64% and 84% of miss errors for older adults (675/1058) and younger adults (213/255), respectively, as shown in Fig. 12. Consistent with our overall findings for miss errors, the number of miss errors in each sub-category increased as target width decreased for both age groups. The distribution of miss errors in each sub-category across target widths mostly followed the overall pattern for miss errors (i.e., near miss > not-so-near miss > other > accidental taps, in terms of proportions). However, older adults were prone to accidental taps for all target widths, having more accidental taps than other errors (19 vs. 10) with medium targets, and more accidental taps than not-so-near miss errors (20 vs. 8) and other errors (20 vs. 4) with the large targets. To better illustrate the relationship between distance and miss errors, histograms with a bin size of 25% of the target radius are included for both age groups and across all target widths in Appendix B.



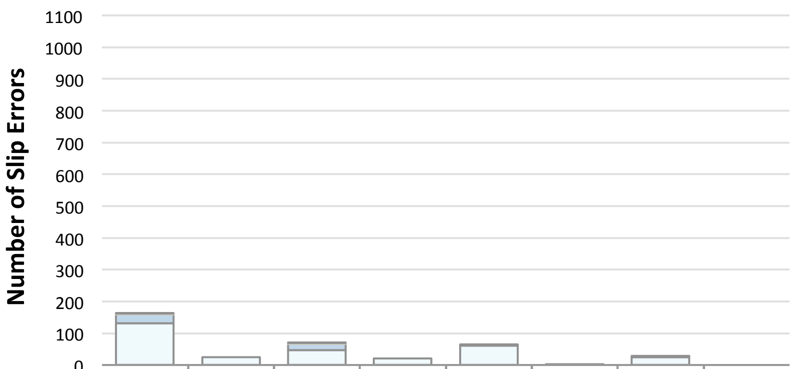
	OA (1058)	YA (255)	OA (710)	YA (204)	OA (252)	YA (44)	OA (96)	YA (7)
	All Target Widths		4.88 mm		7.22 mm		9.22 mm	
Accidental Tap	77	3	38	1	19	2	20	0
Other	92	1	78	1	10	0	4	0
Not-So-Near-Miss	214	38	172	36	34	2	8	0
Near Miss	675	213	422	166	189	40	64	7

Fig. 12. Breakdown of miss errors by subcategory for older (n = 20) and younger (n = 16) adults. Across age groups and target widths, near miss errors mostly dominated over all other subcategories of miss errors.

4.2.2 Slip Errors

As with miss errors, older adults generated significantly more slip errors than younger adults ($F_{1,\,33}$ = 9.94, p < .005, η_p^2 = .23), making over five times as many (see Table 3). There was also a significant effect of target width on slip errors ($F_{1.34,\ 44.28}$ = 7.27, p = .0054, η_p^2 = .18), with pairwise comparisons revealing that slip errors were lower for the largest target width than for the medium (p < .001) and smallest (p < .01) widths, but no difference was found between the medium and smallest widths (p = .611). However, unlike for miss errors, the age × width interaction was not significant (p = .195), potentially due to the much lower overall rate of slip errors than miss errors observed in our study.

Fig. 13 shows the distribution of slip errors across the sub-categories. Narrow slip errors (i.e., those less than 50% of the target radius away from the target boundary) dominated, accounting for 80% (131/163) of slip errors for older adults and all (24) slip errors for younger adults. For older adults, the bulk of the remaining slip errors (18%, 29/163) were moderate (i.e., between 50% and 100% of the target radius away), with the remaining two categories only accounting for 1 and 2 slip errors each, respectively. The distribution of slip errors in each sub-category across target widths mostly followed the overall pattern, i.e., number of slip errors in each category decreased as width increased. There was only one exception, where there were somewhat more narrow slips on the medium sized target than the smallest (60 vs. 46). The proportions of errors in each sub-category (narrow > moderate > large > very large) were also fairly consistent across target widths, except for the smallest targets, where there were more very large slip errors than large slip errors (2 vs. 1). More fine-grained histograms detailing slip error distances across age and target widths are included in Appendix B.



	OA (163)	YA (24)	OA (70)	YA (21)	OA (65)	YA (3)	OA (28)	YA (0)
	All Target Widths		4.88 mm		7.22 mm		9.22 mm	
Very Large Slip	2	0	2	0	0	0	0	0
Large Slip	1	0	1	0	0	0	0	0
Moderate Slip	29	0	21	0	5	0	3	0
Narrow Slip	131	24	46	21	60	3	25	0

Fig. 13. Breakdown of slip errors by subcategory for older (n = 20) and younger (n = 16) adults. For both age groups and for all target widths, narrow slip errors dominated over all other subcategories. Younger adults did not slip on the 9.22 mm targets.

5 Discussion

Our findings both confirm the results of prior research on age-related target selection performance and broaden these results with a more detailed analysis of the kinds of selection errors older adults encounter during touch interaction.

5.1 Movement Time Increases with Age and Decreases with Target Size

Consistent with prior work, older adults were significantly slower than their younger counterparts. Although we did not measure target verification time or the number and the duration of pauses during a target selection task, we observed older adults pausing as they neared the target regions before finalizing their selection, which may have contributed to the longer selection times for older adults as has been observed for mouse [Keates and Trewin 2005] and pen interaction [Ketcham et al. 2002]. Our movement times across target width and amplitude also aligned with previous work on mouse [Keates and Trewin 2005] and pen [Moffatt and McGrenere 2007] interaction in that both groups were slower with smaller and more distant targets. Like prior results on angular movement with pen input [Hancock and Booth 2004], we also observed that selecting the upper-right targets were faster than selecting the lower-right targets. Participants (both younger and older) also had relatively quicker selection time with the vertical (top and bottom) targets, and slower selection time with the upper-left targets. We did not find any interaction effect between age and width, amplitude, or angle, meaning that older adults were not disproportionately slowed by any of these factors.

5.2 Smaller Targets Disproportionately Reduced Accuracy for Older Adults

With respect to accuracy, older adults made significantly more errors, and showed a greater selection endpoint variability than younger adults. These results are consistent with past findings for mouse [Keates and Trewin 2005; Keates et al. 2005; Ketcham and Stelmach 2004;

Smith et al. 1999; Walker et al. 1997] and pen [Hourcade and Berkel 2008; Ketcham et al. 2002; Moffatt and McGrenere 2007] inputs, but differ from past findings for touch input, which found no relationship between age and errors [Findlater et al. 2013]. A likely explanation for this departure—and one that is consistent with the significant interaction effect we observed between age and target width—is the different target sizes used in the two studies: our largest target width of 9.22 mm was the smallest target width used by Findlater et al. [2013]. Note that our smallest target was roughly the size of a menu icon on the Android phone used in our experiment, so the difficulty participants encountered reflects a real problem affecting individuals on a daily basis, and potentially hindering adoption. In addition to making more errors, older adults in our study required more corrective attempts to recover from them. While most targets were acquired with just one (no error) or two (one error and one corrective) attempts, over 15% of trials on the smallest target (4.88 mm) required 10 or more corrective attempts for the older adults. Such trials were frustrating for participants and reflect substantial difficulty acquiring small targets. All older adult participants reported in the post-experiment questionnaire that relative to the other target sizes, they encountered more errors and required more corrective attempts to select the smallest targets, which made such targets to be the most difficult ones to select. While troublesome from an accessibility standpoint, this result is not entirely unexpected: similar studies with younger nondisabled individuals have also observed high error rates for small targets with touch input [Bi et al. 2013; Cockburn, Ahlström and Gutwin 2012; Sasangohar, MacKenzie and Scott 2009], and even though the smallest targets were less problematic for our younger adult participants, the majority (12/16) reported difficulty with them. Difficulties with small targets have been attributed to the "fat finger problem" [Vogel and Baudisch 2007] in which the shape of the finger, its size relative to the target, and misconceptions about the exact location of the selection point [Holz and Baudisch 2011] reduce pointing precision and hinder target verification prior to selection. Some of our participants made similar comments about their finger being bigger than the smallest targets might have caused lower selection rate. Thus, our results may suggest a tipping point, with small targets representing a manageable inconvenience for younger adults but presenting a barrier to use for older adults.

5.3 Miss Errors are More Prevalent than Slip Errors

In terms of the types of selection errors encountered, older adults exhibited a broader range of selection errors than younger adults. While younger adults slipped rarely, older adults both slipped from and missed targets (though misses dominated over slips for them as well). This result is somewhat surprising. Although it aligns with the pattern previously observed for mouse input [Keates and Trewin 2005], it differs from that observed for pen input [Moffatt and McGrenere 2007], despite both pen and touch being forms of direct interaction. This difference may point to a tradeoff. As the tip of a pen is much smaller than a finger, pen input affords higher precision, potentially reducing misses; however, fingers offer higher friction against the screen than a hard-plastic pen tip, potentially reducing slips. Additionally, aging contributed to both miss and slip errors in our study of touch interaction, but was only observed to contribute to slip errors for pen interaction [Moffatt and McGrenere 2007]. We also observed a higher proportion of accidental taps for older adults, relative to studies of mouse [Keates and Trewin 2005] and pen [Moffatt and McGrenere 2007] interaction.

