Tablets, Tabletops, and Smartphones: Cross-Platform Comparisons of Children's Touchscreen Interactions

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ABSTRACT

The proliferation of smartphones and tablets has increased children's access to and usage of touchscreen devices. Prior work on smartphones has shown that children's touch interactions differ from adults'. However, larger screen devices like tablets and tabletops have not been studied at the same granularity for children as smaller devices. We present two studies: one of 13 children using tablets with pen and touch, and one of 18 children using a touchscreen tabletop device. Participants completed target touching and gesture drawing tasks. We found significant differences in performance by modality for tablet: children responded faster and slipped less with touch than pen. In the tabletop study, children responded more accurately to changing target locations (fewer holdovers), and were more accurate touching targets around the screen. Gesture recognition rates were consistent across devices. We provide design guidelines for children's touchscreen interactions across screen sizes to inform the design of future touchscreen applications for children.

CCS CONCEPTS

• **Human-centered computing→Touch screens**

KEYWORDS

Touchscreen; tablet; tabletop; target interaction; gesture interaction; gesture recognition; pen; touch; children.

ACM Reference format:

Julia Woodward, Alex Shaw, Aishat Aloba, Ayushi Jain, Jaime Ruiz, and Lisa Anthony. 2017. Tablets, Tabletops, and Smartphones: Cross-Platform Comparisons of Children's Touchscreen Interactions. *In Proceedings of the 19th ACM International Conference on Multimodal Interaction (ICMI'17).* ACM, New York, NY, USA, 10 pages. http://dx.doi.org/10.1145/3136755.3136762

ICMI '17, November 13-17, 2017, Glasgow, United Kingdom

ACM ISBN 978-1-4503-5543-8/17/11…$15.00
http://dx.doi.org/10.1145/3136755.3136762

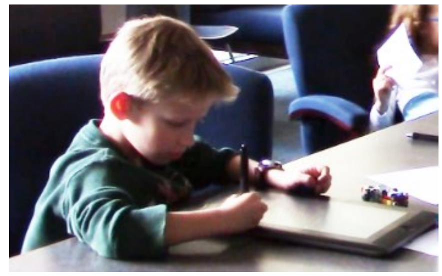

Figure 1. A child participating in our tablet study.

1 INTRODUCTION

The recent availability of touchscreen devices has affected both adults' and children's interactions with technology. A 2015 survey reported that 97% of U.S. children describe using mobile touchscreens regularly [22]. Previous work has examined children's interactions on small-screen smartphones [2–4,10,21,24,25,42], finding significant differences in how they touch targets and make gestures as compared to adults. Previous work on adults' touchscreen interactions illustrates that screen size can significantly affect target selection performance and efficiency [9,11,28]. Shaw and Anthony [33] also found gesture features involving time, distance, and size differed between children and adults. Therefore, it is important to examine children's touchscreen interactions on larger devices like tablets and tabletops. In addition, tablet users often employ digital pens or styluses; children's motor skills development [14,29] is likely to affect their performance with these implements differently. For example, 5- and 6-year-olds are still developing their grasp of writing instruments [18]. Thus, previous findings about adults' pen and touch interactions [6,34] may not generalize to children.

To investigate children's interactions with pen and touch on large screen devices, we conducted two studies. The first study investigated pen and touch input by 13 children on a tablet device. The second study investigated 18 children's interactions on a tabletop device. Children in our studies ranged from 5 to 10 years old. We modeled our studies after several previous studies on smartphones [1,3,42] so our results would be directly comparable to theirs. In our tablet study, we used the Wacom Cintiq Companion Hybrid tablet (Fig. 1), because it can measure detailed touch data [38]. Our second study used a second-generation Microsoft Surface (Samsung SUR40) tabletop.

In both experiments, participants completed a target touching task and a gesture drawing task. In our tablet experiment, we found that input modality (pen versus touch) affected target misses, response time, and input drag (tendency to slip the pen or finger during a touch). In both experiments, we found a significant effect of target size on miss rate and response time which is consistent with previous studies on smartphones [3,42]. In the tablet experiment, there was a significant effect of location on accuracy, with higher miss rates for targets at the top of the screen, but this was not true of the tabletop experiment. On the tabletop, children had lower holdover rates (touching in the area of the previous target) than the tablet and previous studies on smartphones [3,42]. Gesture recognition rates for both studies were similar to rates on smartphones.

Our contributions include: (a) a demonstration of the importance of input modality when designing touchscreen applications for children, (b) direct comparison of interaction behaviors by children on touchscreens of different sizes, and (c) a set of updated design implications offering guidelines for developers of touchscreen applications for children on various devices. This work will inform the design of future touchscreen applications for children across devices.

2 RELATED WORK

Work on children's touchscreen interactions, cross-modality comparisons, tabletops, and motor development informs us.

2.1 Children's Touchscreen Interactions

A large body of work on the topic of children's touchscreen interactions has focused on improving the design of applications for children through understanding their interaction behaviors [3,24,25,42]. Anthony et al. [3] conducted a study with children ages 7 to 16, offering a number of guidelines, such as suggesting designers align targets to the edge of the screen on smartphones and design gesture sets to limit easily confused pairs. Woodward et al. [42] showed that children ages 5 to 10 years old exhibit similar interaction patterns in touch and gesture tasks in both simple and complex interfaces. McKnight and Cassidy [24] studied the interactions of 7- to 10-year-olds with various types of small-screen mobile devices to create a set of ten guidelines for designers, though several of them focused on hardware rather than software challenges.

