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# Physical Dimensions of Children's Touchscreen Interactions: Lessons from Five Years of Study on the MTAGIC Project

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## Abstract

Touchscreen interaction is nearly ubiquitous in today's computing environments. Children have always been a special population of users for new interaction technology: significantly different from adults in their needs, expectations, and abilities, but rarely tailored to in new contexts and on new platforms. Studies of children's touchscreen interaction have been conducted that focus on individual variables that may affect the interaction, but as yet no synthesis of studies replicating similar methodologies in different contexts has been presented. This paper reports the results across five years of focused study in one project aiming to characterize the differences between children's and adults' physical touchscreen interaction behaviors. Six studies were conducted with over 180 people (116 children) to understand how children touch targets and make onscreen gestures. A set of design recommendations that summarizes the findings across the six studies is presented for reference. This paper makes the entire set available for reference in one place and highlights where the findings are generalizable across platforms. These recommendations can inform the design of future touchscreen interfaces for children based on their physical capabilities. Also, this paper outlines the future challenges and open questions that remain for understanding child-computer interaction on touchscreens.

## Keywords

Child-computer interaction; touchscreen; gesture interaction; gesture recognition; MTAGIC.

## Highlights

- Five years of study examining children's touchscreen interactions compared to adults'.
- Data has been collected from over 180 people (60 adults, 120 children).
- Results focus on findings that are robust to screen size and touchscreen platform.
- The set of cumulative design recommendations captures in one place an easy reference for future design.
- Open questions in the design of touch-based interactions for children on future platforms.

## 1 Introduction

Over the past decade, there has been an undeniable revolution in the way we interact with computers. Touchscreen devices exploded into the mainstream with the release of the Apple iPhone in 2007[2]. A recent market survey indicates that there were 1.86 billion smartphone users worldwide by 2015, forecast to reach nearly 3 billion by 2019 (Statista, 2018b). Smartphones and tablets are now an integral part of life in the 21st century, in some cases becoming the primary means end users are interacting with computing devices in their daily lives.

Though designed for adults, mobile devices are commonly used by children who either own their own device or have access to one; for example, a 2017 Common Sense Media survey found that 98% of children in the United States ages 0 to 8 live in a home with at least one mobile device (Common Sense Media, 2017). In addition, mobile devices are now the most popular gaming device for children in the United States, ages 2 to 17 (Statista, 2018a). Children are using touchscreen devices in a variety of contexts, including in the home, in their classrooms, and out

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in the world. A significant body of work in child-computer interaction has established that children have unique needs, expectations, and abilities when it comes to technology interfaces (for a review, see (Hourcade, 2007)), given the changes in children's motor skills and cognitive capabilities as they grow and develop (Erhardt, 1994; Feder & Majnemer, 2007; Gesell, Ilg, Ames, & Bullis, 1946; Piaget, 1983; Rosenbloom & Horton, 1971; Santrock, 2006; Thomas, 1980). For example, early work on children interacting with computers through a standard mouse and keyboard set-up found that drag-and-drop interactions were too difficult for most young children (Inkpen, 2001; Joiner, Messer, Light, & Littleton, 1998), and that children have more difficulty acquiring targets in terms of both speed and accuracy than do adults (Hourcade, Bederson, Druin, & Guimbretière, 2004).

Children's development also affects their interactions with touchscreen interfaces. Researchers in child-computer interaction have examined the limitations of current interfaces through empirical studies with children in order to recommend better design choices for children on these devices (Abdul Aziz, 2013; Abdul Aziz, Batmaz, Stone, & Chung, 2013; Arif & Sylla, 2013; Hamza & Salivia, 2015; Hiniker et al., 2016, 2015; Hourcade, Perry, & Sharma, 2008; Ibharim, Borhan, & Yatim, 2013; McKnight & Cassidy, 2010; McKnight & Fitton, 2010; Nacher, Jaen, Navarro, Catala, & González, 2015; Vatavu, Cramariuc, & Schipor, 2015). Such studies often focus on a single variable or interaction task, which makes replication or general synthesis across the studies difficult. In contrast, our five-year project's past work on understanding how children's physical (motor) capabilities affect their interactions on touchscreens has contributed evidence-based design recommendations for this context, in a series of studies using similar methodologies and interaction tasks that enables a broader synthesis across contexts (Anthony, Brown, Nias, & Tate, 2013; Anthony, Brown, Nias, Tate, & Mohan, 2012; Anthony et al., 2014; Brewer et al., 2013; Rust, Malu, Anthony, & Findlater, 2014; Woodward et al., 2017, 2016).

In this paper, we synthesize and report the cumulative results of this five-year project to explore the space of children's touchscreen interactions from an interaction efficacy perspective (Anthony, Brown, et al., 2013, 2012; Anthony et al., 2014; Woodward et al., 2017, 2016). This perspective emphasizes enabling children to experience successful interactions with touchscreen technology, in which their intended interaction is correctly recognized and carried out by the system. We make the assumption that successful interaction will improve children's ability to obtain the targeted benefits of apps developed with these recommendations in mind, for example, growth and development-based learning apps. We conducted empirical user studies with 60 adults and 116 children and collected over 55,000 touch events and 35,000 gestures to study the differences and similarities in their behaviors. As a result of these studies, we developed recommendations for other researchers and especially mobile application developers and interaction designers to use in their professional practice of designing for children. This paper contributes a cumulative look at the common themes, the differences between platforms and contexts, and the complete body of design recommendations we produced throughout this project. This paper will serve as a comprehensive reference for the design of future touchscreen interfaces for children with respect to physical (motor) adaptations as identified by the Mobile Touch and Gesture Interaction for Children (MTAGIC) project.

## 2 Project Studies and Methods

Over the course of five years, we conducted a series of five empirical studies with children. Our initial studies were broad in our target age range (ages 5 to 17) (Anthony, Brown, et al., 2013, 2012; Anthony et al., 2014), but as we identified patterns by age group in these studies, children who were closer to the teen years exhibited interaction behaviors that looked more like adults than their younger counterparts. Therefore, later studies focused on the age range of 5 to 10 years old (Brewer et al., 2013; Woodward et al., 2017, 2016).

The first study conducted was designed to compare between adults (ages 18 and up) and children (ages 7 to 16) using touch and gesture interaction on smartphones in simple apps focusing on isolated interactions (Anthony, Brown, et al., 2012). We conducted several follow-up studies on smartphones to explore different factors that might affect interaction, including how important it is for children to receive visual feedback as they created their gestures (Anthony, Brown, et al., 2013; Anthony et al., 2014). The next major study involved the use of an app that used contextualized interactions to determine how well our previous findings would hold in a more realistic interaction scenario (Woodward et al., 2016). Follow-up studies tested how well our previous findings on small-screen smartphones would extend to larger screen devices such as tablets and tabletop computers (Woodward et al., 2017). Table 1 summarizes the design of each study, along with the data we collected and the hardware we used.

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| Study | Hardware (screen size and display resolution) | No. of Participants (age range in parentheses) | | Conditions | Touch Events | Gestures |
|---|---|---|---|---|---|---|
| | | **Children** | **Adults** | | | |
| **Abstract Interface Smartphone Study** (Anthony, Brown, et al., 2012; Anthony et al., 2014) | Google Nexus S (4.4 in, 480x800) | 16 (7 to 16) | 14 (18 to 29) | Touch, Gesture | 4,650 | 3,600 |
| **Visual Feedback Smartphone Study** (Anthony, Brown, et al., 2013; Anthony et al., 2014) | Google Nexus S (4.4 in, 480x800) | 25 (10 to 17) | 16 (20 to 33) | Feedback, No Feedback (Gesture) | 5,921 | 9,840 |
| **Gamification Study** (Brewer et al., 2013) | Google Nexus S (4.4 in, 480x800) | 14 (5 to 7) | None | Original, Gamified (Touch, Gesture) | 7,351 | 2,022 |
| **Interface Complexity Smartphone Study** (Woodward et al., 2016) | Google Nexus S (4.4 in, 480x800) | 30 (5 to 10) | 30 (17 to 33) | Abstract, Complex (Touch, Gesture) | 18,892 | 14,400 |
| **Tablet Study** (Woodward et al., 2017) | Wacom Cintiq Companion Hybrid (13.3 in, 1080x1920) | 13 (5 to 10) | None | Pen, Touch (Touch, Gesture) | 10,438 | 3,120 |
| **Tabletop Study** (Woodward et al., 2017) | Samsung SUR40 (40 in, 1920x1080) | 18 (6 to 10) | None | Touch, Gesture | 8,529 | 2,160 |
| | ***Total:*** | **116 (5 to 17)** | **60 (18 to 33)** | | **55,781** | **35,142** |

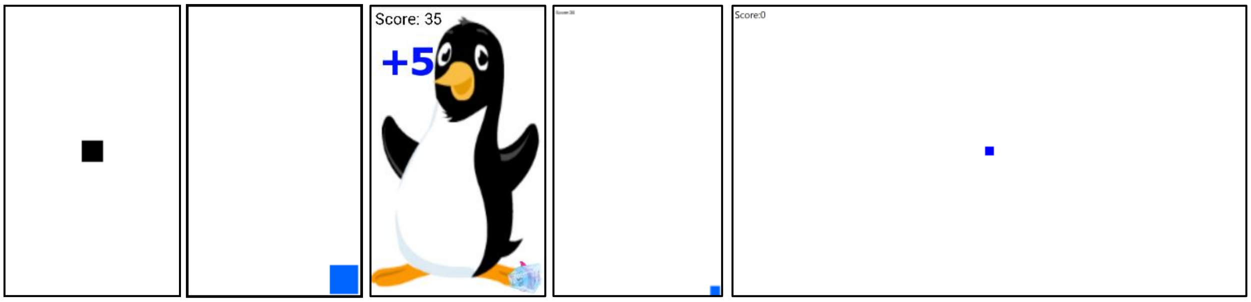
Table 1. Summary of our empirical studies with children on touchscreen devices over five years.