5.4 Affordance Matters

During our study sessions, we observed a number of difficulties encountered by older participants, including finding the correct angle to position the finger on the target and determining which part of the finger needs to be in contact with the screen to register a touch.

Participants explored a number of strategies to overcome these difficulties. Many tried adjusting their finger angle and rotation, while others tried to roll their fingers to select targets with the sides of their fingertips. Most promisingly, some adopted a strategy in which they intentionally landed outside the target bounds and then dragged their fingers into the target before lifting. This technique has been previously observed by Potter et al. [1988] and Moffatt et al. [2003], but relies on a solid understanding of how selection occurs. While some successfully adopted this approach in our study, we observed that others were unclear on selection behavior with some older participants expecting that landing within the target region should be sufficient to correctly select the target.

5.5 Directions for Future Research

The most obvious way to reduce errors is to simply make the targets bigger. Considering both our results, in which errors significantly decreased at each larger target width up to our maximum target size of 9.22 mm, and the results of Findlater et al. [2013], in which no significant differences were found for accuracy across target sizes of 9.22 mm and larger, a starting guideline would be to ensure all targets are at least 9.22 mm wide. Although this is consistent with the standard icon sizes of 9–10 mm of the most popular smartphones, many selectable elements on current devices can be as small as 4 mm (roughly the size of our smallest target). Thus, it is likely not possible to simply make targets bigger, given current constraints on screen real estate. At the very least doing so would require making accommodations elsewhere that could introduce other potential accessibility barriers (e.g., from increased scrolling).

Further research is thus needed to identify alternative approaches to making smaller targets easier to select. While no research has specifically addressed the problem of older adults selecting small targets using touch, we can draw inspiration from research that has examined the similar problem of younger individuals selecting even smaller targets. As a starting point, we can draw inspiration from these techniques. Offset cursor [Potter, Weldon and Shneiderman 1988] applied a "finger-mouse" strategy to drag the finger to the target to avoid missing targets that are slightly smaller than the finger, while slide-touch [Ren and Moriya 2000] used a similar strategy, but with a pen to select very small (1.88 mm) targets. Zooming [Albinsson and Zhai 2003; Olwal and Feiner 2003] and control display manipulation [Albinsson and Zhai 2003; Benko, Wilson and Baudisch 2006] have shown promise for increasing pointing precision at the pixel level, and shifting [Vogel and Baudisch 2007] was found to be successful for selecting very small targets, especially those located at the edge of the screen and difficult to select by zooming and offsetting techniques. Alternative approaches include back of the device interaction [Baudisch and Chu 2009], which makes use of the back of the screen for input was successful with very small touchscreen (diagonally 6.3 cm) devices, and finger print tracking [Holz and Baudisch 2010], which uses the finger print to better detect selection points.

Our study results showed that major proportion of errors in both older and younger adults were miss errors. That means while developing touch interaction techniques, future research must emphasize on minimizing miss errors. To reduce miss errors, we can get inspirations from prior work on pen interaction. Moffatt and McGrenere [2010] combined two slip error minimizing mouse interaction techniques: bubble cursor [Grossman and Balakrishnan 2005] and steady clicks [Trewin, Keates and Moffatt 2006] to design steadied-bubble technique that successfully reduced slip errors in older adults with pen interaction. Similar approach can be taken by exploring mouse interaction techniques that have been successful on reducing miss errors on able-bodied younger adults, for example, area cursor [Worden et al. 1997], target expansion [McGuffin and Balakrishnan 2002], and bubble cursor [Grossman and Balakrishnan 2005] to implement touch interaction techniques for older adults to avoid miss errors.

The viability and effectiveness of the afore-mentioned techniques has to be determined before applying them to older adults, as each introduces complexity that may present new accessibility challenges. Exploring these techniques for older adults may also require gaining a deeper understanding of qualitative perceptions of pointing. Zhai, Kong and Ren [2004] explored two-dimensional Fitts' task and identified the users' bias towards the speed-accuracy trade-off. Similar studies can be conducted on older adults to understand their preference on speed and accuracy for such target selection tasks. In general, further research is needed to understand how best to support mental models of touch-based pointing and help individuals to develop appropriate compensation strategies. Previous studies that reported analyses of mouse trajectory [Hwang, Keates, Langdon and Clarkson 2005; MacKenzie, Kauppinen and Silfverberg 2001], pen movement profile [Ketcham et al. 2002], and finger properties (e.g., finger angle, rotation, direction, etc.) [Holz and Baudisch 2011] found to be useful to understand selection difficulties with those input devices. Similar analyses with touch input may also help to gain deeper understanding of age-related selection difficulties with touch-screen interfaces.

6 CONCLUSION

Aging can introduce declines in motor ability that can hinder the usage of technology, including modern touch-screen devices like smartphones and tablets. Previous studies on age-related selection difficulties with mouse and pen interaction suggested that older adults more likely take more time for target selection and generate more errors with both direct (pen) and indirect (mouse) input devices. Moreover, input method (e.g., mouse or pen) may have influence on selection errors in older adults, having miss errors to be the dominating error type for mouse, and slip error for pen interaction. We extended these studies for touch interaction to gain deeper understanding on age-related selection difficulties with touch input. Consistent with past findings, older adults in our study required longer movement time, generated higher error rates, and encountered broader range of selection errors that needed more error corrective attempts for recovering, compared to younger adults. Study results also conformed to the selection endpoint variability and angular movement behavior as reported in previous studies with mouse and pen interaction. Our investigation on the range of selection errors concluded that miss errors are more prevalent than slip errors for touch interaction in both younger and older adults. These results, when compared to previous findings for pen interaction, indicate that even though both pen and finger are direct input selection devices, selection errors vary across these two mediums. Moreover, selection errors found in touch input shows more similarities with that of mouse input (i.e., both having misses as the dominating selection error), despite the former is a direct and the latter is an indirect form of interaction. These findings suggest that age-related touch input selection difficulties are significantly different than age-related pen input selection difficulties, hence, directly applying the accessible pen interaction techniques (that are developed for older adults) on touch interaction may not be sufficiently accessible for this population. This also indicates that there is a need for designing novel accessible selection techniques for older adults with touch input to increase their adoption of such devices.

Our findings highlighted some possible recommendations for designing accessible touch-screen interfaces for older adults, such as: increasing the target size, and exploring accessible touch interaction techniques like, zooming, offsetting, shifting, etc. that have been previously successful with younger adults. However, further studies on these proposed design implications are required to assess their usability for older adults. The results presented in this paper are based on one type of small touchscreen device run on android platform. Greater diversity in the experiment factors would enrich the experiment dataset for future analysis. For example, future work could extend this study to other commercially available touchscreen devices that are equipped with different hardware, operating systems, sizes, etc. to gain more insight on the impact of a more diverse set of target size, amplitude, and location. Selection performance of older adults in different postures (e.g., sitting, and standing), screen orientation (portrait vs. landscape, and handheld vs. reclined on a tabletop) could also be explored. Analysis of individual movement time and error characteristics could offer new research directions for ability-based adaptive user interfaces that can be helpful for the older adults who are facing age-related motor-sensory declines. Findings from pointing selection performance can be extended to other input selection (e.g., text-entry) and gestures (e.g., zooming) to ensure overall accessibility of the touchscreen devices. Finally, supporting the mental model of older adults for target selection also seems promising. In-depth analyses on finger movement, finger trajectory, and the influence of finger properties can provide deeper understanding of touch interaction behavior of older adults, and may help to develop accessible touch-screen interfaces for them.

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REFERENCES

Pär-Anders Albinsson and Shumin Zhai. 2003. High precision touch screen interaction. In *Proceedings of the SIGCHI Conference on Human factors in Computing Systems* (CHI '03). ACM, New York, NY, 105-112.

M. Atsou and H. Iwase. 2002. Empirical study on improvement of usability for touch-panel for elderly-comparison of usability between touch-panel and mouse. In *Proceedings of the IEEE International Conference On Systems Man And Cybernetics*, MA1I4-MA1I4.

Theodore R. Bashore, Allen Osman, and Earle F. Heffley III. 1989. Mental slowing in elderly persons: A cognitive psychophysiological analysis. *Psychology and Aging 4 (2)*, 235.

Patrick Baudisch and Gerry Chu. 2009. Back-of-device interaction allows creating very small touch devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '09). ACM, , New York, NY, 1923-1932.

Horvoje Benko, Andrew D. Wilson, and Patrick Baudisch. 2006. Precise selection techniques for multi-touch screens. In *Proceedings of the SIGCHI conference on Human Factors in computing systems* (CHI '06). ACM, , New York, NY, 1263-1272.

Xiaojun Bi, Yang Li, and Shumin Zhai. 2013. FFitts law: modeling finger touch with fitts' law. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, 1363-1372.

Alex Chaparro, Michael Bohan, Jeffrey Fernandez, Sang D. Choi, and Bheem Kattel. 1999. The impact of age on computer input device use: Psychophysical and physiological measures. *International Journal of Industrial Ergonomics 24 (5)*, 503-513.