2.2 Comparing Pen and Touch Input

A number of studies have investigated pen and touch interaction, focusing mainly on differences between pen and touch in surface gesture interactions [7,34,35], but not target acquisition tasks. Tu et al. [34,35] compared pen and touch input for adults' gestures and found similarities in features such as articulation time, indicative angle difference, axial symmetry, and proportional shape distance, and differences in features such as size ratio and average speed. Anthony & Wobbrock [6] found that adults' gestures were recognized more accurately by $N-Protractor when the gestures were produced using touch compared to pen. Arif and Sylla [7] investigated the differences between touch and pen gesture input for adults and older children (ages 8 to 11) using tablets. They found that adults were faster and their gestures were recognized more accurately with pen than touch, while there was no difference for children. Our study directly compares pen and touch input in terms of *both* target acquisition and gesture recognition. Also, we focus on younger children (5 to 10 years old) than previous work has studied.

2.3 Touchscreen Interactions on Tabletops

Several prior studies have addressed tabletop interaction, though none have explicitly compared children's interactions on these devices with smaller screen devices [8,13,15,17,19,30]. A number of these studies have examined collaboration using tabletop devices, in the context of, for example, high school and university classrooms [15,27] and museum exhibits for both children and adults [8,17]. Other work has examined gesture interaction, focusing on understanding users' preferred gesture types [19,30]. Rust et al. [30] showed that 7- to 11-year-old children's touchscreen gesture interactions with tabletops were mostly based on the gestures they knew from smaller screen devices (i.e., legacy bias [39]). Our study adds to existing work by characterizing touch and gesture interactions on tabletop devices by examining children's specific interaction behaviors and comparing them with interactions on smaller screens.

2.4 Motor Development in Children

Smooth touchscreen interactions depend on a user's motor skills, which are still developing in children. General developmental changes that occur as children grow up have been widely studied [14,18,29,31,32]. We concentrate on the developmental changes that occur from ages 5 to 10 (the age group in our studies). At 5 years old, children are more precise than younger children when performing actions that require motor coordination, such as grasp and release [18,31]. The *dynamic tripod* grasp, the optimal grasp to hold a pencil to write, emerges between ages 4 and 6 [14,29]. At 6 and 7 years, children are starting to become more aware of their ability to use their hands (i.e., proprioception [16]) as tools for finer manipulation [18]. At 8 to 10, children can use their hands independently with more ease and precision [31], and fine motor performance has increased in speed and smoothness [18]. Schneck & Henderson [32] noted that the type of pencil grip applied by children depends on the type of task for which the writing implement is used. Hence, we designed our tasks to be completed easily by children of different ages without pencil grip influencing the results. Also, in our analysis, we grouped children by ages that have similar motor development skills.

3 METHOD

We present two separate experiments: one on a tablet, and the other on a tabletop. The experiments each consisted of two different tasks: (1) a *target touching task*—touching targets of various sizes, and (2) a *gesture drawing task*—drawing various letters, numbers, shapes, and symbols. The task applications used similar interfaces to previous studies [1,3,4,42]; see Fig. 2. The gestures in the gesture task were taken from previous studies of children's touchscreen gesture interactions, and included: A, E, K, Q, X, 2, 4, 5, 7, 8, minus, plus, arch, arrowhead, checkmark, circle,

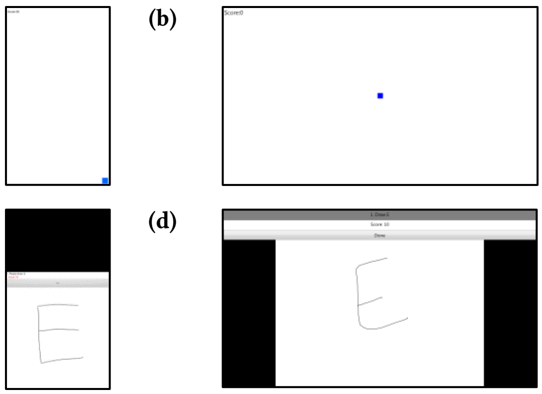

Figure 2. Target task interface for (a) Tablet and (b) Tabletop. Gesture task interface for (c) Tablet and (d) Tabletop. Applications inspired by Anthony et al. [1,3,4].

rectangle, triangle, diamond, and heart [3,42]. To encourage completion of the tasks, we used a gamified approach [10] in which the participants were awarded prizes for each task completed. The apps awarded points for each touch or gesture, and the children gained a prize upon completing each task. To ensure the behavior of the participant was as natural as possible, they knew the tasks were not timed and they were free to interact with the device as they felt comfortable. In the tablet study, all participants rested the tablet flat on the table; in the tabletop study, participants were free to move around the table.

3.1 Design of Applications

3.1.1 Target Application. Participants were asked to touch a total of 104 distinct targets that appeared onscreen one at a time. The targets were blue squares on a white background (Fig. 2a and 2b). The location, size, and frequency of the targets was based on those in previous studies [3,4,42]: very small, small, medium, and large. In our tablet experiment, as for previous smartphone studies, target sizes were 0.125 *in*, 0.25 *in*, 0.375 *in*, and 0.5 *in*; in our tabletop experiment, because of the larger screen size, targets were 0.4 *in*, 0.6 *in*, 0.8 *in*, and 1.0 *in*. (These sizes were centered around the recommended platform target size of 0.7 inches [43]). The application would not advance past a target until the participant successfully touched it within its bounds. Consecutive targets were never in the same location or the same size, and all participants had the same order of targets. As in the previous studies [3,4,42], half of the targets had edge padding [3], in which the target is slightly inset from the side of the screen instead of directly aligned to the edge. Edge padding was 10 pixels in both studies (tablet: 0.06 *in*, tabletop: 0.18 *in*), as in previous studies (smartphone: 0.04 *in*) [42]. The physical size of padding differed slightly between studies by screen DPI.