In each of our studies, we used variations of the same basic data collection tasks. We describe their overall structure, plus specific important variations next. Both tasks were designed to elicit natural touchscreen interaction behaviors from children, and were inspired by the types of low-level atomic interactions expected on touchscreens, that is, tapping and gesturing. The original task designs were based on a survey of 23 touchscreen apps popular at the time (Anthony, Brown, et al., 2012).

## 2.1 Target Touching Task.

To collect examples of how children would touch targets (i.e., interface widgets) on touchscreens, we designed the Target Touching Task. This task consisted of a set number (usually 103) of onscreen targets that would appear one at a time. Children would touch the target, and as soon as the device registered a touch within the bounds of the current target, it would display the next target, similar to a classic psychology stimulus-response set-up. The task was designed to include a variety of target sizes and locations, similar to the layout of onscreen widgets in touchscreen apps; the targets near the screen edges could also be laid out flush to the screen edge or with a subtle buffer, or *edge padding*, between the edge and the target.

The targets appeared in the same locations and in the same order for every participant, but were balanced across locations on the screen and sizes. We typically used four target sizes (“very small,” “small,” “medium,” and “large”), and the actual physical sizes of these targets varied based on the platform used for the study. All target sizes were centered around the platform-recommended sizes, with some larger and some smaller sizes selected to understand the limitations of children’s target acquisition abilities. Figure 1 shows a series of screenshots of these



**Abstract Smartphone Study** (black squares) (Anthony, Brown, et al., 2012)

**Visual Feedback Smartphone Study** (blue squares) (Anthony et al., 2014)

**Interface Complexity Study** (melting fish) (Woodward et al., 2016)

**Tablet Study** (blue squares, larger screen) (Woodward et al., 2017)

**Tabletop Study** (blue squares, larger screen, larger physical targets) (Woodward et al., 2017)

Figure 1. Screenshots of the apps used for the Target Touching Task across our studies.

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targets from some of our studies. In one condition of the Interface Complexity Study, the targets were designed to be more realistic: they were small fish trapped in ice cubes that the children had to “melt” to activate the target and move on.

In all studies, the participants completed the Target Touching Task using touch directly with their fingers. In the Tablet Study, children also used a stylus in a second condition to complete the same task, due to the prevalence of stylus use on this platform compared to the others (Woodward et al., 2017).

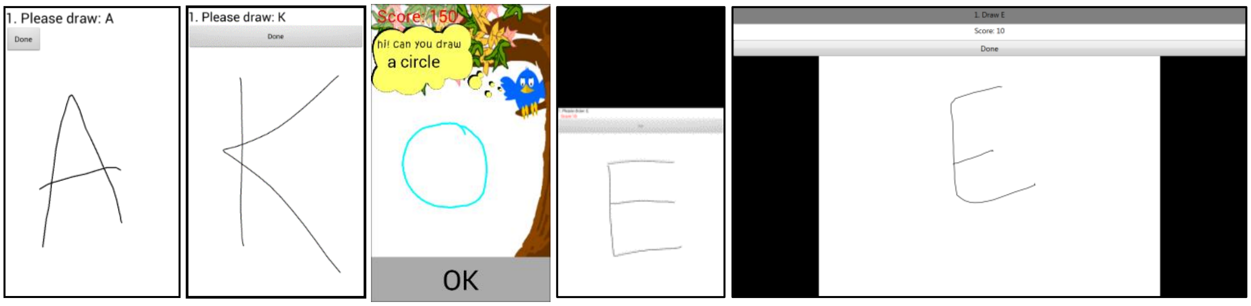
### 2.2 Gesture Execution Task.

To collect examples of how children would make gestures on touchscreens, we designed the Gesture Execution Task. This task prompted children to enter examples of a set of 20 gestures, chosen based on an initial survey we conducted of gestures used in mobile apps and the child development literature (Anthony, Brown, et al., 2012; Beery, Buktenica, & Beery, 2004). We opted to focus on execution of shape-based gestures such as letters, numbers, shapes, and symbols, rather than more abstract gestures like swipe and pinch for two reasons. One is that existing children’s apps often use these types of gestures as part of an educational experience to “teach” the children these gestures, and as such, it is important to understand how children actually produce these gestures to ensure the app can successfully recognize them. The second reason is that prior literature has already showed children have difficulty with complex multi-touch gestures like rotate and pinch (Abdul Aziz et al., 2013; Hamza & Salivia, 2015; Nacher et al., 2015). Figure 2 shows the set of gestures included in the task in all of our studies.

Figure 2. Gesture set of 20 letters, numbers, symbols, and shapes we used in all of our studies to elicit examples of children’s gesture interactions in the Gesture Execution Task.

Figure 3 shows a series of screenshots of the Gesture Execution Task from some of our studies. In one condition of the Interface Complexity Study, the experience was designed to be more realistic: an animated background was used with a little bird who prompted the children for what to produce.

In all studies, the participants completed the Gesture Execution Task using touch directly with their fingers. In the Tablet Study, children also used a stylus in a second condition to complete the same task, due to the prevalence of stylus use on this platform compared to the others (Woodward et al., 2017).



**Abstract Smartphone Study** (plain canvas) (Anthony, Brown, et al., 2012)

**Visual Feedback Smartphone Study** (feedback trace shown or not) (Anthony et al., 2014)

**Interface Complexity Study** (animated background) (Woodward et al., 2016)

**Tabletop Study** (plain canvas, larger screen, inactive areas) (Woodward et al., 2017)

**Tablet Study** (plain canvas, larger screen, inactive areas) (Woodward et al., 2017)

Figure 3. Screenshots of the apps used for the Gesture Execution Task across our studies.

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### 2.3 Gamification.

As part of this work, we also innovated regarding the challenges of collecting large empirical datasets from young children. We have collected over 48,000 touch events and 33,000 gestures from children and adults in this work in laboratory studies. In our early studies, the youngest children (ages 5 to 7 years) experienced attentional fatigue during the studies and so we explored the addition of gamification (Brewer et al., 2013). We added "points" to the empirical data collection applications and awarded children small prizes for finishing "levels" in the experiment. These additions helped improve completion rates of children in the study (on average per child from 73% to 97%), and did not affect the quality of the collected data (Brewer et al., 2013). We continued to use this paradigm in all of our remaining studies (Woodward et al., 2017, 2016).

### 2.4 Hardware.

In all of the smartphone studies (Abstract Interface Smartphone Study, Visual Feedback Smartphone Study, Gamification Study, and Interface Complexity Smartphone Study), we used the same make and model of smartphone, the Google Nexus S, a top of line model available at the time. The smartphone was running the Android 4.0.4 operating system at the time, and measured 4.88 x 2.48 x 0.43 inches (123.9 x 63 x 10.9 mm) with a 4-inch (101.6-mm) diagonal screen. The display resolution was 480 x 800 pixels, with a pixel density of approximately 233 pixels per inch (ppi). For the Tablet Study, we used 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. For the Tabletop Study, we used a Samsung SUR40 with 4GB RAM. The resolution was 1920 x 1080 (55 DPI), and the display size was 40 inches, measured diagonally.

## 3 Cumulative Results and Findings

In deriving this synthesis, the author considered the six studies and what findings have been consistently replicated across all of them, thus lending strength to the empirical results. Here we present the three findings that have been the most consistently observed across the six studies, and especially those that are robust to differences in screen size or context: (1) unintended touches, i.e., holdovers; (2) targeting inaccuracies; and (3) gesture execution inconsistencies. Given that our tasks were inspired by real-world touchscreen app interfaces, it is likely that these same interaction behaviors will occur during children's real-world use of touchscreen interfaces. Thus, we believe these findings are the most important to remember and support in order to enable more successful interactions with touchscreen technology for children.

### 3.1 Unintended Touches (or Holdovers).

Most users who have interacted with touchscreen devices at one time or other have experienced an inconvenient consequence of the device registering a touch that was unintentional (e.g., (Annett, 2017; Annett, Gupta, & Bischof, 2014)). The idea of separating out intended input from unintended input is known as the "segmentation problem," and is a challenge that is present in most recognition-based modalities (e.g., (Mitra & Acharya, 2007; Weinland, Ronfard, & Boyer, 2011; Yilmaz, Javed, & Shah, 2006)). The device must be able to distinguish when the user's action is intended as input or not. Unintended touches on touchscreens can occur due to holding the device in one hand while trying to interact with it (in the case of mobile screen sizes like smartphones), or other fingers or hands being registered if they get to close to the screen (in the case of larger screens like tabletops). Unintended touches have been established as a larger problem for children, who are less dexterous than adults, in prior work (Abdul Aziz, 2013; McKnight & Cassidy, 2010; McKnight & Fitton, 2010; Valderrama Bahamóndez, Kubitza, Henze, & Schmidt, 2013; Vatavu, Cramariuc, et al., 2015).

In our project, we have seen that a reliable subset of touch event data can be classified as "unintentional" in some way. In our early studies on smartphones, we saw children (and adults) would tend to generate a few more touch events intended for the current onscreen target, even after the target hit had been accepted and the screen updated (Anthony, Brown, et al., 2012; Anthony et al., 2014; Woodward et al., 2017, 2016). We termed these occurrences "*holdovers*," meaning they were held over from the previous target. This type of occurrence could easily happen on real mobile devices; for example, if a user selects an onscreen widget that takes a second to process, they may hit it again and accidentally undo their selection. Figure 4 shows the distribution of touch events between two adjacent targets (black outlines), in which there is a noticeable number of holdovers on the left-hand side of the screen. Holdovers are experienced by users of all ages, but are most prevalent among the youngest users and for very small onscreen targets (Anthony, Brown, et al., 2012; Anthony et al., 2014).