Alex Chaparro, Michael Rogers, Jeffrey Fernandez, Mike Bohan, Sang D. Choi, and Laszlo Stumpfhauser. 2000. Range of motion of the wrist: implications for designing computer input devices for the elderly. *Disability & Rehabilitation 22 (13-14)*, 633-637.

Neil Charness, Patricia Holley, Jeffrey Feddon, and Tiffany Jastrzembski. 2004. Light pen use and practice minimize age and hand performance differences in pointing tasks. *Human Factors: The Journal of the Human Factors and Ergonomics Society 46 (3)*, 373-384.

Andy Cockburn, David Ahlström, and Cari Gutwin. 2012. Understanding performance in touch selections: Tap, drag and radial pointing drag with finger, stylus and mouse. *International Journal of Human-Computer Studies 70 (3)*, 218-233.

Leah Findlater, Jon E. Froehlich, Kays Fattal, Jacob O. Wobbrock, and Tanya Dastyar. 2013. Age-related differences in performance with touchscreens compared to traditional mouse input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, 343-346.

Leah Findlater and Joanna Mcgrenere. 2010. Beyond performance: Feature awareness in personalized interfaces. *International Journal of Human-Computer Studies 68 (3)*, 121-137.

Paul M. Fitts. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology 47 (6)*, 381-393.

Qin Gao and Qiqi Sun. 2015. Examining the usability of touch screen gestures for older and younger adults. *Human Factors: The Journal of the Human Factors and Ergonomics Society 57(5)*, 835-863.

Tovi Grossman and Ravin Balakrishnan. 2005. The bubble cursor: Enhancing target acquisition by dynamic resizing of the cursor's activation area. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '05), ACM, New York, NY, 281-290.

Mark S. Hancock and Kellogg S. Booth. 2004. Improving menu placement strategies for pen input. In *Proceedings of Graphics Interface* (GI 2004), Canadian Human-Computer Communications Society, 221-230.

Christian Holz and Patrick Baudisch. 2010. The generalized perceived input point model and how to double touch accuracy by extracting fingerprints. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10), ACM, New York, NY, 581-590.

Christian Holz and Patrick Baudisch. 2011. Understanding touch. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10), ACM, New York, NY, 2501-2510.

Juan Pablo Hourcade and Theresa R. Berkel. 2008. Simple pen interaction performance of young and older adults using handheld computers. *Interacting with Computers 20(1)*, 166-183.

Faustina Hwang, Simeon Keates, Patrick Langdon, and J. Clarkson. 2005. A submovement analysis of cursor trajectories. *Behaviour & Information Technology 24(3)*, 205-217.

Simeon Keates and Shari Trewin. 2005. Effect of age and Parkinson's disease on cursor positioning using a mouse. In *Proceedings of the 7th international ACM SIGACCESS conference on Computers and Accessibility* (ASSETS 2005). ACM, New York, NY, 68-75.

Simeon Keates, Shari Trewin, and Jessica Paradise. 2005. Using pointing devices: Quantifying differences across user groups. In *3rd International Conference on Universal Access in Human-Computer Interaction.*

Caroline J. Ketcham, Rachael D. Seidler, Arend W. A. Van Gemmert, and George E. Stelmach. 2002. Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences 57(1)*, P54-P64.

Caroline J. Ketcham and George E. Stelmach. 2004. Movement control in the older adult. In *Technology for adaptive aging*, R.W. Pew and S. B. V. Hemel Eds. National Academies Press, Washington DC, USA, 64-92.

I. Scott MacKenzie. 1992. Fitts' law as a research and design tool in human-computer interaction. *Human-computer interaction 7(1)*, 91-139.

I. Scott MacKenzie, Tatu Kauppinen, and Miika Silfverberg. 2001. Accuracy measures for evaluating computer pointing devices. In *Proceedings of the SIGCHI Conference on Human factors in Computing Systems* (CHI '01). ACM, New York, NY, 9-16.

Michael McGuffin and Ravin Balakrishnan. 2002. Acquisition of expanding targets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '02). ACM, New York, NY, 57-64.

Karyn Moffatt, Leah Findlater, Rhian Davies, and Joanna Mcgrenere. 2003. Participatory Design with Aphasic Individuals. *Extended Abstracts of Graphics Interface* (GI 2003).

Karyn Moffatt and Joanna Mcgrenere. 2007. Slipping and drifting: using older users to uncover pen-based target acquisition difficulties. In *Proceedings of the 9th international ACM SIGACCESS conference on Computers and Accessibility* (ASSETS '07). ACM, New York, NY, 11-18.

Karyn Moffatt and Joanna Mcgrenere. 2010. Steadied-bubbles: combining techniques to address pen-based pointing errors for younger and older adults. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10). ACM, New York, NY, 1125-1134.

Lilian Genaro Motti, Nadine Vigouroux, and Philippe Gorce. 2013. Interaction techniques for older adults using touchscreen devices: a literature review. In *25ème IEME Conférence Francophone sur l'Interaction Homme-Machine,* (IHM'13), 125-134.

Atsau Murata and Hirokazu Iwase. 2005. Usability of touch-panel interfaces for older adults. *Human factors 47(4)*, 767-776.

Alex Olwal and Steven Feiner. 2003. Rubbing the Fisheye: precise touch-screen interaction with gestures and fisheye views. In *Conference Suppliment of the ACM Symposium on User Interface Software and Technologyy* (UIST '03). ACM, 83-84.

Jessica Paradise, Shari Trewin, and Simeon Keates. 2005. Using pointing devices: difficulties encountered and strategies employed. In *Proceedings of the 3rd International Conference on Universal Access in Human-Computer Interaction* Lawrence Erlbaum Associates Mahwah, 22-27.

PEW 2017. Technology adoption climbs among older adults http://www.pewinternet.org/2017/05/17/tech-adoption-climbs-among-older-adults/.

Richard L. Potter, Linda J. Weldon, and Ben Shneiderman. 1988. Improving the accuracy of touch screens: an experimental evaluation of three strategies. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '88). ACM, New York, NY, 27-32.

Xiangshi Ren and Shinju Moriya. 2000. Improving selection performance on pen-based systems: a study of pen-based interaction for selection tasks. *ACM Transactions on Computer-Human Interaction (TOCHI) 7(3)*, 384-416

Cameron N. Riviere and Nitish V. Thakor. 1996. Effects of age and disability on tracking tasks with a computer mouse: Accuracy and linearity. *Journal of Rehabilitation Research and Development 33(1)*, 6.

Wendy A. Rogers, Arthur D. Fisk, Anne Collins McLaughlin and Richard Pak. 2005. Touch a screen or turn a knob: Choosing the best device for the job. *Human Factors: The Journal of the Human Factors and Ergonomics Society 47(2)*, 271-288.

Timothy A. Salthouse. 1988. Cognitive aspects of motor functioning. *Annals of the New York Academy of Sciences 515(1)*, 33-41.

Farzan Sasangohar, I. Scott MacKenzie, and Stacey D. Scott. 2009. Evaluation of mouse and touch input for a tabletop display using Fitts' reciprocal tapping task. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. SAGE Publications, 839-843.

K. Warner Schaie. 2004. Cognitive aging. In *Technology for adaptive aging*, R. W. Pew and S. B. V. Hemel Eds. National Academies Press, Washington, DC, USA, 43-63.

Frank Schieber. 2003. Human factors and aging: Identifying and compensating for age-related deficits in sensory and cognitive function. In *Impact of technology on successful aging*, N. Charness and K. W. Schaie Eds. Springer, New York, NY, USA, 42-84.

Nicole Schneider, Janet Wilkes, Morten Grandt, and Christopher M. Schlick. 2008. Investigation of input devices for the age-differentiated design of human-computer interaction. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. SAGE Publications, 144-148.

Michaek W. Smith, Joseph Sharit, and Sara J. Czaja. 1999. Aging, motor control, and the performance of computer mouse tasks. *Human Factors: The Journal of the Human Factors and Ergonomics Society 41(3)*, 389-396.

Esther Strauss, Elisabeth M. Sherman, and Otfried Spreen. 2006. *A compendium of neuropsychological tests: Administration, norms, and commentary*. American Chemical Society.

Alvardo D. Taveira and Sang D. Choi. 2009. Review study of computer input devices and older users. *Intl. Journal of Human–Computer Interaction 25(5)*, 455-474.

Shari Trewin, Simeon Keates, and Karyn Moffatt. 2006. Developing steady clicks: a method of cursor assistance for people with motor impairments. In *Proceedings of the 8th international ACM SIGACCESS Conference on Computers and Accessibility* (ASSETS '06). ACM, New York, NY, 26-33.

Daniel Vogel and Patrick Baudisch. 2007. Shift: a technique for operating pen-based interfaces using touch. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (CHI '07). ACM, New York, NY, 657-666.

Neff Walker, David A. Philbin, and Arthur D. Fisk. 1997. Age-related differences in movement control: Adjusting submovement structure to optimize performance. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences 52(1)*, 40-53.

Alan T. Welford, A. H. Norris, and N. W. Shock. 1969. Speed and accuracy of movement and their changes with age. *Acta psychologica 30*, 3-15.