3.1.2 Gesture Application. The gesture application's interface consisted of a white canvas on which the participant could draw gestures (Fig. 2c and 2d). Visual feedback of the gesture input was provided. In our gesture app, we reduced the size of the canvas (black space visible in the figure) to prevent children from artificially increasing the size of their gestures. The size of the canvas was still much larger than the corresponding applications for phones in previous studies [1,3,4,42]: tablet: 1080 x 1280 pixels, and tabletop: 1280 x 1080 pixels. At the top of the screen, a prompt instructed the participant to draw a specific gesture from the set. The participant drew the gesture and clicked an onscreen "Done" button when finished. Participants were not able to erase any gestures, as this feature could have led them to produce beautified, rather than natural, gestures [1].

4 EXPERIMENT 1: TABLET

The first of the two experiments examined children's interactions with a tablet device. We had two objectives in conducting this study: (1) to understand children's touchscreen interactions on a tablet and compare with smaller devices from previous work, and (2) to compare children's interactions using touch and pen. The applications in our experiment were run on a Wacom Cintiq Companion Hybrid tablet with 8 GB of DDR3 RAM. The resolution was 1080 x 1920 (166 DPI), and the display size was 13.3 inches, measured diagonally. Though Wacom tablets may not typically be used by children, we used them in our study because they can measure detailed touch data [38].

4.1 Participants

The participants in our tablet study included 13 children ages 5 to 10 (M = 7.31, [SD = 1.6]). There were 2 five-year-olds, 2 six-year-olds, 4 seven-year-olds, 1 eight-year-old, 3 nine-year-olds, and 1 ten-year-old. Six participants were female. One participant was left handed. A total of 10,438 touch events were generated by the participants in our tablet study, and a total of 3,120 gestures (2 conditions x 20 gestures x 6 repetitions x 13 participants). Each participant completed both tasks twice: once using touch and once using a pen. The order of the tasks and input modality was counterbalanced across participants, so that 7 children completed the pen task first while the other 6 completed the touch task first.

4.2 Results

We present our results, organized by task, comparing the results for each input modality. We divide the participants into age groups: 5- to 6-year-olds (4 participants), 7- to 8-year-olds (5 participants), and 9- to 10-year-olds (4 participants), informed by our review of the motor development literature [14,18,29,31,32].

4.2.1 Target Results. We analyzed the data from participants' interaction events when touching targets in the target application. We removed the first target as a warm-up, and analyzed 103 targets per participant. We compared the touch and pen modality using several metrics from previous studies [3,42].

Holdovers. We examined holdovers [3], which are caused when a touch is generated in the vicinity of the previous target rather than the current one; typically holdovers are explained as the participant not noticing the intended target having been activated. Of the 3,624 touch events using the touch modality, 9.9% were holdovers. For the pen modality, 5.8% of the 6,814 touch events were holdovers. Both these results are higher than that found in previous studies on smartphones (3.9%) [4]. We suspect the higher percentage is due to the larger screen size of the tablet: children had a harder time noticing the appearance of a new target when the previous target had been activated because, as the targets were the same physical size as in previous studies [3,42], targets were proportionally smaller onscreen.

Per-User Misses. We calculated the proportion of targets missed on the first try for each participant in the study. Like previous studies [3,42], we excluded holdovers and only considered first attempt touch events. We ran a two-way repeated measures ANOVA on *per-user miss rate* with within-subjects factors of *input modality* (touch vs. pen) and *target size* (0.125 *in*, 0.25 *in*, 0.375 *in*, 0.5 *in*). We found a significant main effect of input modality ($F_{1,12}$ = 5.73, $p < 0.05$). Children missed more targets when using touch (41% [SD=10%]) than when using pen (32% [13%]). We believe this behavior is because the nib of a pen is thinner than the width of a finger, which makes it easier to acquire targets [20]. We also found a significant main effect of target size ($F_{3,36}$ = 128.9, $p < 0.0001$), which is consistent with previous studies [3,42]. In general, children found smaller targets harder to hit than larger targets. There was no interaction effect between modality and target size ($F_{3,36}$ = 0.34, *n.s.*).

Edge Padding. We also examined the impact on miss-rate of target edge padding [3], which (as in previous studies) is a small buffer between a target and the edge of the screen. We ran a two-way repeated measures ANOVA on *miss rate* with within-subjects factors of *input modality* (touch vs. pen) and *edge padding*, and found no significant effect of input modality ($F_{1,12}$ = 2.67, *n.s.*). In contrast to previous studies on smartphones [3,42], we found no significant effect of edge padding here ($F_{1,12}$ = 0.84, *n.s.*). In our study, the miss rate was very similar on targets with edge padding (41% [15%]) and without edge padding (38% [13%]), whereas in previous studies on smartphones, targets with edge padding had almost double the miss rate for children [3,42]. Possible explanations include the slightly different physical size of the edge padding buffer, platform specific behaviors for near-edge touches, and bezel width differences. We found no interaction between modality and edge padding ($F_{1,12}$ = 0.03, *n.s.*)