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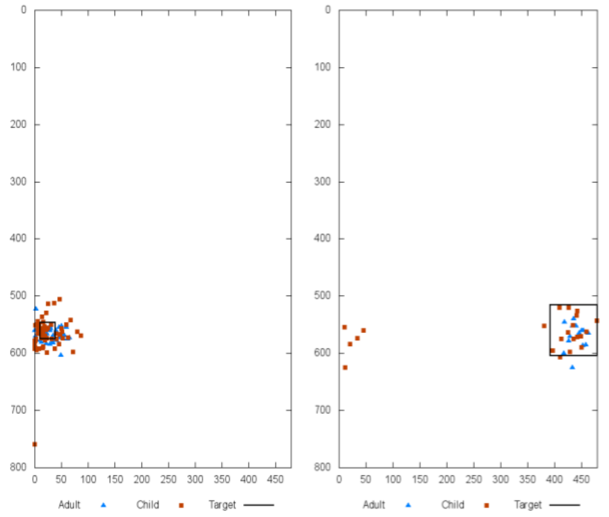

(a) (b)

Figure 4. Holdover patterns exhibited from the target shown in (a) in the black outline on the left, to the target shown in (b) in the black outline on the right. Touches are still generated by some children in the location of target (a) after the screen has updated. Blue triangles are adults' data and red squares are children's data. (Anthony, Brown, et al., 2012).

In general, holdovers are not a high percentage of the touch events that were registered. However, they occurred on nearly every target, and with nearly every user, across all of our studies. Children tended to exhibit holdovers as a behavior more often than did adults (Anthony, Brown, et al., 2012). As a percentage of the total number of touch events collected during each study, holdover prevalence ranged from about 3% on tabletops (Woodward et al., 2017) to approximately 4% on smartphones (Anthony et al., 2014; Woodward et al., 2016), to nearly 10% on tablets (Woodward et al., 2017). Unlike in our studies, in real apps, onscreen widgets typically stay in the same place instead of appearing and disappearing. Therefore, we expect this phenomenon to potentially result in unintended interactions as widgets are activated and then de-activated before the child realizes. We suggested methods in our papers to filter and ignore holdover touches (Anthony, Brown, et al., 2012; Anthony et al., 2014; Woodward et al., 2016), that could be applied to the intelligence behind real app interfaces. For example, by disregarding touches that occur within a short time threshold of previous touches, a software system could avoid erroneously responding to most holdovers automatically. We suggested the exact threshold should be tweaked to identify a reasonable trade-off between maximizing true positives and minimizing false positives.

In a later study on tabletop devices, we again saw interference from unintended touches, but this time it was due to the differences in the touchscreen technology registering activity very close to the screen as being an actual contact with the screen (Woodward et al., 2017). We termed these occurrences "*hovers*," as users had a tendency to hover their hand near the screen to prepare to touch the next onscreen target, but this behavior generated a large amount of "noisy" data in our touch event samples. These non-contact events would be impossible to distinguish programmatically from "real" contact events based on the sensor data. We developed a heuristic to filter out unintentional touches caused by this issue (Woodward et al., 2017): when two subsequent touch events have (1) the exact same timestamp; (2) a time difference below the hardware's touchscreen sampling rate; or (3) a time difference two standard deviations above or below the user's recent average. We also suggested designing tabletop interfaces a little differently to make it easier to separate the touches, for example, by spacing out the widgets farther from each other (Woodward et al., 2017).

We developed four design recommendations that would help decrease the impact of unintentional touches, or holdovers, on a child's touchscreen interaction experience:

- Use timing and location of touches and interface widgets to identify and ignore holdover touches (corollary: improve interface responsiveness to prevent holdovers) (Anthony, Brown, et al., 2012; Anthony et al., 2014).
- Use consistent, platform-recommended target sizes (Anthony, Brown, et al., 2012; Anthony et al., 2014).
- Provide salient visual feedback of accepted input to prevent holdovers (Woodward et al., 2016).
- For the tabletop, space widgets farther apart for both children and adults (Woodward et al., 2017).

### 3.2 Targeting Inaccuracies.

One of the main results from our studies is to verify and quantify the degree to which children are less accurate at acquiring onscreen targets than adults are (Anthony, Brown, et al., 2012; Anthony et al., 2014; Woodward et al., 2016). We showed that children are consistently less accurate across target sizes, but also that children are especially inaccurate on the smallest targets (Anthony, Brown, et al., 2012; Anthony et al., 2014; Woodward et al., 2017, 2016). This result may seem surprising, given the fact that children have smaller fingers and might be expected to be less susceptible to the "fat finger" problem identified in prior work on mobile touchscreen interfaces (Baudisch & Chu, 2009; Siek, Rogers, & Connelly, 2005). However, these results indicate that motor dexterity is the dominant factor and prevents children from being able to exert the fine-grained precision needed when targets are too small. Because of these targeting inaccuracies, children may be more likely to experience unintended touches, described in the previous section, when their touches may be registered as being intended for another widget onscreen, or non-responsiveness from the application when their touches are not registered for any specific onscreen widget at all.

We have investigated the factors that affect these targeting inaccuracies. Detailed numerical results are shown in Appendix B; graphs are provided here for readability. The main factor we investigated was target size, as mentioned. In our studies, we selected the physical target sizes to be centered around the recommended platform sizes, plus some that were larger and some that were smaller. In our smartphone studies, the target sizes were 0.5" (large), 0.375" (medium), 0.25" (small), and 0.125" (very small) (Anthony, Brown, et al., 2012; Anthony et al., 2014; Woodward et al., 2016); in our tablet study, they were the same physical size (Woodward et al., 2017); and in our tabletop study, we enlarged the targets to 1.0" (large), 0.8" (medium), 0.6" (small), and 0.4" (very small) (Woodward et al., 2017). In all cases, there was a consistent increase in accuracy, measured as the number of targets acquired successfully on the first attempt, as size of the target increased. Figure 5 shows the average miss rate across all studies for adults and children by target size, as well as the overall average. Since we only included adults in the first two studies the graph on the left has fewer bars. If an overall average is not shown, it is the same as the previous study. In general, we found that children (and adults) are highly consistent in their miss patterns on smartphones. When children used larger screen devices like tablets and tabletops, their miss rates increased considerably. Some of this effect could be due to relative screen sizes being larger compared to the targets; and certainly some of it is due to the noisy unintentional touches mentioned in the previous section.

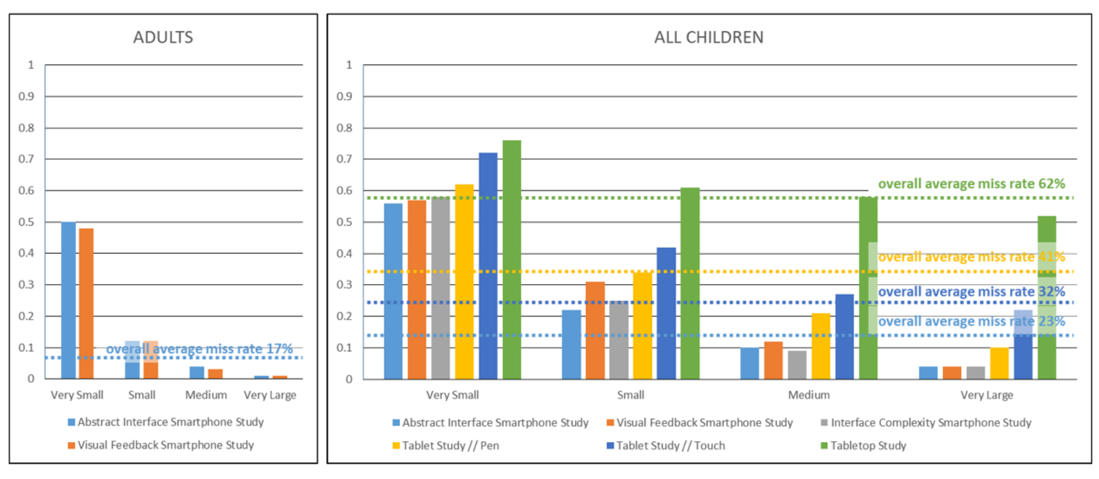

Figure 5. Miss rate by target size from very small to very large for adults (left) and all children together (right) in each study (different colored bars, from left to right in order: Abstract Interface Smartphone Study, Visual Feedback Smartphone Study, Interface Complexity Smartphone Study, Tablet Study: Pen Modality, Tablet Study: Touch Modality, and Tabletop Study). The overall average miss rate per study is overlaid on the graph. Children miss more often than adults, and have more trouble with smaller targets. The Tabletop Study showed high miss rates across all target sizes.

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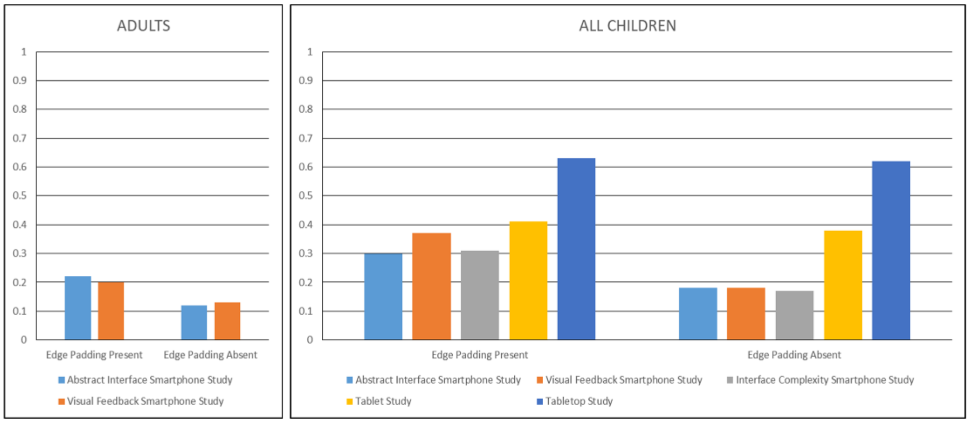

Figure 6. Miss rates by presence or absence of edge padding on interface widgets near the edge of the screen for adults (left) and all children together (right) in each study (different colored bars, from left to right in order: Abstract Interface Smartphone Study, Visual Feedback Smartphone Study, Interface Complexity Smartphone Study, Tablet Study, and Tabletop Study). When interface widgets have edge padding, the miss rate generally doubles for both children and adults. Again, in the Tabletop Study, miss rates are high across the board. Unlike the other studies, in the Tablet Study, edge padding had no effect on miss rate.