Alan T. Welford. 1981. Signal, noise, performance, and age. *Human Factors: The Journal of the Human Factors and Ergonomics Society 23(1)*, 97-109.

Alan T. Welford. 1988. Reaction time, speed of performance, and age. *Annals of the New York Academy of Sciences 515(1)*, 1-17.

Aileen Worden, Nef Walker, Krishna Bharat and Scott Hudson. 1997. Making computers easier for older adults to use: area cursors and sticky icons. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (CHI '97). ACM, New York, NY, 266-271.

Jin H. Yan. 2000. Effects of aging on linear and curvilinear aiming arm movements. *Experimental Aging Research 26(4)*, 393-407.

Shumin Zhai, J. Kong and Xiangshi Ren. 2004. Speed–accuracy tradeoff in Fitts' law tasks—on the equivalency of actual and nominal pointing precision. *International Journal of Human-Computer Studies 61(6)*, 823-856

Appendix A: Inferential Statistics

We present all inferential statistics from our study in this appendix. All main and interaction effects reported here are from repeated measure ANOVAs having target width, amplitude and angle as within subject and age as between subject factors. All pairwise comparisons were corrected with a Bonferroni correction. Mauchly's test was conducted to identify sphericity violations, and corrected with Greenhouse-Geisser corrections; where degrees of freedom (*df*) are non-integer, a correction has been applied.

Table 4. Statistical Inference from Movement Time

Factor	F-Statistics	Statistical Significance	Effect Size
Age	$F_{1, 33} = 19.01$	$p < .0005$	$\eta_p^2 = .37$
Target Width	$F_{1.17, 38.59} = 37.46$	$p < .00001$	$\eta_p^2 = .53$
Target Amplitude	$F_{1, 33} = 119.40$	$p < .00001$	$\eta_p^2 = .78$
Target Angle	$F_{4.73, 156.07} = 17.13$	$p < .00001$	$\eta_p^2 = .34$
Age × Target Width	$F_{1.17, 38.59} = 0.19$	$p = .701$	$\eta_p^2 = .41$
Age × Target Amplitude	$F_{1, 33} = 0.01$	$p = .930$	$\eta_p^2 = .00$
Age × Target Angle	$F_{4.73, 156.07} = 1.47$	$p = .206$	$\eta_p^2 = .04$
Age × Target Width × Target Amplitude	$F_{2, 66} = 0.44$	$p = .648$	$\eta_p^2 = .01$
Age × Target Width × Target Angle	$F_{7.90, 260.71} = 0.50$	$p = .851$	$\eta_p^2 = .02$
Age × Target Amplitude × Target Angle	$F_{4.99, 164.94} = 0.26$	$p = .934$	$\eta_p^2 = .01$
Age × Target Width × Target Amplitude × Target Angle	$F_{8.13, 268.29} = 1.31$	$p = .237$	$\eta_p^2 = .04$
Target Width × Target Amplitude	$F_{2, 66} = 3.14$	$p < .05$	$\eta_p^2 = .09$
Target Width × Target Angle	$F_{7.90, 260.71} = 1.07$	$p = .386$	$\eta_p^2 = .03$
Target Amplitude × Target Angle	$F_{4.99, 164.94} = 2.03$	$p = .077$	$\eta_p^2 = .06$
Target Width × Target Amplitude × Target Angle	$F_{8.13, 268.29} = 0.90$	$p = .518$	$\eta_p^2 = .03$

Table 5. Statistical Inference from Error Rate

Factor	F-Statistics	Statistical Significance	Effect Size
Age	$F_{1, 33} = 42.23$	$p < .0001$	$\eta_p^2 = .56$
Target Width	$F_{1.35, 44.68} = 153.60$	$p < .0001$	$\eta_p^2 = .82$
Target Amplitude	$F_{1, 33} = 0.73$	$p = .398$	$\eta_p^2 = .02$
Target Angle	$F_{4.66, 153.73} = 1.04$	$p = .397$	$\eta_p^2 = .03$
Age × Target Width	$F_{1.35, 44.68} = 27.68$	$p < .0001$	$\eta_p^2 = .46$
Age × Target Amplitude	$F_{1, 33} = 4.01$	$p = .054$	$\eta_p^2 = .11$
Age × Target Angle	$F_{4.66, 153.73} = 0.52$	$p = .751$	$\eta_p^2 = .02$
Age × Target Width × Target Amplitude	$F_{2, 66} = 0.08$	$p = .927$	$\eta_p^2 = .00$
Age × Target Width × Target Angle	$F_{8.13, 268.18} = 0.55$	$p = .821$	$\eta_p^2 = .02$
Age × Target Amplitude × Target Angle	$F_{7, 231} = 0.65$	$p = .711$	$\eta_p^2 = .02$
Age × Target Width × Target Amplitude × Target Angle	$F_{8.40, 277.27} = 1.08$	$p = .375$	$\eta_p^2 = .03$
Target Width × Target Amplitude	$F_{2, 66} = 0.10$	$p = .901$	$\eta_p^2 = .00$

Target Width × Target Angle	$F_{8.13, 268.18} = 0.93$	$p = .496$	$\eta_p^2 = .03$
Target Amplitude × Target Angle	$F_{7, 231} = 1.83$	$p = .082$	$\eta_p^2 = .05$
Target Width × Target Amplitude × Target Angle	$F_{8.40, 277.27} = 0.97$	$p = .464$	$\eta_p^2 = .03$

Table 6. Statistical Inference from Miss Errors

Factor	**F-Statistics**	**Statistical Significance**	**Effect Size**
Age	$F_{1, 33} = 36.27$	$p < .0001$	$\eta_p^2 = .52$
Target Width	$F_{1.27, 41.96} = 141.36$	$p < .0001$	$\eta_p^2 = .81$
Target Amplitude	$F_{1, 33} = 0.09$	$p = .768$	$\eta_p^2 = .00$
Target Angle	$F_{4.56, 150.55} = 1.22$	$p = .302$	$\eta_p^2 = .04$
Age × Target Width	$F_{1.27, 41.96} = 27.71$	$p < .00001$	$\eta_p^2 = .46$
Age × Target Amplitude	$F_{1, 33} = 2.66$	$p = .112$	$\eta_p^2 = .08$
Age × Target Angle	$F_{4.56, 150.55} = 0.88$	$p = .492$	$\eta_p^2 = .03$
Age × Target Width × Target Amplitude	$F_{1.71, 56.26} = 0.26$	$p = .735$	$\eta_p^2 = .02$
Age × Target Width × Target Angle	$F_{7.47, 246.36} = 0.38$	$p = .923$	$\eta_p^2 = .01$
Age × Target Amplitude × Target Angle	$F_{7, 231} = 0.90$	$p = .511$	$\eta_p^2 = .03$
Age × Target Width × Target Amplitude × Target Angle	$F_{8.20, 270.47} = 0.52$	$p = .848$	$\eta_p^2 = .02$
Target Width × Target Amplitude	$F_{1.71, 56.26} = 0.80$	$p = .438$	$\eta_p^2 = .02$
Target Width × Target Angle	$F_{7.47, 246.36} = 0.79$	$p = .600$	$\eta_p^2 = .02$
Target Amplitude × Target Angle	$F_{7, 231} = 1.96$	$p = .062$	$\eta_p^2 = .06$
Target Width × Target Amplitude × Target Angle	$F_{8.20, 270.47} = 0.68$	$p = .714$	$\eta_p^2 = .02$

Table 7. Statistical Inference from Slip Errors

Factor	**F-Statistics**	**Statistical Significance**	**Effect Size**
Age	$F_{1, 33} = 9.94$	$p < .005$	$\eta_p^2 = .23$
Target Width	$F_{1.34, 44.28} = 7.27$	$p = .0054$	$\eta_p^2 = .18$
Target Amplitude	$F_{1, 33} = 1.42$	$p = .243$	$\eta_p^2 = .04$
Target Angle	$F_{3.81, 125.60} = 0.43$	$p = .776$	$\eta_p^2 = .01$
Age × Target Width	$F_{1.34, 44.28} = 1.74$	$p = .195$	$\eta_p^2 = .04$
Age × Target Amplitude	$F_{1, 33} = 4.01$	$p = .054$	$\eta_p^2 = .11$
Age × Target Angle	$F_{3.81, 125.60} = 0.44$	$p = .771$	$\eta_p^2 = .01$
Age × Target Width × Target Amplitude	$F_{1.64, 54.18} = 0.31$	$p = .694$	$\eta_p^2 = .01$
Age × Target Width × Target Angle	$F_{6.77, 233.40} = 0.87$	$p = .526$	$\eta_p^2 = .03$
Age × Target Amplitude × Target Angle	$F_{4.43, 146.26} = 0.42$	$p = .814$	$\eta_p^2 = .01$
Age × Target Width × Target Amplitude × Target Angle	$F_{5.35, 176.62} = 1.24$	$p = .291$	$\eta_p^2 = .04$
Target Width × Target Amplitude	$F_{1.64, 54.18} = 1.32$	$p = .273$	$\eta_p^2 = .04$
Target Width × Target Angle	$F_{6.77, 233.40} = 0.66$	$p = .700$	$\eta_p^2 = .02$
Target Amplitude × Target Angle	$F_{4.43, 146.26} = 0.64$	$p = .651$	$\eta_p^2 = .02$
Target Width × Target Amplitude × Target Angle	$F_{5.35, 176.62} = 0.57$	$p = .735$	$\eta_p^2 = .02$