Location. We examined the effect of vertical and horizontal location of the targets on the participants' performance. We ran a two-way repeated measures ANOVA on *miss rate* with within-subjects factors of *input modality* (touch vs. pen) and *vertical region* (top, center, and bottom), and found a significant main effect of vertical region ($F_{2,24}$ = 18.6, $p < 0.0001$). Children missed more when targets were located at the top of the screen (50% [18%]) than when targets were located at the center and bottom of the screen (38% [13%]), which is consistent with previous studies [3,42]. We ran the same test for *horizontal regions* (left, center, right) and found a significant main effect of horizontal region ($F_{2,24}$ = 7.57, $p < 0.01$). However, contrary to previous studies, children missed more when targets were on the left side of the screen (44% [16%]) than the right and center (37% [13%]). We suspect that children missed more when targets were located at the top and left side of the screen because (1) children rested the tablet on the table with the bottom closest to them, making it hard to reach the top of the screen, and (2) since most of our participants were right handed it was more difficult to reach targets on the left. For both analyses, there was no significant effect of input modality: vertical: ($F_{1,12}$ = 1.94, *n.s.*), horizontal: ($F_{1,12}$ = 3.98, *n.s.*); and no interaction between input modality and location: vertical: ($F_{2,24}$ = 0.69, *n.s.*), horizontal: ($F_{2,24}$ = 1.58, *n.s.*).

Response Time. Response time is the time it takes a participant to generate the first touch event after a target appears on the screen. Like previous studies [3,42], we excluded holdovers, and only considered first attempt touch events. We examined participants' response times when using pen and touch. We ran a repeated measures ANOVA on *response time* with within-subjects factors of *input modality* (touch vs. pen) and *target size* (0.125 *in*, 0.25 *in*, 0.375 *in*, 0.5 *in*), and a between-subjects factor of *age group* (5-6, 7-8, 9-10). We found significant main effects of input modality ($F_{1,10}$ = 49.3, $p < 0.0001$) and target size ($F_{3,30}$ = 25.2, $p < 0.0001$). We observed a speed-accuracy tradeoff in children's performance: children had a faster response time when using touch (1159 ms [300 ms]) but missed targets more frequently, and vice versa for pen (1641 ms, [323 ms]). There was also a significant main effect of age group ($F_{2,10}$ = 4.18, $p < 0.05$) and an interaction effect between age group and target size ($F_{6,30}$ = 3.12, $p < 0.05$). The youngest children have slower response times than older children (5-6: 1672 ms [224 ms]; 7-8: 1256 ms [268 ms]; 9-10: 1268 ms [118 ms]). Children also have slower response times when touching the smallest targets (1670 ms [449 ms]) compared to the largest targets (1190 ms [208 ms]), which is in line with previous studies [3,42].

Input Drag. Input drag refers to the distance between the position where the input device first touches the screen and the position where the input device leaves the screen (similar to Vatavu et al.'s offset-distance metric [37], which they found to be higher for younger children). In our analysis, we excluded holdovers and only considered successful first attempt touch events. We ran a repeated measures ANOVA on input drag with within-subjects factors of *input modality* (touch vs. pen) and *target size* (0.125 *in*, 0.25 *in*, 0.375 *in*, 0.5 *in*), and a between-subjects factor of *age group* (5-6, 7-8, 9-10). We found significant main effects of input modality ($F_{1,10}$ = 26.5, $p < 0.001$) and target size ($F_{3,30}$ = 19.2, $p < 0.0001$), but no interaction ($F_{3,30}$ = 0.84, *n.s.*). Children had less input drag when using touch (6.4px [1.92 px])

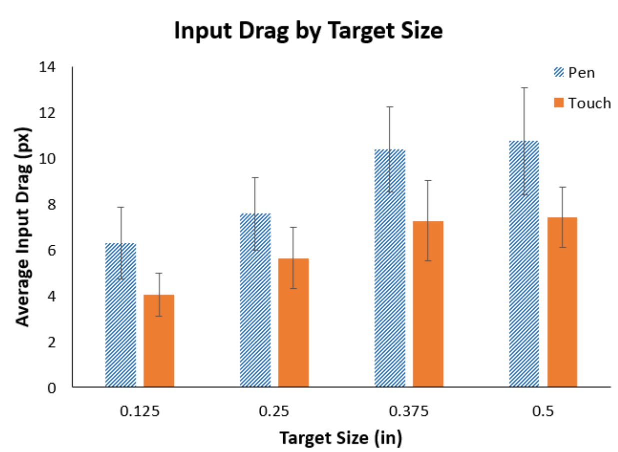

Figure 3. Average input drag by target size in the tablet target task. Error bars represent 95% confidence interval.

than when using pen (9.0px [2.97 px]) (Fig. 3). Prior work has found accidental slips on touchscreens [37] as well as in mouse usage for young children [21]. We suspect this is because children are still developing the fine motor skills required to use pens properly [23,26]. The difference in friction on the surface between finger and pen could also explain this variation.

4.2.2 Gesture Results. To study the effect of input modality and age on recognition accuracy, we analyzed the gestures our participants made on the tablet by running recognition experiments. Since recognition is more accurate for more consistent gesturing [12], a change in accuracy could indicate a difference in gesturing patterns. We performed the gesture recognition experiments using our own Java-based implementation of the $P recognizer [36], a multi-stroke gesture recognizer. Both user-dependent (within user) and user-independent (between users) experiments were run. Each gesture task consisted of 6 rounds of 20 gestures each. The first round was treated as warm-up, leaving a total of 5 samples per gesture per user for our experiments (total of 2,600 gestures).