Edge padding is another factor that affected accuracy significantly. In mobile applications, the onscreen interactive widgets can be either laid out flush against the screen edge, or inset slightly. Typically this inset look is chosen to enhance the “style” of the app, but it is not clear to what extent this behavior affects interaction. On desktops, decades of work on modeling mouse pointing behavior based on Fitts’ law (MacKenzie, 1992) implied that targeting performance could be improved by laying out widgets flush against the screen edges (e.g., so that flicking the mouse to the screen edge will still activate the desired target in spite of inaccurate targeting). Similar relationships may govern mobile interactions (Harrison & Hudson, 2009; K. B. Perry & Hourcade, 2008). Figure 6 shows the miss rate in our studies when edge padding was present or absent. In general, our studies showed that the presence of edge padding significantly increased the miss rate, almost doubling it, for both children and adults[3]. Miss rates were fairly consistent across studies, except for the Tabletop Study, which had a higher degree of misses due to unintentional touches being registered, as discussed above. The Tablet Study was the only study in which edge padding did not have a significant effect on miss rate, perhaps due to the finer precision granted by the use of a stylus.

We also examined target location in several studies. Location of onscreen targets is known to affect accuracy in mobile device use, particularly depending on the hand posture used to hold and interact with the device (Aşçı & Rızvanoğlu, 2014; Eardley, Roudaut, Gill, & Thompson, 2017; Henze, Rukzio, & Boll, 2011; K. B. Perry & Hourcade, 2008). Figure 7 shows the miss rates by target location onscreen. We divided the screen into thirds vertically and horizontally to consider whether location within each third affected miss rates. Location-related miss rates were reported for three studies, one on each platform. On smartphones, in the Interface Complexity Smartphone Study, and on tablets, in the Tablet Study, there was a significant effect of location for both vertical and horizontal divisions. On smartphones, children tend to miss more often on the top/center and left side of the screen, rather than the bottom or center/right. On tablets, children tend to miss more often on the top/left of the screen rather than the center or bottom/right. On tabletops, in the Tabletop Study, there was no effect of location, most likely because children could move around the entire tabletop to get closer to targets that were farther away if they wanted.

We developed six design recommendations related to these issues of targeting inaccuracies:

- Use consistent, platform-recommended target sizes (Anthony, Brown, et al., 2012; Anthony et al., 2014). [*repeated from 3.1*]
- Increase active area for interface widgets to allow slightly out-of-bounds touches to register and activate the intended widget (Anthony, Brown, et al., 2012; Anthony et al., 2014).
- Align targets to edge of screen, or count edge touches (Anthony, Brown, et al., 2012; Anthony et al., 2014).
- Avoid small targets at the screen edges, especially in visually complex interfaces (Woodward et al., 2016).

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[3] Recent work has replicated similar results for adults on tablets (Avrahami, 2015).

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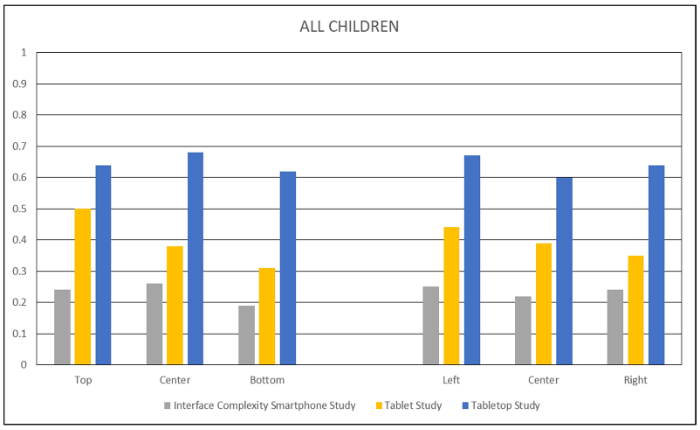

Figure 7. Miss rates by location on the screen of the target (e.g., top, center, or bottom thirds; or left, center, or right thirds) for all children together in each study (different colored bars, from left to right in order: Interface Complexity Smartphone Study, Tablet Study, and Tabletop Study). On smartphones, children tend to miss more often on the top/center and left side of the screen, rather than the bottom or center/right. On tablets, children tend to miss more often on the top/left of the screen rather than the center or bottom/right. On tabletops, children could move around the entire surface and there was no effect of location.

- For all devices, favor placing widgets closer to the child (Woodward et al., 2017).
- For the tabletop, space widgets farther apart for both children and adults (Woodward et al., 2017). [*repeated from 3.1*]

### 3.3 Gesture Execution Inconsistencies.

Another key result that is consistent across all of our studies is that children's gestures on touchscreens are recognized much less accurately than those of adults (Anthony, Brown, et al., 2013, 2012; Anthony et al., 2014; Woodward et al., 2016). In addition, the gestures of the youngest children (e.g., 5 and 6 years old) are recognized the most poorly (Anthony, Brown, et al., 2013, 2012; Anthony et al., 2014; Woodward et al., 2017, 2016). Prior work has set some guidelines for what recognition accuracy level is minimally required for children to "tolerate" the errors, about 91% in a free-form handwriting interface (Read, MacFarlane, & Casey, 2003). In our studies, modern recognizers that have been tested on children's gestures are only able to consistently achieve accuracies above 91% for children older than age 10 (Anthony, Brown, et al., 2013), e.g., with the $P recognizer (Vatavu, Anthony, & Wobbrock, 2012), and on average across all ages of children the best accuracy rates are only about 81%. Accuracy rates for younger children can be as low as 66% for 5-year-olds (Woodward et al., 2017). Figure 8 shows the recognition rates in the various configurations tested in our studies, for adults (left), the oldest children (ages 8 to 10, middle), and the youngest children (ages 5 to 7, right). The three configurations include user-dependent with $N-Protractor (Anthony & Wobbrock, 2012), user-dependent with $P (Vatavu et al., 2012), and user-independent with

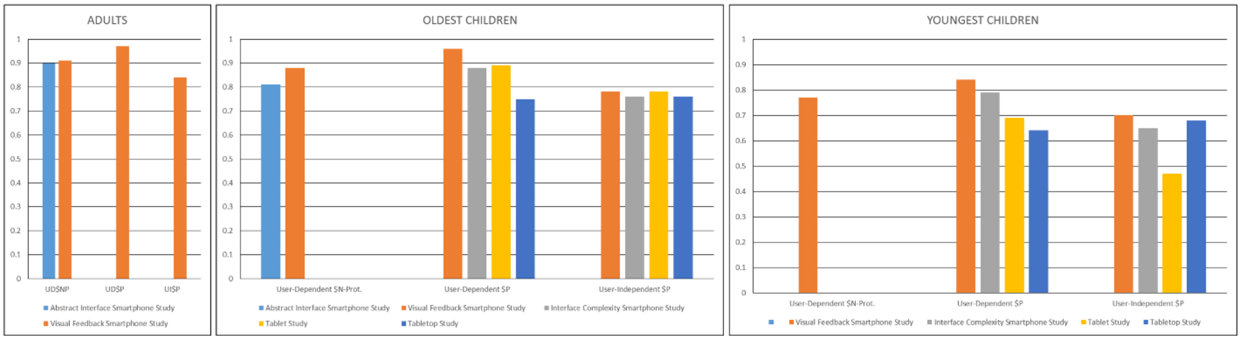

Figure 8. Recognition rates as tested for adults (left), the oldest children (middle), and the youngest children (right) in each of our studies (different colored bars, from left to right in order: Abstract Interface Smartphone Study, Visual Feedback Smartphone Study, Interface Complexity Smartphone Study, Tablet Study, and Tabletop Study). The testing configurations include both user-dependent and user-independent with $N-Protractor (Anthony & Wobbrock, 2012) and $P (Vatavu et al., 2012) for different studies. Children in the oldest group are approximately 8 to 10, and children in the youngest group are approximately 5 to 7, depending on the study.

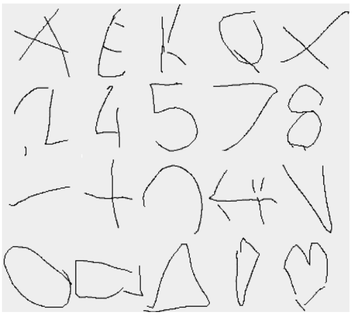

Figure 9. Children’s gesture patterns are heavily affected by their writing ability: this figure shows the same gesture set in the order shown in Figure 2, as written by a five-year-old during our Interface Complexity Study (Woodward et al., 2016).

$P, the most challenging configuration, since the recognizer is tested on samples from children it has not been trained on. Recognition rates for adults are above 90% when trained and tested on the same users, but only above 80% for older children (ages 8 to 10) and only 60 about 80% for the youngest children (ages 5 to 7). Detailed numerical results are shown in Appendix B; graphs are provided here for readability. Poor recognition rates in a live application can be distracting to children at best, and can prevent them from successfully interacting with the application at worst.

We investigated the reasons underlying why children’s gestures are more poorly recognized. A main cause seems to be that, due to children’s still developing motor skills, their writing and gesturing abilities are inconsistent and unpredictable. Figure 9 shows a set of gestures written by a 5-year-old from our dataset; these gestures are the same ones shown in Figure 2, but it is clear that these gestures would be quite difficult to recognize. Most recognition-based approaches seek to find patterns in how users make a gesture in order to classify future gestures successfully. Current investigations into children’s inconsistent gesturing behaviors have been focusing on filtering out problematic gesture execution behaviors that make recognition hard, and testing new approaches to recognition (Shaw, 2017).

We developed ten design recommendations related to these issues of inaccurate gesture recognition. Four of these recommendations focus on how to design effective gesture-based interactions for children:

- Design gesture sets to avoid confusions caused by recognizer limitations (corollary: train recognizers specifically to problematic pairs) (Anthony, Brown, et al., 2012).
- Design gestures and gesture sets that make conceptual sense to children and are easy for them to execute (Anthony et al., 2014).
- DON’T include gestures unfamiliar to users (Anthony, Brown, et al., 2013).
- DO provide visual feedback for surface gesture interaction on mobile devices (Anthony, Brown, et al., 2013).