Table 8.Statistical Inference from Finger Pressure

Factor	**F-Statistics**	**Statistical Significance**	**Effect Size**
Age	$F_{1, 33} = 8.18$	$p < .01$	$\eta_p^2 = .20$
Target Width	$F_{2, 66} = 28.77$	$p < .00001$	$\eta_p^2 = .47$
Target Amplitude	$F_{1, 33} = 1.06$	$p = .31$	$\eta_p^2 = .03$
Target Angle	$F_{3.42, 231} = 10.67$	$p < .00001$	$\eta_p^2 = .24$
Age × Target Width	$F_{2, 66} = 0.76$	$p = .474$	$\eta_p^2 = .02$
Age × Target Amplitude	$F_{1, 33} = 0.65$	$p = .424$	$\eta_p^2 = .02$
Age × Target Angle	$F_{3.43, 113.26} = 2.07$	$p = .1$	$\eta_p^2 = .06$
Age × Target Width × Target Amplitude	$F_{2, 66} = 0.35$	$p = .706$	$\eta_p^2 = .01$
Age × Target Width × Target Angle	$F_{8.02, 264.51} = 0.80$	$p = .602$	$\eta_p^2 = .02$
Age × Target Amplitude × Target Angle	$F_{4.58, 151.06} = 0.90$	$p = .509$	$\eta_p^2 = .03$
Age × Target Width × Target Amplitude × Target Angle	$F_{7.96, 262.82} = 0.71$	$p = .681$	$\eta_p^2 = .02$
Target Width × Target Amplitude	$F_{2, 66} = 1.20$	$p = .307$	$\eta_p^2 = .04$
Target Width × Target Angle	$F_{8.02, 264.51} = 0.79$	$p = .617$	$\eta_p^2 = .02$
Target Amplitude × Target Angle	$F_{4.58, 151.06} = 2.48$	$p < .05$	$\eta_p^2 = .07$
Target Width × Target Amplitude × Target Angle	$F_{7.96, 262.82} = 1.54$	$p = .143$	$\eta_p^2 = .05$

Appendix B: Error Distribution Analysis

In this appendix we present the histograms of error distributions of miss and slip errors across age groups and target widths. All of the histograms have intervals of 1/4th width of the corresponding target widths. For the histograms showing all errors have intervals of 1/4th width of the smallest (4.88 mm) targets. In the width specific histograms we mapped the error distribution categories from prior work for mouse [Keates and Trewin 2005] and pen [Moffatt and McGrenere 2007] interaction. All histograms conform with the error distributions from prior work for, i.e., having more errors closer to the target boundaries.

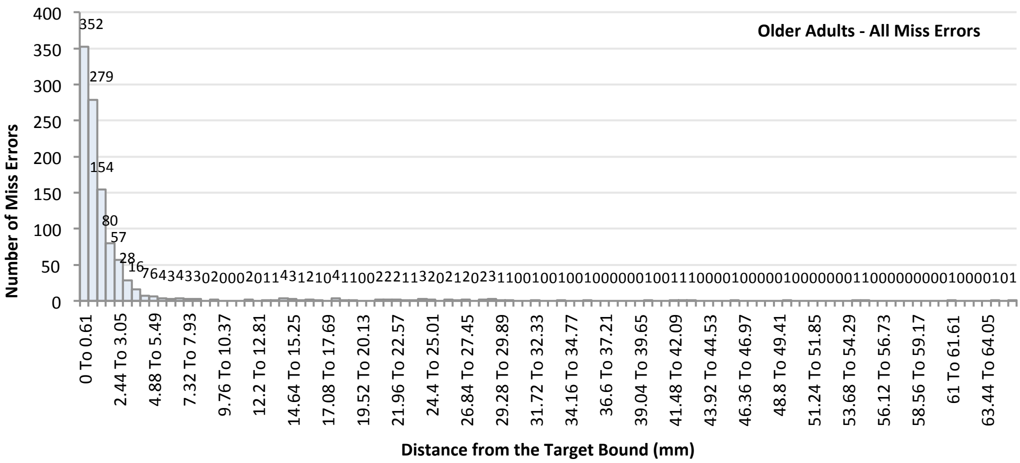

Fig. 14. Histogram of all miss errors for older adults.

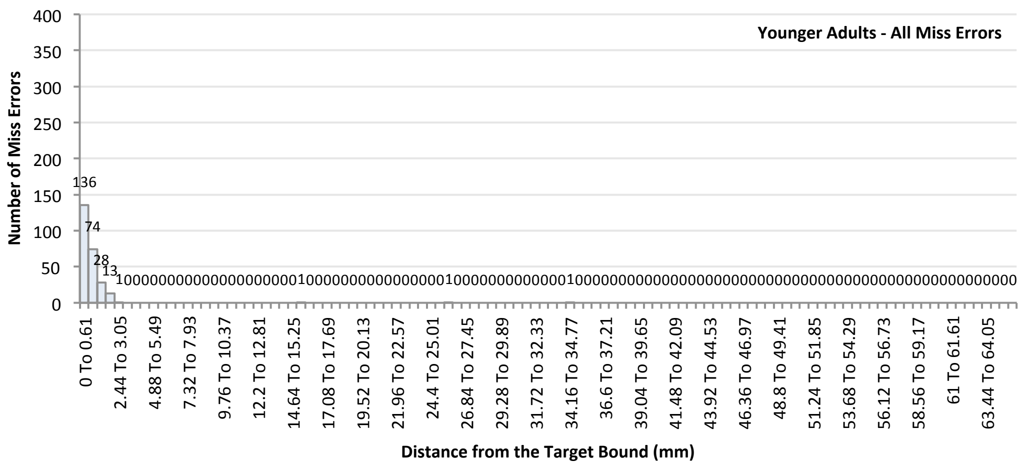

Fig. 15. Histogram of all miss errors for younger adults.

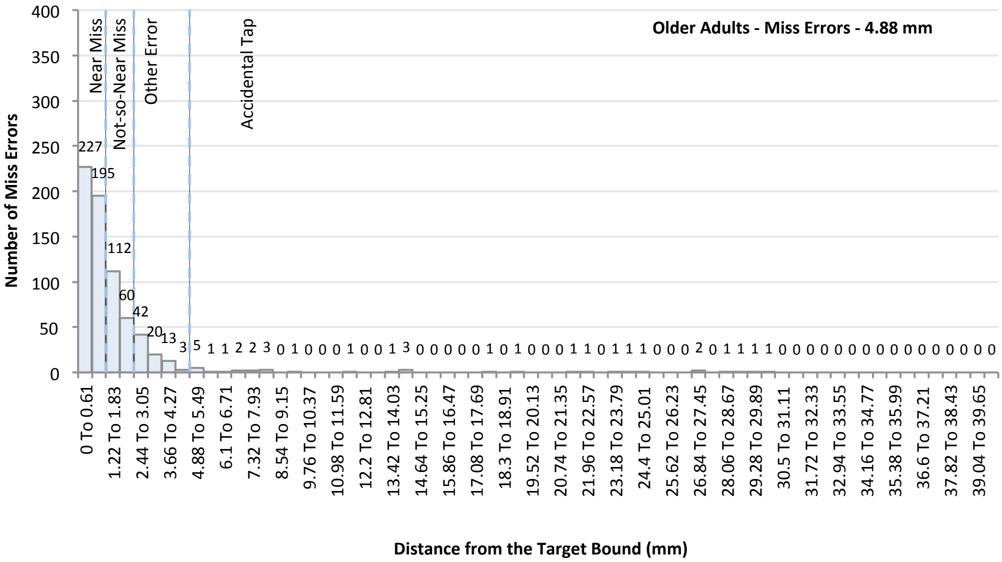

Fig. 16. Histogram of all miss errors for older adults with the smallest (4.88 mm) targets. For space constrains, we did not show the last five miss errors in the histogram, one error each in the 42.70-43.31, 54.29-54.90, 64.05-64.66 and 65.27-65.88 mm intervals.