User-Dependent Recognition Experiments. In user-dependent experiments, the recognizer is trained and tested on samples from the same user, showing user-adapted recognition rates. We used the testing procedure introduced by Wobbrock et al. [41] and used in many studies [5,6,36]. We systematically increased the number of training examples from T = 1 to 4 (1 must be chosen for testing, leaving a maximum of 4 for the training set). There were about 19,690 user-dependent recognition tests (2 input modalities x 10 trials x 13 participants x 4 values of T x 20 gestures; actual value is lower because some users were missing gestures).

A repeated measures ANOVA on *accuracy* with a between-subjects factor of *age* (5, 6, 7, 8, 9, 10) and a within-subjects factor of *input modality* (touch vs. pen) showed a significant effect of age on accuracy ($F_{2,12} = 4.43$, $p < .05$). Accuracy was worst for the 5-year-olds (66.22% [5.4%]) and improved for older children (e.g., 10-year-olds: 81.81% [1.33%]), which is consistent with prior work that has shown that accuracy increases with age [3,42]. The same ANOVA found no significant difference ($F_{1,8} = 3.83$, *n.s.*) between pen (81.81% [13.49%]) and touch (81.04% [11.86%]). Thus, application designers can expect similar gesturing performance for children in both pen and touch modalities.

User-Independent Recognition Experiments. In these tests, the recognizer is trained and tested on samples from different users, showing off-the-shelf recognition rates (these tend to be lower than the user-dependent case [3,42]). We used the procedure explained by Vatavu et al. [36], with 10 trials. Because the amount of participants is different in each age group, the maximum value of training participants varies by age. To make our results comparable, we used 3 randomly chosen training participants for each age group (since some groups had only 4 participants and one must be the test participant) and 5 training examples. We used these results to analyze the differences by age group and input modality.

For age, a one-way ANOVA on *accuracy* with a between-subjects factor of *age group* (5-6, 7-8, 9-10) showed a significant effect of age on recognition accuracy ($F_{2,9} = 16.34$, $p < 0.001$). As with the user-dependent scenario, accuracy was directly proportional to age: worst for the youngest children and best for the oldest children (5-6: 46.78% [4.93%]; 7-8: 57.71% [5.12%]; 9-10: 78.36% [4.26%]). As is typical with previous children's gesture recognition experiments, user-independent accuracy rates are lower than those of user-dependent rates [1,3,4,42]. A repeated measures ANOVA on accuracy with *input modality* (pen vs. touch) as a within-subjects factor found no significant difference ($F_{1,21} = 0.411$, n.s.) between pen (66.23% [10.76%]) and touch (63.60% [10.45%]). There was no effect of input modality on recognition rates in both the user-independent and user-dependent case. Therefore, designers can expect similar accuracy for touch and pen even when the recognizer is trained on different children's gestures.

4.2.3 Summary. For the target task on the tablet, per-user misses, response time, and input drag show clear effects of input modality on target interactions, but no effect of input modality was shown for location and edge padding. In the gesture task, we found that gesture accuracy was lowest for the youngest children and increased for older children, with no significant effect of input modality on accuracy.

5 EXPERIMENT 2: TABLETOP

In our second experiment, children interacted with a tabletop computer. The objective was to compare children's touchscreen interactions on a large screen to devices of different sizes, e.g., smartphones from prior work [2,3,42] and tablets in Experiment 1. The applications in our experiment were run on a Samsung SUR40 with 4GB RAM. The resolution was 1920 x 1080 (55 DPI), and the display size was 40 inches, measured diagonally.

5.1 Participants

The participants in our tabletop study included 18 children, ages 6 to 10 (M = 7.83, [SD = 1.38]): 4 six-year-olds, 4 seven-year-olds, 3 eight-year-olds, 5 nine-year-olds, and 2 ten-year-olds. Ten participants were female, and three participants were left handed. A total of 8,529 touch events were generated, as well as 2,160 gestures (20 gestures x 6 repetitions x 18 participants).

5.2 Results

We divide the participants into two age groups (6- to 7-year-olds and 8- to 10-year-olds) since we did not have any 5-year-olds.

5.2.1 Target Results. To analyze the touch interaction data, we first removed two participants, one 7-year-old and one 9-year-old (both male), who were outliers in terms of their total number of touch attempts (over two standard deviations above the mean). To compute our results, we analyzed 103 targets per person after excluding the first target as practice. Thus, we had a set of 16 participants with complete data for the target tasks, consisting of 6,097 total touch events.

Holdovers. As in Experiment 1, holdovers occur when touches are located in the same vicinity as the previous target instead of the current target [3]. Out of the 6,097 touch events, 2.9% (178) were holdovers. This is lower than previous studies (3.9% [4], 4.8% (238 out of 4,962) [42]) and Experiment 1 (9.9%, 357 out of 3,624 touch events). We believe the sensitivity of the

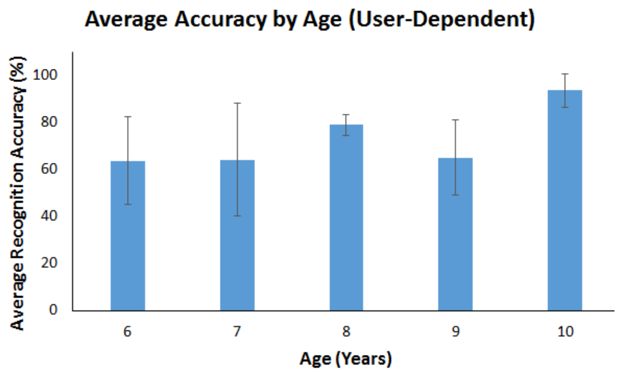

Figure 4. Average recognition rate by age in the tabletop gesture task. Error bars represent 95% confidence interval.

tabletop registered extra events and caused the proportion of holdovers among the entire dataset to be lower. We further discuss the impact of this hardware limitation later in the paper.