The other six recommendations focus on how to configure a gesture recognizer before deploying the application:

- Train age-specific recognizers to improve accuracy on kids’ gestures (Anthony, Brown, et al., 2012; Anthony et al., 2014).
- Develop child-specific recognizers from the ground up (Anthony et al., 2014).
- Allow recognizers to learn over time and adapt to an individual child’s gestures (Anthony et al., 2014).
- DO test new gesture sets with the target recognizer in advance (Anthony, Brown, et al., 2013).
- Train gesture recognizers for younger children (e.g., ages 5 to 7) with more examples (Woodward et al., 2016).
- Collect gesture data [for training] on whichever device is most convenient for the youngest children (e.g., ages 5 to 7) (Woodward et al., 2017).

### 3.4 Other Findings.

While most of our analyses have focused on target acquisition accuracy and gesture recognition accuracy, we have also examined a few other behavioral measures, including response time (or reaction time) and input drag, which also led to design recommendations. Our studies showed that children tended to have a slower response time than adults, especially in visually complex interfaces like the ones used in the Interface Complexity Smartphone study (Woodward et al., 2016). Unlike prior work which suggests a *speed-accuracy trade-off* (e.g., (Seow & C., 2005)), in which users slow down usually to *increase* their accuracy, the interactions of the children we studied do not demonstrate this effect. The children were the slowest on the targets on which they also had the highest miss rates (Woodward et al., 2017, 2016). In certain types of games or applications in which fast response times are a goal, our findings indicate that a higher response time threshold will have to be accepted from children.

The second issue was identified based on our observations that children tended to "slip" when touching targets onscreen, especially in the Tablet Study Pen Modality. This behavior has been documented in prior work both in children's mouse movements and touchscreen interactions (Hourcade et al., 2008; Inkpen, 2001; McKnight & Cassidy, 2010; Vatavu, Anthony, & Brown, 2015; Vatavu, Cramariuc, et al., 2015). In our Tablet Study, we showed that the effect was stronger when children used a stylus, perhaps due to lower friction on the screen (Woodward et al., 2017). Such behavior in a real application could cause the intended interface widget not to register the child's interaction as the interaction point slips out of the widget's bounds before it has been activated. For very young children, this issue could considerably impact their ability to make their interactions successfully.

We developed design recommendations related to these two issues:

- Consider the trade-off between visual saliency and response time when designing games or applications for speedy input (Woodward et al., 2016).
- Account for children's tendency to drag pens while touching targets (Woodward et al., 2017).

### 3.5 Data Collection Lessons Learned.

Over the course of the MTAGIC project, we interacted with over 110 children in laboratory studies to collect samples of touch interaction and gesture interaction behaviors. In our studies, children spent 5 to 10 minutes completing the target task activities, and 10 to 15 minutes providing 120 (or more) samples of their gestures. The redundancy and repetitiveness in the activities could have been a significant challenge, but early on in our studies, we examined ways of increasing children's motivation to complete the tasks to ensure we obtained full datasets. In the Abstract Interface Smartphone Study and Visual Feedback Smartphone Study (Anthony, Brown, et al., 2013, 2012), most children were older and completion was not much of a challenge. When we wanted to understand how well these behaviors would generalize to younger children, we began recruiting children as young as five years old. In the Gamification Study (Brewer et al., 2013), we compared completion rates for 14 children ages 5 to 7 who tried either a "gamified" experience of the apps in which they could earn points and small prizes as they completed the tasks. These "points" were meaningless, but they served well: completion rates went from 73% to 97%, as mentioned above. We used the gamified protocol in all remaining studies (Woodward et al., 2017, 2016). In addition, to increase our data collection abilities, we often conducted study sessions with more than one child at a time (each using their own device). We progressively learned how to reduce distractions and encourage children (gently!) to provide full data samples for us, as we note in the design recommendations below.

Through this experience, we developed four lessons learned on the subject of data collection with children in HCI that other researchers may find useful to consider:

- Use gamification elements such as points, prizes, or game design patterns (Brewer et al., 2013).
- Personalize motivating elements to the individual child (Brewer et al., 2013).
- Avoid conducting sessions with children who know each other (Brewer et al., 2013).
- Consider a balance of distraction in controlled environments (Brewer et al., 2013).

## 4 Design Implications

As mentioned, over the course of the MTAGIC project, we strove to generate reliable design recommendations that could be adopted by other researchers and practitioners engaged in the design of interactive touchscreen experiences for children. Table 2 includes the full list of MTAGIC design recommendations that we derived from our empirical studies with children and adults. This table is also available as a one-page download for easy reference at our archival website for the MTAGIC project: http://mtagic.wordpress.com.

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| **Interaction** | **Recommendation** |
|---|---|
| ***Touch Interactions*** | Use timing and location of touches and interface widgets to identify and ignore holdover touches (corollary: improve interface responsiveness to prevent holdovers) (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Use consistent, platform-recommended target sizes (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Increase active area for interface widgets to allow slightly out-of-bounds touches to register and activate the intended widget (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Align targets to edge of screen, or count edge touches (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Provide salient visual feedback of accepted input to prevent holdovers (Woodward et al., 2016). |
| | Avoid small targets at the screen edges, especially in visually complex interfaces (Woodward et al., 2016). |
| | Consider the trade-off between visual saliency and response time when designing games or applications for speedy input (Woodward et al., 2016). |
| | Account for children’s tendency to drag pens while touching targets (Woodward et al., 2017). |
| | For all devices, favor placing widgets closer to the child (Woodward et al., 2017). |
| | For the tabletop, space widgets farther apart for both children and adults (Woodward et al., 2017). |
| ***Gesture Interactions*** | Train age-specific recognizers to improve accuracy on kids’ gestures (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Design gesture sets to avoid confusions caused by recognizer limitations (corollary: train recognizers specifically to problematic pairs) (Anthony, Brown, et al., 2012). |
| | Design gestures and gesture sets that make conceptual sense to children and are easy for them to execute (Anthony et al., 2014). |
| | Develop child-specific recognizers from the ground up (Anthony et al., 2014). |
| | Allow recognizers to learn over time and adapt to an individual child’s gestures (Anthony et al., 2014). |
| | DO provide visual feedback for surface gesture interaction on mobile devices (Anthony, Brown, et al., 2013). |
| | DON’T include gestures unfamiliar to users (Anthony, Brown, et al., 2013). |
| | DO test new gesture sets with the target recognizer in advance (Anthony, Brown, et al., 2013). |
| | Train gesture recognizers for younger children (e.g., ages 5 to 7) with more examples (Woodward et al., 2016). |
| | Collect gesture data [for training] on whichever device is most convenient for the youngest children (e.g., ages 5 to 7) (Woodward et al., 2017). |
| ***Data Collection*** | Use gamification elements such as points, prizes, or game design patterns (Brewer et al., 2013). |
| | Personalize motivating elements to the individual child (Brewer et al., 2013). |
| | Avoid conducting sessions with children who know each other (Brewer et al., 2013). |
| | Consider a balance of distraction in controlled environments (Brewer et al., 2013). |

Table 2. Cumulative list of design recommendations from our empirical studies (and their corresponding citation).

### 4.1 Challenges and Changes Over Time

Of course, over the course of conducting these six studies across five years, the project did experience some challenges and make some changes over time. One challenge was the gradual increase in touchscreen familiarity, and change in primary device, in the recruited child participants over the years of this project (2011 to 2017). When we began in 2011, 63% of children (and 79% of adults) reported using a touchscreen smartphone daily, but by 2017, only 17% of children were using touchscreen smartphones daily. By then, 58% of children were instead using touchscreen tablet devices daily. Our last study with adults in 2016 showed they were still using smartphones daily by a large margin (93% for smartphones vs. 30% for tablets). As a result of this change, the children in our later studies may have been more familiar with tablet interaction paradigms and norms than smartphone norms. However, our findings with respect to interaction behaviors remained robust across all six studies, indicating that these findings are more related to the child’s own developmental progress rather than being dominated by touchscreen familiarity. One area of investigation that would be fruitful beyond the scope of this project is to use existing child developmental scales such as the Haugland Developmental Software Scale (Haugland, 1999) to correlate touchscreen interaction performance with an individual child’s development, rather than the coarsely granular age ranges we analyzed.

Another challenge we experienced was the recruitment of a balanced number of children across age groups. It was important to our analysis to be able to compare and contrast the touchscreen interaction behaviors of children of different ages. However, when recruiting from elementary schools, we found that parents (and children) were more open to older children participating in pure research studies, than for younger children. Given that our studies did not include a learning-oriented component, it was not straightforward that there was any benefit to the child for participating. If we were to continue to pursue this avenue of research, we would consider increasing the complexity

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of our interaction tasks to include some simple learning goals, such as counting practice for the youngest children and simple arithmetic practice for the older children. These types of tasks would not only help to increase the benefits to everyone for a child participating, but also to keep the child more engaged as the task would have more complex goals and the possibility of failure. This would also enable the interplay between learning and interaction to be studied explicitly, such as what types of interaction behaviors most strongly signal growth or lack of growth in learning apps.

We conducted the studies across a range of hardware devices. We used mobile Android-based devices in our project because of the open-source nature of development on this platform as compared to iOS. However, in the time since we began our project, the iOS market share has outpaced Android by nearly 100%: in 2018, market share was 37% Android and 63% iOS in the United Stated (Kielty, 2019). It is likely that most children using touchscreens are using iOS touchscreens. While the hardware capabilities are similar between platforms, it is possible that iOS devices may provide data at a different sampling rate or may use different recommended platform standards. Future work could consider replicating our studies on touchscreen iOS devices. Also, when we expanded to considering larger screen sizes like tablets and tabletops, we encountered several challenges of collecting interaction data on these platforms, for example, some of which contributed to the increased rate of unintentional touches seen on the tabletop and discussed in Section 3.1. While we would have liked to continue to explore other variables on the larger form factor, such as collaborative multi-user interaction, the challenges we experienced with the hardware not working well for children precluded such investigations.