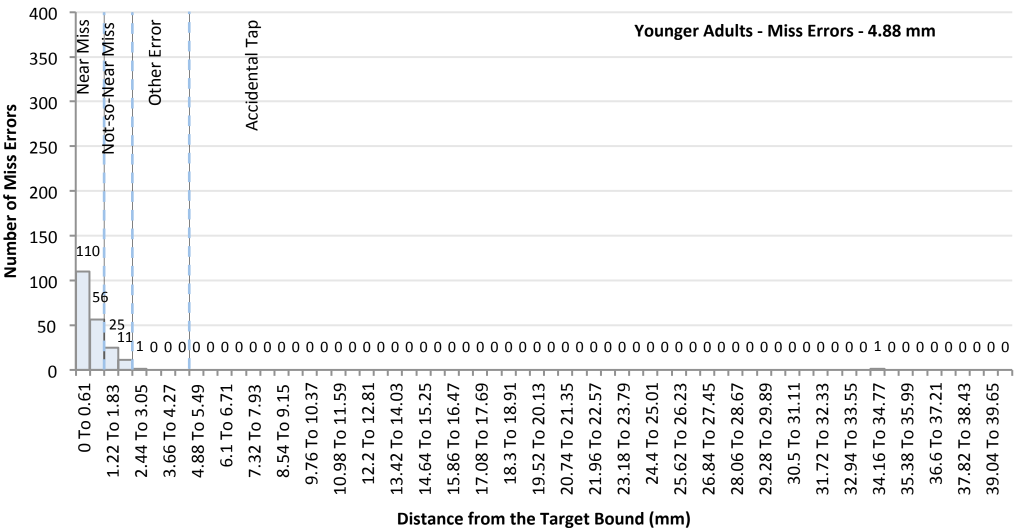

Fig. 17. Histogram of all miss errors for younger adults with the smallest (4.88 mm) targets.

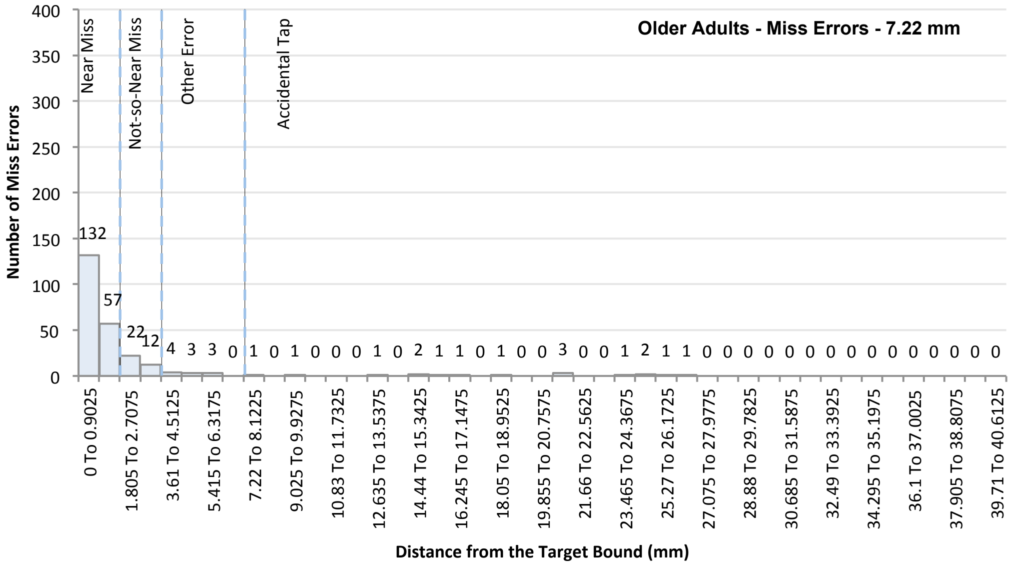

Fig. 18. Histogram of all miss errors for older adults with the medium (7.22 mm) targets. For space constrains, we did not show the last three miss errors in the histogram, one error each in the 42.42-43.32, 45.13-46.03, and 49.64-50.54 mm intervals.

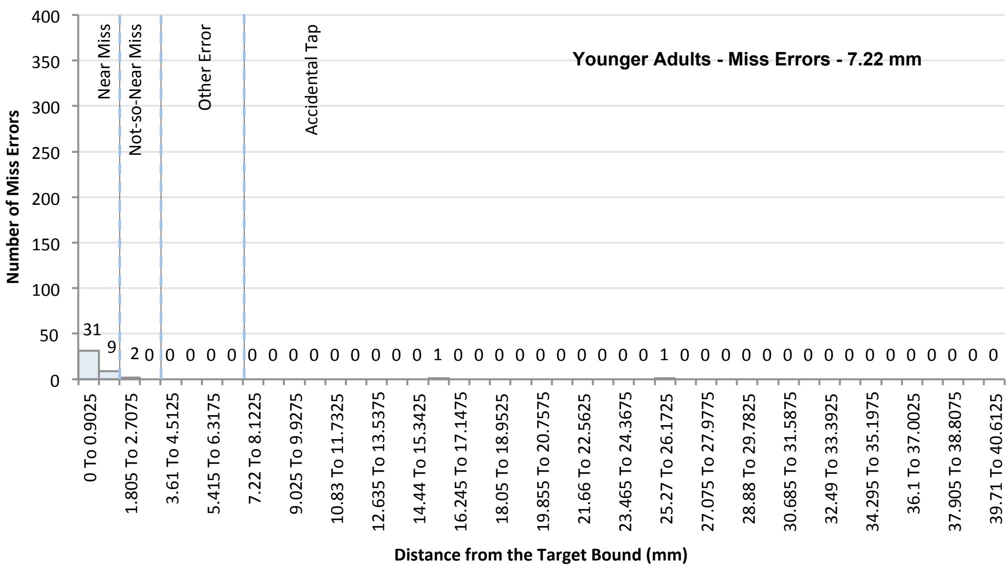

Fig. 19. Histogram of all miss errors for younger adults with the medium (7.22 mm) targets.

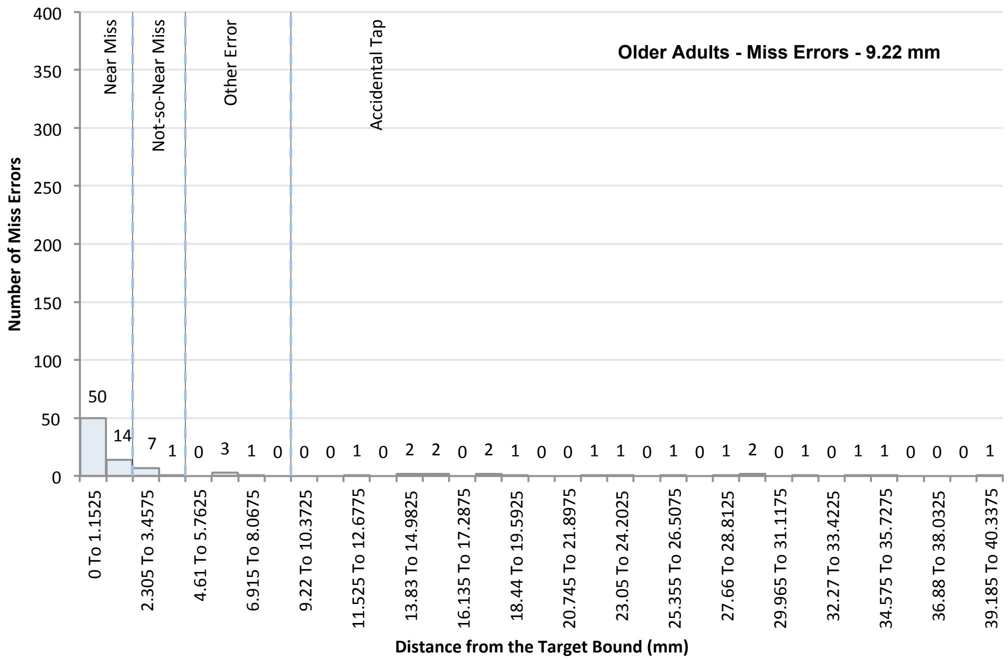

Fig. 20. Histogram of all miss errors for older adults with the largest (9.22 mm) targets. For space constrains, we did not show the last two miss errors in the histogram, one error each in the 41.49-42.64, and 61.08-62.24 mm intervals.

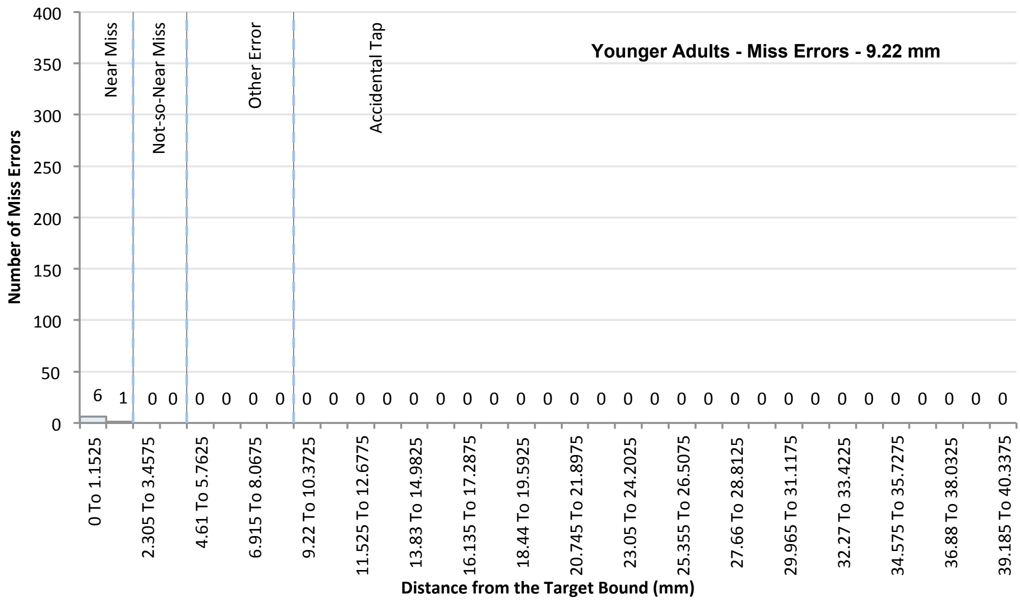

Fig. 21. Histogram of all miss errors for younger adults with the largest (9.22 mm) targets.