Per-User Misses. We calculated the per-user proportion of misses over all targets, and like previous studies we excluded holdovers and only looked at first attempts [3,4,42]. The average miss rate was 62% [SD=16%], which is higher than Experiment 1 (41% [23%]) and previous studies [3,42], due to the sensitivity of the tabletop. We ran a two-way repeated measures ANOVA on *per-user miss rate* with a within-subjects factor of *target size* (0.4 *in*, 0.6 *in*, 0.8 *in*, 1 *in*) and a between-subjects factor of *age group* (6-7, 8-10). We found a significant effect of target size ($F_{3,42} = 16.61$, $p < 0.0001$), consistent with Experiment 1 and previous studies [3,42]. Children still had a harder time touching the smallest targets (76% [15%]) than the largest targets (52% [19%]), even though they were physically larger than the tablet targets. There was no significant effect of age group ($F_{1,14} = 0.14$, *n.s.*).

Edge Padding. We also examined edge padding [3] which is, as in Experiment 1, a small buffer between a target and the edge of the screen. We ran a two-way repeated measures ANOVA on *miss rate* with a within-subjects factor of *edge padding* and a between-subjects factor of *age group* (6-7, 8-10). We found no significant effect of edge padding ($F_{1,14} = 0.12$, *n.s.*) or age group ($F_{1,14} = 0.09$, *n.s.*), and no interaction between them ($F_{1,14} = 0.20$, *n.s.*). The miss rate for targets with edge padding (63% [14%]), and targets without edge padding (62% [18%]) were very similar. This finding is unlike previous studies [3,42], in which the miss rate doubled on targets with edge padding, but it is similar to our results from Experiment 1. As in Experiment 1, causes might include the different physical size of the buffer, platform specific behaviors for near-edge touches, or bezel width differences.

Location. We examined the effect of vertical and horizontal location of the targets on the participants' performance. We ran a two-way repeated measures ANOVA on *miss rate* with a within-subjects factor of *vertical region* (top, center, bottom) and a between-subjects factor of *age group* (6-7, 8-10). We found no significant effect of vertical region ($F_{2,28} = 1.79$, *n.s.*) or age group ($F_{1,14} = 0.07$, *n.s.*), and no interaction ($F_{2,28} = 1.10$, *n.s.*). We ran the same test for *horizontal region* (left, center, right), and found no significant effect of horizontal region ($F_{2,28} = 2.27$, *n.s.*) or age group ($F_{1,14} = 0.11$, *n.s.*), as well as no interaction effect ($F_{2,28} = 0.27$, *n.s.*). These findings are contrary to our results from Experiment 1 and previous studies [42], in which there was a significant effect of vertical and horizontal region (participants missed more on the top of the screen than the center or bottom, and on the left-hand side of the screen than the center or right). We believe that the location of the target did not affect miss rate here because the users were able to move freely around the tabletop. Indeed, we frequently observed participants moving around the tabletop in order to better access targets.

Response Time. We calculated response time by the same method as in Experiment 1. Like previous studies [3,42], we excluded holdovers, and only considered first attempt touch events. We ran a two-way repeated measures ANOVA on *response time* with a within-subjects factor of *target size* (0.4 *in*, 0.6 *in*, 0.8 *in*, 1 *in*) and a between-subjects factor of *age group* (6-7, 8-10). We found a significant effect of target size ($F_{3,42} = 4.82$, $p < 0.01$) and a marginal effect of age group ($F_{1,14} = 4.43$, $p = 0.05$). Children have slower response times when touching the smallest targets (1445 ms [692 ms]) than the largest targets (1097 ms [436 ms]), and younger children also have slower response times than older children (6-7: 1593 ms [687 ms]; 8-10: 1063 ms [390 ms]). These findings are consistent with Experiment 1 and previous studies [42]. Children take longer to acquire smaller targets, and younger children have slower response times, since their fine motor performance is less efficient than in older children [17]. There was no interaction between target size and age group ($F_{3,42} = 0.34$, *n.s.*) unlike Experiment 1 and previous work [3,38], possibly because the base size of the smallest targets (0.4 *in*) was similar to the largest size in Experiment 1 and previous studies (0.5 *in*) [3,42]. Therefore, the targets were large enough that the younger children did not have even slower response times than older children on smaller targets. Even though there was no interaction effect, there was still an effect of target size, and children were slower with the smaller targets (<0.7 *in*). This finding confirms the platform-recommendations of 0.7 *in* are a reasonable target.