## 5 Open Questions in the Research

These five years of study have established beyond doubt the extent to which children exhibit different interaction behaviors on touchscreen devices than adults do. These differences, in many cases, significantly affect children's ability to interact as successfully with these devices as their designers intended. As touchscreen devices continue to expand in prevalence and evolve in their functionality and affordances, some of our findings will continue to apply. Others may need to be adapted for new technology, new contexts, or new populations. Here we present some of the main open challenges that we see for the next generation of natural user interfaces for children.

### 5.1 New Technologies.

Touchscreen interactions as we have studied them are focused heavily on the current marketplace of mobile, flatscreen touch devices. As new platforms that enable touch and/or gestural interaction become more widespread, it is less clear the extent to which our existing design recommendations will apply to those platforms.

Interactive touchscreens in other form factors such as deformable displays or spherical displays may offer new challenges for supporting children as potential users. For example, *deformable* interactive displays are not exactly touchscreens, but they can respond to users' tangible deformations of the screens as an interaction modality (Alexander et al., 2012; Schwesig, Poupyrev, & Mori, 2003). Researchers have proposed folding, bending, pushing, and pulling (Alexander et al., 2012; Gomes & Vertegaal, 2015; Khalilbeigi, Lissermann, Kleine, & Steimle, 2012; Lahey, Girouard, Burleson, & Vertegaal, 2011; Nakagawa, Kamimura, & Kawaguchi, 2012) as interactive "gestures" for such devices. Interactive *spherical* displays are just becoming commercially available (flointerfaces, 2013; VisionSystems Design, 2012). Researchers have considered the interaction challenges of spherical displays (e.g., (Benko, 2009; Benko, Wilson, & Balakrishnan, 2008) identified issues of limited visible area and territorial control in collaborative applications), but no such work has included children. In addition, researchers in human-computer interaction have investigated on-body or on-surface interaction that is *decoupled* from the screen itself (Chen, Schwarz, Harrison, Mankoff, & Hudson, 2014; Harrison, Benko, & Wilson, 2011; Harrison, Tan, & Morris, 2011). It is not well-understood to what degree children would be able to successfully interact with these types of platforms. Direct manipulation interfaces, in which the interaction occurs *in the same place* as the information being displayed, such as windows-based interaction as opposed to command-line interfaces, for example, have been noted as superior for children's development in terms of the fluency it can allow and the ability to develop a holistic overview of the entire task space (Crook, 1991). For static displays like large spheres (or even large interaction wall-mounted displays), children's height can be a limiting factor in reaching elements of the display that are too high for them. On-surface interaction that does not provide relevant tactile cues (Robinson et al., 2016) may be more difficult for children to use as they need the visual and tactile feedback loop to help them develop their sense of proprioception (Smyth, 1989; Vinter & Meulenbroek, 1993).

Virtual and augmented reality, currently undergoing a revolution of their own, also present interaction challenges. While the *display* aspects of VR/AR are challenging graphical and HCI design problems in and of themselves (e.g., (Azuma & T., 1997; Baumeister et al., 2017; Bujak et al., 2013)), there are also the questions of interaction and input. Researchers have considered the use of AR for educational applications for children (e.g., (Alrashidi, Gardner, & Callaghan, 2017; Davidsson, Johansson, & Lindwall, 2012; Nilsson, Arvola, Szczepanski, & Bång, 2012; J. Perry et al., 2008; Radu, Guzdial, & Avram, 2017; Radu, MacIntyre, & Lourenco, 2016)). For example, (Radu et al., 2017, 2016) have examined children's usability problems in AR and developed design recommendations for supporting their interactions more effectively. Previous work has identified some of the key affordances of AR for educational interfaces (Bujak et al., 2013; Pemberton & Winter, 2009): AR allows multiple views of the same information to be presented, allowing learners to explore familiar situations and extrapolate beyond what they have seen before; and AR supports collaborative learning, helping learners engage with their peers to strengthen mutual understanding. However, not much has been studied with respect to the affordances of VR for educational technology for children. Some studies have been done on using VR as a therapy and rehabilitation tool for children with autism, cerebral palsy, and so on (Bryanton et al., 2006; Gershon, Zimand, Pickering, Rothbaum, & Hodges, 2004; Strickland, Marcus, Mesibov, & Hogan, 1996). There are also ethical issues with respect to the effects of prolonged exposure to VR for children's development of their sight and vestibular system (Gent, 2016).

As these emerging interactive technologies continue to develop and become more commonplace, it is likely that children will become a significant portion of the userbase. Researchers will need to understand not only the expected interaction behaviors from children in these technologies, to the extent they differ from current technologies, but also the best ways to tailor interaction in these platforms to children's developmental stages and abilities.

### 5.2 Children with Disabilities.

In none of our studies did we have any child participants with cognitive or physical impairments that affected their interactions with our apps. However, there is a clear opportunity to examine children with special needs as a unique population whose interactions might be even more challenging for current technology to understand and interpret. Some researchers are already considering these challenges (e.g., (Anthony, Kim, & Findlater, 2013)). Our design recommendations, even though developed over the significant sample size we have worked with, still may not apply to all children.

There has been a significant amount of work on human-computer interaction for children with cognitive or physical impairments, in particular designing systems to help their development or learning (e.g., (Hernandez et al., 2012; Mora-Guiard, Crowell, Pares, & Heaton, 2016; Nikkila, Patel, Sundaram, Kelliher, & Sabharwal, 2012; Strickland et al., 1996)). However, most work that has examined the fine-grained input and interaction behaviors from users with impairments in order to develop algorithms for better recognition and interpretation of their input has been focused on adults (e.g., (Findlater, Moffatt, Froehlich, Malu, & Zhang, 2017; Kane, Morris, & Wobbrock, 2013; Mott, Vatavu, Kane, & Wobbrock, 2016)). Researchers have extensively examined touchscreen interaction patterns for adults with disabilities. For example, (Findlater et al., 2017) compared touchscreen and mouse performance across 32 adult users with and without upper body motor impairments for target acquisition speech and accuracy. (Mott et al., 2016) applied template-matching techniques to recognize touchscreen gesture input by adult users with motor impairments based on a study of their interaction behaviors and challenges the system would have to address. (Kane et al., 2013) examined how to provide better tactile feedback to assist users with vision impairments in interacting with touchscreen devices.

As the MTAGIC project's work has shown in the touchscreen interaction domain, children's development already provides significant challenges for technology to be able to support their natural interaction behaviors. Children with disabilities deviate even further from current system-expected "norms" of behaviors, especially when considering both motor and cognitive development variables (e.g., (Manjiviona & Prior, 1995; Palisano et al., 2008)). To support children with disabilities in educational settings, it is common practice to provide individualized interventions such as an Individual Education Plan (IEP), which can include recommendations for the use of assistive technology (Barton, 2013). The world of assistive technology for children (and adults) is characterized by individually adapted solutions, which must be updated and changed over time as their development continues and/or their disability severity changes (e.g., (Anthony, Kim, et al., 2013; Hurst & Tobias, 2011)). For example, alternative and augmented communication (AAC) devices must be able to grow with an individual child's needs and abilities as they develop

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(Light & Drager, 2002), and lack of ability to personalize such devices is often cited as a reason for technology abandonment (Hurst & Tobias, 2011; Phillips & Zhao, 1993).

Ultimately the idea of "one size fits all" interaction will have to be abandoned as our field moves toward more inclusive design across all sections of the population, including children. Researchers are already calling for such universal design approaches when considering design for adults with or without disabilities (Wobbrock, Kane, Gajos, Harada, & Froehlich, 2011). To support children with disabilities, it is likely that we will have to pursue approaches that are based on user modeling and adaptation, rather than pre-building global models across a population.

### 5.3 Multimodal Interaction.

Touchscreen interactions are only one aspect of the potential future of ubiquitous computing. We are already seeing a commercial eruption of voice-based interfaces like Amazon's Echo/Alexa, Google Home, and Microsoft Cortana. In many ways, the recent spread of these types of interactive technologies echoes the spread of touchscreen interaction from the mid-2000s. It seems plausible that, as we move closer to the vision of the "smart home", children will be important to serve. Multimodal—the combination of one or more natural user interface modalities into a single system or interface—rather than unimodal, interaction for children is poised to be the next frontier.

Most work in multimodal human-computer interaction has been conducted with adults (e.g., (Bolt, 1980; Jaimes & Sebe, 2007; Mignot, Valot, & Carbonell, 1993; Oviatt, Coulston, & Lunsford, 2004)). Since Bolt's seminal prototype work on the "Put That There" system in the 1980s (Bolt, 1980), researchers have been investigating ways to support natural human-like communication in simultaneous modalities. Multimodal communication is characterized by three main features: (1) users (adults) switch fluidly back and forth between input streams for their primary communication modality; (2) users can include both simultaneous and redundant, as well as asynchronous and disparate, information in the multiple input streams; and (3) users integrate the information presented in the multiple modalities in different ways depending on the context, linguistic demands of the communicative act, and other factors (Oviatt, 1999b). Effectively supporting multimodal interaction relies on fusion of the content carried by the multiple streams of input from the user to recognize user intent (Atrey, Hossain, El Saddik, & Kankanhalli, 2010). These streams are frequently incomplete on their own; the complete content and message is only understandable when considering all potential modality streams (Oviatt, 1999a, 1999b, 2000).

Some work in educational technology has considered multimodal *delivery* of content to children and how it affects their learning (e.g., Mayer's key work on *Multimedia Learning* (Mayer, 2001)), but there has been very little work that considered multimodal *input* by children into these systems. Some exceptions are the investigation of pen and speech input systems for math learning (Anthony, Yang, & Koedinger, 2007, 2008, 2012; Oviatt, Arthur, & Cohen, 2006), and conversational agents or robots for learning or social interaction (Belpaeme et al., 2012; Buisine & Martin, 2005; Kanda, Hirano, Eaton, & Ishiguro, 2004). As the MTAGIC project, and work by others, has shown, input by children tends to be less structured, organized, and consistent than that of adults (Anthony, Brown, et al., 2012; Anthony et al., 2014; Anthony, Vatavu, & Wobbrock, 2013; Oviatt et al., 2006; Xiao, Girand, & Oviatt, 2002; Yildirim & Narayanan, 2009), which is a large obstacle to being able to create algorithms that can handle such messy input in more than one modality. Child development literature can tell us much about the potential challenges that research will face in being able to support children well in multimodal interaction. For example, speech development literature indicates that before the age of five, children frequently repeat syllables or words while speaking, have difficulty physically making certain sounds (e.g., l, s, r, v, z, ch, sh, and th), and construct verbal utterances with overgeneralized grammatical rules (e.g., "she goed" instead of "she went") (NIDCD Information Clearinghouse, 2010). Also, some work in multimodal interaction has found that children (especially younger children) show marked disfluencies when compared to adults, and often display different patterns of multimodal integration (e.g., gestures with speech) than do adults (Yildirim & Narayanan, 2009).