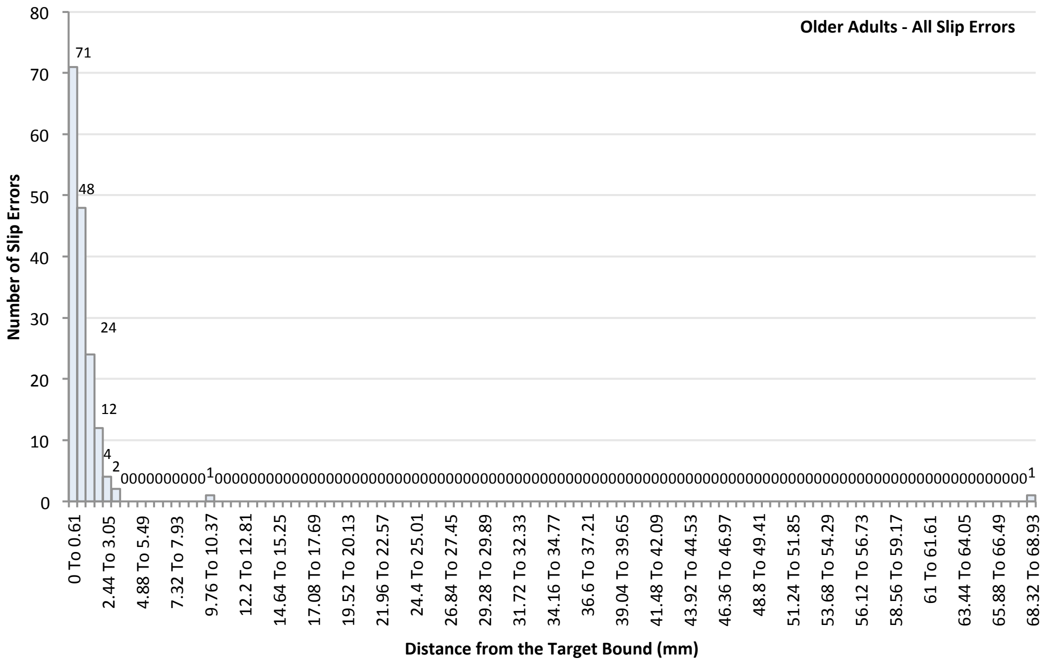

Fig. 22. Histogram of all slip errors for older adults.

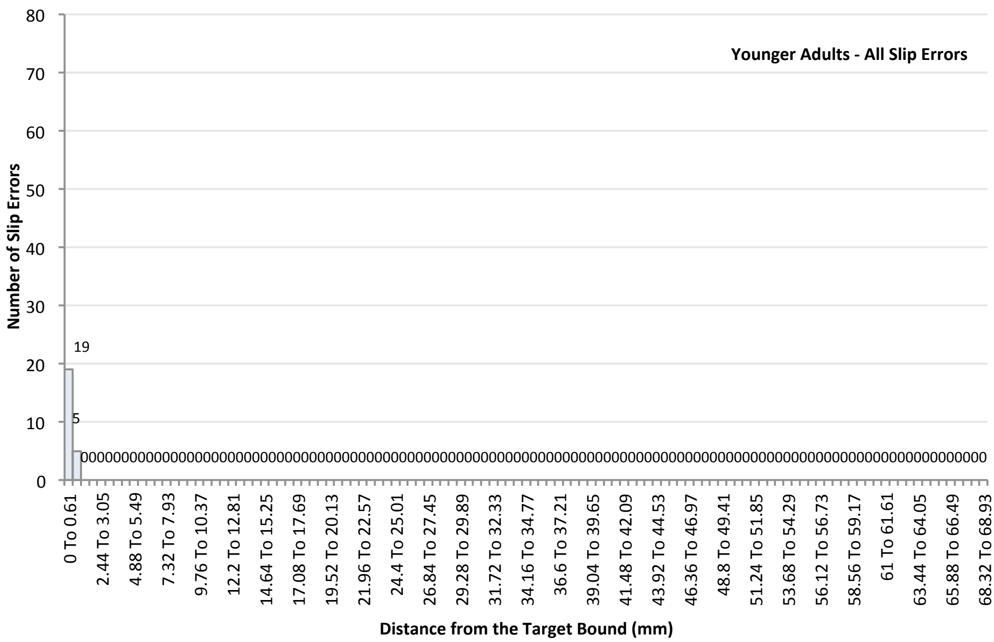

Fig. 23. Histogram of all slip errors for younger adults.

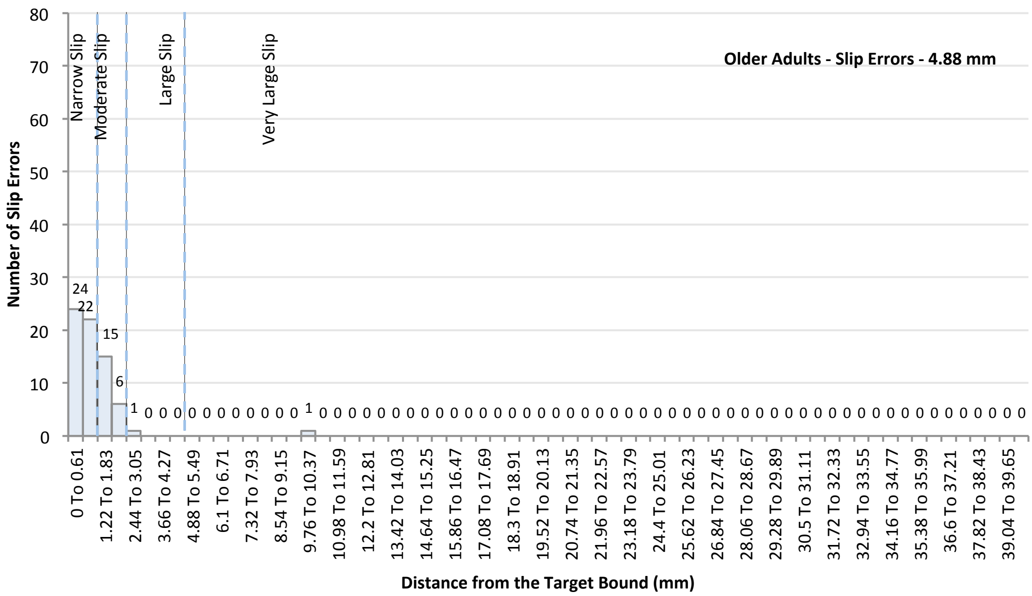

Fig. 24. Histogram of all slip errors for older adults with the smallest (4.88 mm) targets. For space constrains, we did not show the last slip errors in the histogram in the 68.32-68.92 mm interval.

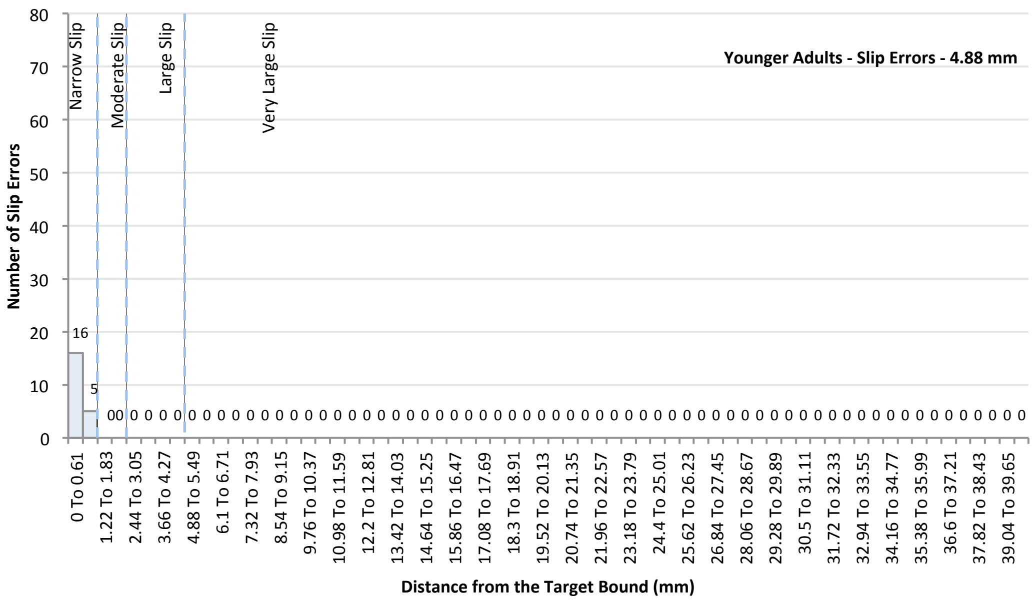

Fig. 25. Histogram of all slip errors for younger adults with the smallest (4.88 mm) targets.