5.2.2 Gesture Results. We used the same recognition algorithm and setup parameters as in Experiment 1.

User-Dependent Recognition Experiments. A one-way ANOVA on *accuracy* with a between-subjects factor of *age* (6, 7, 8, 9, 10) showed no significant effect of age on recognition accuracy ($F_{4,13} = 1.35$, *n.s.*). As in Experiment 1, accuracy was lowest for the youngest children (in this case, 6 year-olds; 63.65% [19.09%]) and increased for older children, with the highest accuracy for 10 year-olds (93.74% [5.09%]), as shown in Fig. 4. The high variance in the 6- and 7-year-olds' data could explain why the result is not significant. Additionally, Experiment 2 did not include 5-year-olds, unlike Experiment 1 and prior work that have both shown a significant effect of age on accuracy [3,42].

User-Independent Recognition Experiments. The ages of the participants in Experiment 2 ranged from 6 to 10, so we used different age groupings in the user-independent case here than in Experiment 1: 6- to 7-year-olds (8 participants) and 8- to 10-year-olds (10 participants). In the case of user-independent recognition, accuracy was lower for the 6- to 7-year-olds (67.63% [13.05%]) than the 8- to 10-year olds (76.45% [11.08%]). However, a one-way

ANOVA showed no significant effect of age on accuracy ($F_{1,16}$ = 2.411, *n.s.*). As in the user-dependent case, this is in contrast to previous work, which showed a significant effect of age on accuracy [3,42]. However, we see the same trend that the youngest children's accuracy had high variance.

5.2.3 Summary. For the tabletop target task, we replicated analyses from previous studies [3,4,42] and Experiment 1. Response time, per-user misses, and edge padding were all consistent with findings from Experiment 1. However, results for holdovers and location were different due to the tabletop's sensitivity and the users' ability to move freely around it. In the gesture task, there was no effect of age on accuracy, which could be because there were no 5-year-olds as in the other studies.

6 DISCUSSION

We first summarize the replications, contradictions, and new findings between our results from Experiments 1 and 2 and previous studies [3,42]. We then discuss limitations of the tabletop and the implications of our results with respect to the design of touchscreen interfaces for children.

6.1 Replications, Contradictions, New Results

For target interactions, we found holdovers to be the highest on tablets (9.9%) and lowest on tabletops (2.9%). We also found a significant effect of target size on per-user miss rate on all devices. Children missed fewer targets on smartphones (23%) [42] than on tablets (41%) and tabletops (62%). However, we found that, while previous work on smartphones showed the miss rate for targets with edge padding (31%) was almost double that of targets without edge padding (17%) [42], the miss rate for targets with and without edge padding was the same in our studies on tablets and tabletops. We also found a significant effect of vertical and horizontal region on target miss rate on tablets but not for the tabletop, while prior work using smartphones also found a significant effect of vertical and horizontal location [3,42]. We found a significant effect of target size and age group for response time on tablets and tabletops, consistent with previous work on smartphones [3,42]. The results for the metrics per-user misses, response time, and edge padding were similar between our two experiments. In Experiment 1, children had similar interaction patterns when touching targets using pen versus touch. In terms of accuracy when touching targets, children performed worse when using the touch modality compared to digital pens. However, children had faster response times when using touch than when using pens, illustrating a speed-accuracy tradeoff: response time was faster but accuracy was lower for touch, and vice versa for pen.

For gesturing, as with previous work on phones, we found a significant effect of age group on user-dependent and user-independent recognition on tablets [2,3,42]. However, we found no effect of age group on either test for the tabletop, which we attribute to the lack of 5-year-olds in that study. To verify this hypothesis, we performed a post-hoc test with Bonferroni correction on the results from Experiment 1 and found the only significant pairs included 5-year-olds, implying that future work should focus on younger children's recognition. Children have similar gesturing abilities using touch and pen on tablets, as recognition rates are remarkably similar between the various modalities. This similarity in accuracy rates also indicates $P [36] performs equally well for pen input, in contrast to its predecessor $N [6], which had higher recognition for touch than stylus on adults' gestures. To determine whether the significance was due to the recognition algorithm or due to the difference in age, we also ran a repeated-measures ANOVA on *accuracy* using $N with a within-subjects factor of *input modality* (pen vs. touch) and found no significant effect of modality ($F_{1,14}$ = 0.015, *n.s.*). Thus, we conclude that significance found in the prior study was due to the use of adults' gestures rather than the recognition algorithm. Children's pen and touch gestures are recognized with similar accuracy, unlike those of adults.

6.2 Limitations of the Tabletop Platform

We observed that the tabletop had increased touch sensitivity compared to the tablet, due to the hardware of the device. Unlike the tablet's resistive screen, the hardware of the tabletop uses PixelSense Technology, a touchscreen technology in which infrared sensors are placed across the screen and each pixel acts as a camera [40]. Thus, it can detect the user's hand hovering over the table's surface as well as unintentional multi-contact touches such as the user's wrist. There is no programmatic way to separate the "real" and non-contact events. The sensitivity of the tabletop increased the total amount of touches in our tabletop dataset compared to the other studies. To determine the impact of this hardware limitation, and to see if the hovering behavior was child-specific, we conducted a pilot study with 8 adults (M = 26.38 years, [SD = 6.21]) from our university, with the target task from Experiment 2. Five participants were female. In the adult pilot data and the children's data from Experiment 2, we saw a similar pattern of hovers and unintentional touches (e.g., events with the exact same timestamp or very minimal time differences). To isolate the effect of these events within our data, we next identified a time-based threshold to use.