To support developing children in interacting successfully multimodally, researchers will need to both understand the types of input behaviors they can expect from children in other modalities, and in multimodality, and also to design and develop natural user experiences in these modalities that make it easy for children to interact with these systems.

## 6 Related Work

In the past five years, the MTAGIC project is not the only one who has examined physical dimensions of children's touchscreen interactions empirically. Other researchers have investigated children's ability to perform standard touchscreen gestures (e.g., not like the shape-based ones we have studied) or children's use of different input modalities when interacting with touchscreens (Abdul Aziz, 2013; Arif & Sylla, 2013; Baloian, Pino, & Vargas, 2013; Ibharim et al., 2013; McKnight & Cassidy, 2010). (Ibharim et al., 2013) conducted a laboratory study with 20 8-year-old children and found that the majority of the children at this age could perform standard touchscreen gestures, except for pinch-to-zoom and rotate. (Abdul Aziz, 2013) observed 33 children ages 2 to 12 years old interacting with five representative touchscreen apps. They found that the youngest children (ages 2 and 3) could not perform gestures like drag and drop and rotate, but by age 4 and up, there were no problems with these gestures. (McKnight & Cassidy, 2010) conducted two studies with children ages 7 to 10 to investigate the effects of finger versus stylus input, as well as different grip styles for stylus input. They found that, for example, children tend to make more errors when targeting with their finger versus with a stylus and that children had the most success with the "pinch grip". (Arif & Sylla, 2013) conducted a comparison of 12 adults and 12 children, ages 8 to 11, drawing gestures on a touchscreen with a stylus or with their finger. They found that children were much slower but also less accurate when inputting gestures, and there was no significant difference of input modality for children. In a study with 30 5- and 6-year-old children, (Baloian et al., 2013) explored how the difficulty of performing touchscreen gestures on a tablet is correlated with improved learning outcomes, and found that tracing, double tapping, and drag-and-drop gestures were the most difficult to perform. In general, difficulty of performing the gestures did not negatively affect learning outcomes, however.

The MTAGIC project's work has focused on children of primary school age (ages 5 to 10), given the context of our studies depending in some cases on familiarity with alphabetical symbols and so on. However, some researchers have considered children of younger ages (Abdul Aziz et al., 2013; Hamza & Salivia, 2015; Hourcade, Mascher, Wu, & Pantoja, 2015; Nacher et al., 2015; Vatavu, Cramariuc, et al., 2015). For example, (Vatavu, Cramariuc, et al., 2015) examined touch interactions of 89 children ages 3 to 6 years of age in a laboratory study. Among other results, they found that the accuracy of children's drag and drop paths on touchscreen devices correlates negatively with the children's finger dexterity, as measured by a motor skills evaluation test. (Hamza & Salivia, 2015) conducted a study to investigate how well children ages 4 and 5 years old could perform standard touchscreen gestures such as drag-and-drop and rotation. They found that 4-year--olds could perform these gestures less well than 5-year-olds, and rotation was the most difficult gesture for all children. (Nacher et al., 2015) investigated how even younger children, ages 2 to 3 years old, can perform standard touchscreen gestures. They found that even this age of child can be successful with a range of gestures, including regular tap, double tap, long press, drag, and two-finger rotation. (Abdul Aziz et al., 2013) also examined touchscreen gesture interactions by 37 children ages 2 to 4 years old and found that performance was mixed on more complex gestures like rotate, pinch (zoom out), and spread (zoom in) for younger children, but by age 4, all children could perform all the gestures. (Hourcade et al., 2015) looked at the youngest children, infants and toddlers aged <12 to 29 months, by surveying videos of babies using iPads that parents had uploaded to YouTube. They analyzed 208 videos and found that, under 12 months, 90% of babies were mostly unable to use the iPads at all, while by age 24 to 29 months, 90% of babies were mostly able to use the iPads successfully.

Finally, while the MTAGIC project has focused on children's physical motor development, other researchers have focused more on children's *cognitive* development and how it may affect their interactions with touchscreen devices (Hiniker et al., 2016, 2015; Kähkönen & Ovaska, 2006; McKnight & Fitton, 2010; Nacher, Jaen, & Catala, 2017). For example, (McKnight & Fitton, 2010) conducted a study with 13 children ages 6 to 7 years old, in which they observed how well children were able to understand standard touchscreen terminology (e.g., "press and hold," "swipe," "slide") and execute the appropriate command. In general, the participants in their study were successful. In contrast, (Hiniker et al., 2015) investigated how well standard touchscreen prompts such as voice prompting for interaction or animations of the desired interaction were understood in a study of 34 children ages 2 to 5 years. They found that children under age 3 were largely unable to follow in-app prompts without an adult's intervention, and that using visual state changes (e.g., pulsing, glowing, or movement) was not effective for any of the children. In a follow-up study, (Hiniker et al., 2016) found that, while many apps (44%) use symbolic references to show progress of a task or game, children ages 2 to 5 years old are not able to connect these progress bar symbols to the completion level of the in-app task they are performing. (Nacher et al., 2017) also tested how well visually animated prompts to help children perform touch gestures were understood by 32 children ages 2 and 3 years old. They found that animated prompts can be effective for this age, but that there were gender-based differences in how well each form of prompt worked. (Kähkönen & Ovaska, 2006) compared three children's apps which either provided instructions in text, or animations plus spoken explanations, or not at all, to identify which method worked best for young early readers. In a study with 28 children ages 5 to 6 years old, they found that instructions cannot compensate for a poorly designed, unusable interface.

Taken together, this body of work, along with the results from our project, contributes a thorough understanding of children's interactions with touchscreen devices, and how these are mediated by age and/or developmental stage, to help inform the design of more successful such interactions in the future.

## 7 Conclusion

Over the past five years, the MTAGIC project team has conducted a series of related studies into the interaction behaviors of children, in particular ages 5 to 10, on touchscreen devices. We have collected over 55,000 touch events and 35,000 gestures from 60 adults and 116 children. We have examined variables such as target size and location, platform, and input modality and how they affect children's performance in touching onscreen targets (widgets). We have also examined gesture execution by children and how it affects recognition. We have contributed a set of design recommendations for touchscreen interface design for children which is grounded in empirical evidence, and solidified by repeated replication across studies, across platforms, and across contexts. Our set of MTAGIC design recommendations are available as a one-page download for easy reference at our archival website for the MTAGIC project: http://mtagic.wordpress.com

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The contact author of this article, Lisa Anthony, was the Principal Investigator on this work. The Co-investigator on this project from 2012-2014 was Quincy K. Brown, formerly of Bowie State University. She is currently a Program Director of STEM Education at the American Association for the Advancement of the Sciences (AAAS).

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## References

Abdul Aziz, N. A. (2013). Children's Interaction with Tablet Applications: Gestures and Interface Design. *International Journal of Computer and Information Technology*, *2*(3), 447–450.

Abdul Aziz, N. A., Batmaz, F., Stone, R., & Chung, P. W. H. (2013). Selection of touch gestures for children's applications. In *Science and Information Conference (SAI)* (pp. 721–726).

Alexander, J., Kildal, J., Hornbaek, K., Aaltonen, V., Lucero, A., & Subramanian, S. (2012). Interaction with deformable displays. In *Proceedings of the International Conference on Human-Computer Interaction with Mobile Devices and Services Companion (MobileHCI)* (pp. 237–240). New York, New York, USA: ACM Press. https://doi.org/10.1145/2371664.2371723

Alrashidi, M., Gardner, M., & Callaghan, V. (2017). Evaluating the Use of Pedagogical Virtual Machine with Augmented Reality to Support Learning Embedded Computing Activity. In *Proceedings of the International Conference on Computer and Automation Engineering (ICCAE)* (pp. 44–50). New York, New York, USA: ACM Press. https://doi.org/10.1145/3057039.3057088

Annett, M. (2017). (Digitally) Inking in the 21st Century. *IEEE Computer Graphics and Applications*, *37*(1), 92–99. https://doi.org/10.1109/MCG.2017.1

Annett, M., Gupta, A., & Bischof, W. F. (2014). Exploring and Understanding Unintended Touch during Direct Pen Interaction. *ACM Transactions on Computer-Human Interaction*, *21*(5), 1–39. https://doi.org/10.1145/2674915

Anthony, L., Brown, Q., Nias, J., & Tate, B. (2013). Examining the need for visual feedback during gesture interaction on mobile touchscreen devices for kids. In *Proceedings of the International Conference on Interaction Design and Children (IDC)* (pp. 157–164). New York, New York, USA: ACM Press. https://doi.org/10.1145/2485760.2485775

Anthony, L., Brown, Q., Nias, J., Tate, B., & Mohan, S. (2012). Interaction and Recognition Challenges in Interpreting Children's Touch and Gesture Input on Mobile Devices. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS)* (pp. 225–234). ACM Press. https://doi.org/10.1145/2396636.2396671

Anthony, L., Brown, Q., Tate, B., Nias, J., Brewer, R., & Irwin, G. (2014). Designing smarter touch-based interfaces for educational contexts. *Personal and Ubiquitous Computing*, *18*(6), 1471–1483. https://doi.org/10.1007/s00779-013-0749-9

Anthony, L., Kim, Y., & Findlater, L. (2013). Analyzing user-generated youtube videos to understand touchscreen use by people with motor impairments. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 1223–1232). Paris, France: ACM Press. https://doi.org/10.1145/2470654.2466158