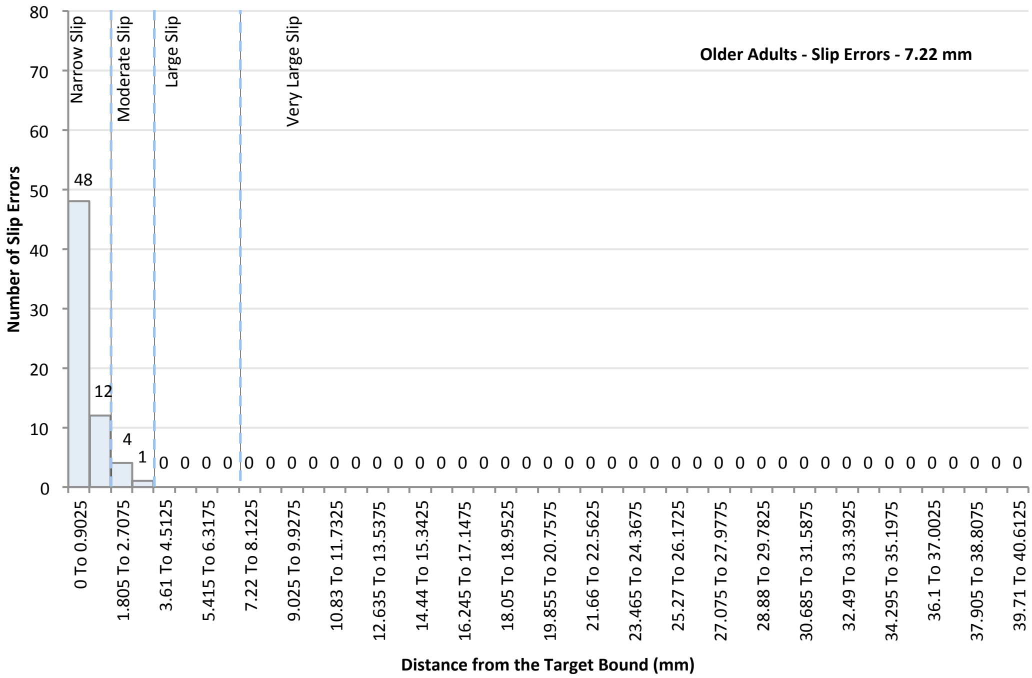

Fig. 26. Histogram of all slip errors for older adults with the medium (7.22 mm) targets.

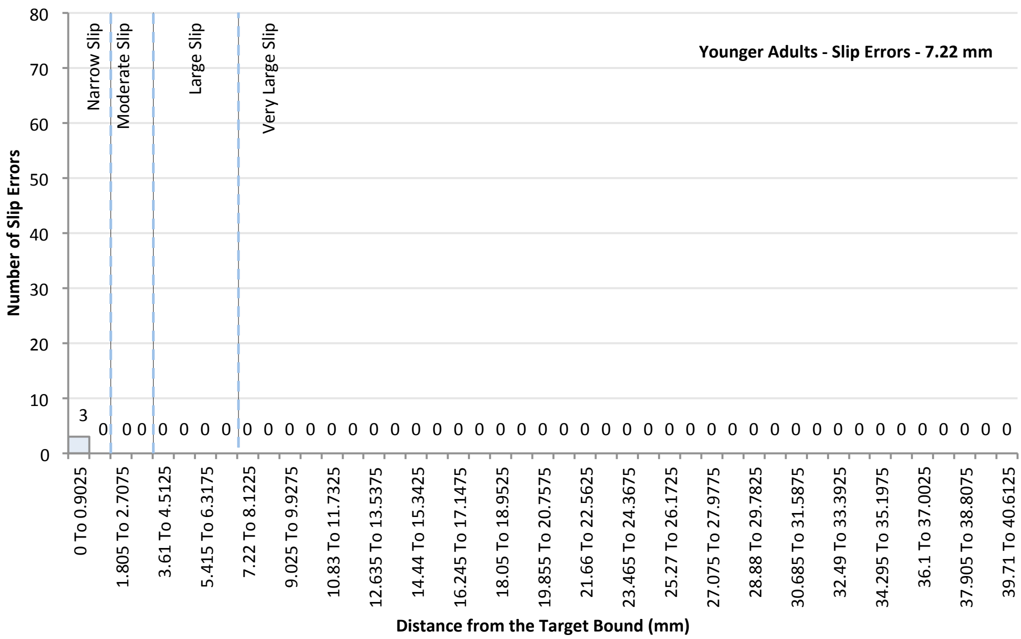

Fig. 27. Histogram of all slip errors for younger adults with the medium (7.22 mm) targets.å

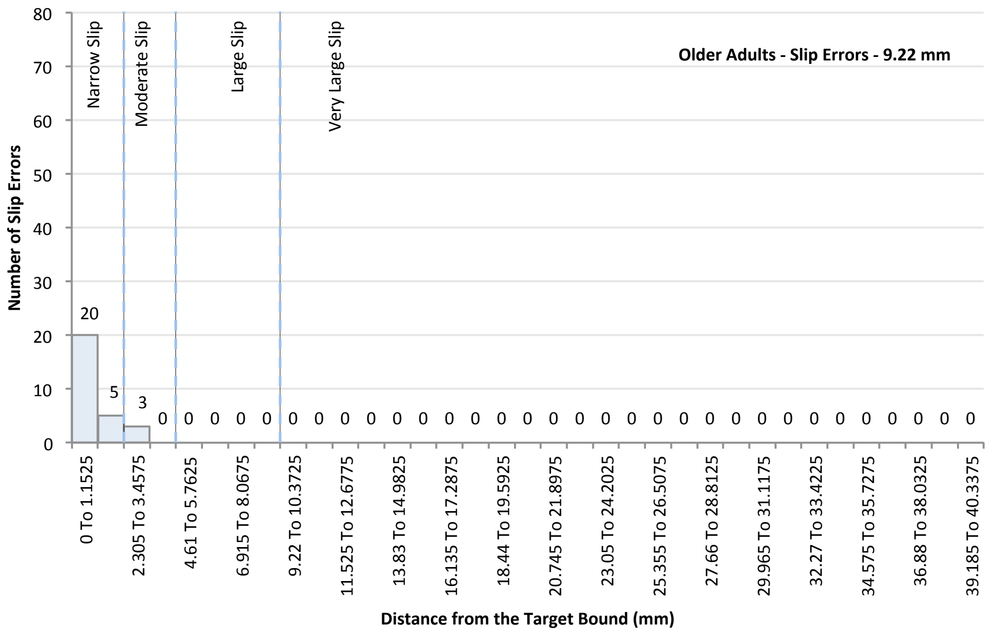

Fig. 28. Histogram of all slip errors for older adults with the largest (9.22 mm) targets.

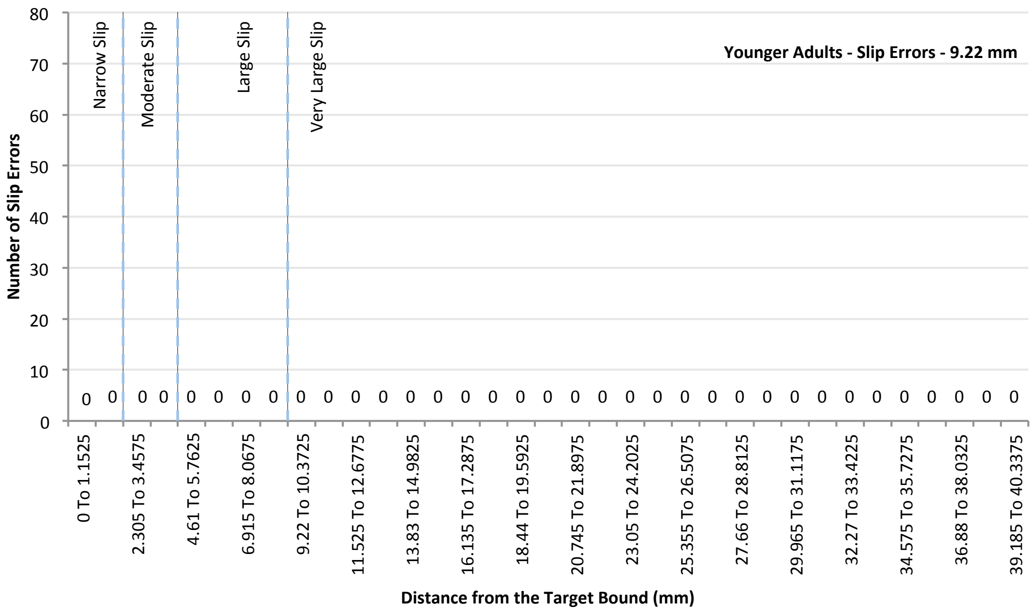

Fig. 29. Histogram of all slip errors for younger adults with the largest (9.22 mm) targets.

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