We tested the tabletop to determine how fast a user could reasonably generate two consecutive touch events by asking 10 (new) adults (M = 24.00 years, [SD = 1.6]) to touch the tabletop as fast as possible. Because this data was itself subject to hovers and unintentional touches, we used three different criteria to filter them out, based on whether two or more consecutive touch events: (1) had the exact same timestamp; (2) had a time difference below the tabletop hardware's sampling rate of 60 Hz (16.7 ms); or (3) had a time difference two standard deviations above or below the participant's own average. Then, to compute a threshold, we used the average of the minimum time difference across participants. Our threshold value is 57 ms [SD = 28 ms].

Looking at our tabletop data, 40% of the children's data (2,433 out of 6,097 touch attempts) and 37% of adults' (pilot) data (709 out of 1,940 touch attempts) were below this threshold. These values estimate the frequency of hovers and unintentional touches being registered by the tabletop. Recall that we found the average miss rate for children (62%) and adults (pilot) (30%) on the tabletop was higher than previous studies [3,42] (*e.g.*, 23% for children and 17% for adults [38]) and Experiment 1 (41% for children). To understand the impact of hovers and unintentional touches on the miss rate and holdover rate (2.9%), we removed all touch events below the 57 ms threshold. The new calculation showed 3.5% were holdovers, which is similar to previous work (3.9%) [2], and the average miss rate decreased (55% [16%]). Taken together, these results illustrate that hovers and unintentional touch issues are real-world challenges on the tabletop and are not specific to children (*e.g.*, rates are the same).

6.3 Design Implications

Our studies show several key differences in how children interact with tablets and tabletops, compared to prior work on smartphones, and in children's use of pen versus touch input. We present a set of design recommendations based on our results to help designers of touchscreen applications for children create interfaces better tailored to their interaction patterns.

Account for children's tendency to drag pens while touching targets. In Experiment 1 (tablet study), we found that the participants often dragged the input device between when the target was first touched and when the input device was lifted, even though the target was not moving. This effect was particularly pronounced when the participants used pen input. Previous work has shown that this behavior is common in 4-year-old children in the mouse modality, who often slip the mouse slightly before releasing the mouse button [21]; others have shown this behavior in older children (ages 7 to 10) in touch as well [24,37]. Our findings show that children have greater control when activating targets using the touch modality. Thus, we recommend that developers plan to accept a degree of input drag in touch events, particularly when a pen is used.

For all devices, favor placing widgets closer to the child. The children in Experiment 1 (and in previous studies on smartphones [3,42]) had much more difficulty with targets at the top of the screen, which were farther to reach, than the bottom. In Experiment 2, children tended to walk around the tabletop when targets were far away, making it easier for them to touch the targets. Thus, we recommend placing widgets closer to where the child can easily reach, taking into account the way the device will be held or how they will be oriented to it.

For the tabletop, space widgets farther apart for both children and adults. Due to the sensitivity of the tabletop we used, we observed a high proportion of hovers and unintentional touches. The device detected these events as intentional touch events, leading to a higher average miss rate. By conducting the adult pilot study, we observed that this behavior is not specific to children. We recommend spacing widgets farther apart to reduce the effect of hovers and unintentional touches on the tabletop. Some methods that can be used to check if a touch is intentional are to examine if the time of event is equal to recent touches (unintentional or multi-touch contact), and to ignore any touch events that are faster than the sampling rate of the device.

Collect gesture data on whichever device is most convenient for the youngest children. In both our experiments, and prior work [3,42], we see similar rates of gesture recognition for children despite the changes in screen size. This finding implies that gesture data need not be collected on the device on which the recognition will take place. It may be convenient, for example, to collect gestures for a tabletop application using a smartphone, due to the difficulty of transporting the tabletop. We ran a paired-samples t-test by age group (5-7, 8-10) between training/testing on the same tablet dataset, versus training on phone gestures and testing on tablet gestures. We found no significant difference for 5- to 7-year-olds ($t(5) = -0.623$, *n.s.*), but there was for 8- to 10-year-olds ($t(5) = -7.472$, $p < 0.05$). For older children, platform-specific gestures may be necessary; but for younger children, this strategy can work.

6.4 Limitations and Future Work

The tasks for both Experiment 1 and 2 were completed in a laboratory setting. Future work could examine other use cases, such as using the tablet while walking, or using the tabletop in an applied setting. Also, in Experiment 1, we used the same size targets as previous work on phone touchscreen interaction [42] despite the larger screen size. In Experiment 2, we did increase the target sizes to compare interactions with larger targets, but the sensitivity of the tabletop caused its own challenges. Finally, the way we handled edge padding could be viewed as a limitation. We used the same size (10px) as in previous studies for smartphones [3,42], since the size appeared to be visible enough on the tablet and the tabletop. In our studies, no impact of edge padding was present. Decreasing the size of the padding may be informative to identify the cut-off point for when it affects miss rate.

7 CONCLUSION

We presented two empirical studies on children's touchscreen interactions: one of 13 children using a tablet device with touch and pen, and one of 18 children on a tabletop device. In our tablet study, we found several differences in children's performance of the tasks based on input modality, such as response time. In our tabletop study, the larger screen caused a change in the effect of target location compared to the tablet study. We found gesture recognition accuracy was similar across platforms. Based on our studies, we provide guidelines that developers can use to improve children's interaction experiences on various touchscreen devices.

ACKNOWLEDGMENTS

This work is partially supported by National Science Foundation Grant Awards #IIS-1218395 / IIS-1433228 and IIS-1552598. Opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect these agencies' views. We thank Wacom for providing us the Wacom Cintiq Companion Hybrid tablets.

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