Anthony, L., Vatavu, R.-D., & Wobbrock, J. O. (2013). Understanding the Consistency of Users' Pen and Finger Stroke Gesture Articulation. In *Proceedings of Graphics Interface* (pp. 87–94). Canadian Information Processing Society. Retrieved from http://dl.acm.org/citation.cfm?id=2532129.2532145

Anthony, L., & Wobbrock, J. O. (2012). $N-protractor: a fast and accurate multistroke recognizer. In *Proceedings of Graphics Interface* (pp. 117–120). Retrieved from http://dl.acm.org/citation.cfm?id=2305276.2305296

Anthony, L., Yang, J., & Koedinger, K. R. (2007). Benefits of handwritten input for students learning algebra equation solving. In *Proceedings of the International Conference on Artificial Intelligence in Education* (Vol. 158, pp. 521–523). Amsterdam, The Netherlands, The Netherlands: IOS Press. Retrieved from http://dl.acm.org/citation.cfm?id=1563601.1563683

Anthony, L., Yang, J., & Koedinger, K. R. (2008). Toward Next-Generation, Intelligent Tutors: Adding Natural Handwriting Input. *IEEE Multimedia*, *15*(3), 64–68. https://doi.org/10.1109/MMUL.2008.73

Anthony, L., Yang, J., & Koedinger, K. R. (2012). A paradigm for handwriting-based intelligent tutors. *International Journal of Human-Computer Studies*, *70*(11), 866–887. https://doi.org/10.1016/j.ijhcs.2012.04.003

Arif, A. S., & Sylla, C. (2013). A comparative evaluation of touch and pen gestures for adult and child users. In *Proceedings of the International Conference on Interaction Design and Children (IDC)* (pp. 392–395). New York, New York, USA: ACM Press. https://doi.org/10.1145/2485760.2485804

Aşçı, S., & Rızvanoğlu, K. (2014). Left vs. Right-Handed UX: A Comparative User Study on a Mobile Application with Left and Right-Handed Users. In *Proceedings of the Third International Conference on Design, User Experience, and Usability. User Experience Design for Diverse Interaction Platforms and Environments - Volume 8518* (pp. 173–183). Springer-Verlag. https://doi.org/10.1007/978-3-319-07626-3_16

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Atrey, P. K., Hossain, M. A., El Saddik, A., & Kankanhalli, M. S. (2010). Multimodal fusion for multimedia analysis: a survey. *Multimedia Systems*, *16*(6), 345–379. https://doi.org/10.1007/s00530-010-0182-0

Avrahami, D. (2015). The Effect of Edge Targets on Touch Performance. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 1837–1846). New York, New York, USA: ACM Press. https://doi.org/10.1145/2702123.2702439

Azuma, R. T., & T., R. (1997). A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355–385. https://doi.org/10.1162/pres.1997.6.4.355

Baloian, N., Pino, J. A., & Vargas, R. (2013). Tablet gestures as a motivating factor for learning. In *Proceedings of the Chilean Conference on Human-Computer Interaction (ChileCHI)* (pp. 98–103). New York, New York, USA: ACM Press. https://doi.org/10.1145/2535597.2535622

Barton, E. E. (2013). Individual Education Plan. In F. R. Volkmar (Ed.), *Encyclopedia of Autism Spectrum Disorders* (pp. 1569–1574). New York, NY: Springer New York. https://doi.org/10.1007/978-1-4419-1698-3_1161

Baudisch, P., & Chu, G. (2009). Back-of-device interaction allows creating very small touch devices. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 1923–1932). New York, New York, USA: ACM Press. https://doi.org/10.1145/1518701.1518995

Baumeister, J., Ssin, S. Y., ElSayed, N. A. M., Dorrian, J., Webb, D. P., Walsh, J. A., … Thomas, B. H. (2017). Cognitive Cost of Using Augmented Reality Displays. *IEEE Transactions on Visualization and Computer Graphics*, *23*(11), 2378–2388. https://doi.org/10.1109/TVCG.2017.2735098

Beery, K. E., Buktenica, N. A., & Beery, N. A. (2004). *The Beery-Buktenica Developmental Test of Visual-Motor Integration, 5th Edition*. New Jersey: Modern Curriculum Press.

Belpaeme, T., Baxter, P. E., Read, R., Wood, R., Cuayáhuitl, H., Kiefer, B., … Humbert, R. (2012). Multimodal Child-Robot Interaction: Building Social Bonds. *Journal of Human-Robot Interaction*, *1*(2), 33–53. https://doi.org/10.5898/jhri.v1i2.62

Benko, H. (2009). Beyond flat surface computing: challenges of depth-aware and curved interfaces. In *Proceedings of the ACM International Conference on Multimedia* (pp. 935–944). New York, New York, USA: ACM Press. https://doi.org/10.1145/1631272.1631462

Benko, H., Wilson, A. D., & Balakrishnan, R. (2008). Sphere: multi-touch interactions on a spherical display. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST)* (pp. 77–86). New York, New York, USA: ACM Press. https://doi.org/10.1145/1449715.1449729

Bolt, R. A. (1980). "Put-That-There": Voice and Gesture at the Graphics Interface. In *ACM SIGGRAPH Computer Graphics* (Vol. 14, pp. 262–270). ACM. Retrieved from http://dl.acm.org/citation.cfm?id=807503

Brewer, R., Anthony, L., Brown, Q., Irwin, G., Nias, J., & Tate, B. (2013). Using gamification to motivate children to complete empirical studies in lab environments. In *Proceedings of the International Conference on Interaction Design and Children (IDC)* (pp. 388–391). New York, New York, USA: ACM Press. https://doi.org/10.1145/2485760.2485816

Bryanton, C., Bossé, J., Brien, M., Mclean, J., McCormick, A., & Sveistrup, H. (2006). Feasibility, Motivation, and Selective Motor Control: Virtual Reality Compared to Conventional Home Exercise in Children with Cerebral Palsy. *CyberPsychology & Behavior*, *9*(2), 123–128. https://doi.org/10.1089/cpb.2006.9.123

Buisine, S., & Martin, J.-C. (2005). Children's and adults' multimodal interaction with 2D conversational agents. In *Extended Abstracts of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 1240–1243). New York, New York, USA: ACM Press. https://doi.org/10.1145/1056808.1056886

Bujak, K. R., Radu, I., Catrambone, R., MacIntyre, B., Zheng, R., & Golubski, G. (2013). A psychological perspective on augmented reality in the mathematics classroom. *Computers & Education*, *68*, 536–544. https://doi.org/10.1016/j.compedu.2013.02.017

Chen, X. "Anthony," Schwarz, J., Harrison, C., Mankoff, J., & Hudson, S. E. (2014). Air+touch: interweaving touch & in-air gestures. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST)* (pp. 519–525). New York, New York, USA: ACM Press. https://doi.org/10.1145/2642918.2647392

Common Sense Media. (2017). *The Common Sense Census: Media Use by Kids Age Zero to Eight 2017*. Retrieved from https://www.commonsensemedia.org/research/the-common-sense-census-media-use-by-kids-age-zero-to-eight-2017

Crook, C. (1991). Computers for preschool children: The role of direct manipulation interfaces. *Early Child Development and Care*, *69*(1), 5–18. https://doi.org/10.1080/0300443910690102

Davidsson, M., Johansson, D., & Lindwall, K. (2012). Exploring the Use of Augmented Reality to Support Science Education in Secondary Schools. In *Proceedings of the IEEE International Conference on Wireless, Mobile* *and Ubiquitous Technology in Education* (pp. 218–220). IEEE. https://doi.org/10.1109/WMUTE.2012.52

Eardley, R., Roudaut, A., Gill, S., & Thompson, S. J. (2017). Understanding Grip Shifts: How Form Factors Impact Hand Movements on Mobile Phones. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 4680–4691). New York, New York, USA: ACM Press. https://doi.org/10.1145/3025453.3025835

Erhardt, R. (1994). *Developmental Hand Dysfunction: Theory, Assessment, and Treatment* (2nd ed.). Pennsylvania State University: Therapy Skill Builders.

Feder, K. P., & Majnemer, A. (2007). Handwriting development, competency, and intervention. *Developmental Medicine and Child Neurology*. https://doi.org/10.1111/j.1469-8749.2007.00312.x

Findlater, L., Moffatt, K., Froehlich, J. E., Malu, M., & Zhang, J. (2017). Comparing Touchscreen and Mouse Input Performance by People With and Without Upper Body Motor Impairments. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 6056–6061). New York, New York, USA: ACM Press. https://doi.org/10.1145/3025453.3025603

flointerfaces. (2013). Pufferfish Multi-Touch Globe. Retrieved May 23, 2016, from https://flointerfaces.wordpress.com/2013/04/17/puffer-fish-multi-touch-globe/

Gent, E. (2016). Are Virtual Reality Headsets Safe for Children? *Scientific American*. Retrieved from https://www.scientificamerican.com/article/are-virtual-reality-headsets-safe-for-children/

Gershon, J., Zimand, E., Pickering, M., Rothbaum, B. O., & Hodges, L. (2004). A pilot and feasibility study of virtual reality as a distraction for children with cancer. *Journal of the American Academy of Child and Adolescent Psychiatry*, *43*(10), 1243–1249. https://doi.org/10.1097/01.chi.0000135621.23145.05

Gesell, A., Ilg, F. L., Ames, L. B., & Bullis, G. E. (1946). *The Child from Five to Ten* (2nd ed.). University of Michigan: Harper & Brothers.

Gomes, A., & Vertegaal, R. (2015). PaperFold: Evaluating Shape Changes for Viewport Transformations in Foldable Thin-Film Display Devices. In *Proceedings of the International Conference on Tangible, Embedded, and Embodied Interaction (TEI)* (pp. 153–160). New York, New York, USA: ACM Press. https://doi.org/10.1145/2677199.2680572

Hamza, Z., & Salivia, G. (2015). Study of Touch Gestures Performance in Touch Devices by Young Children. *International Journal on Recent and Innovation Trends in Computing and Communication*, *3*, 1395–1400. Retrieved from http://www.ijritcc.org/download/1428118950.pdf

Harrison, C., Benko, H., & Wilson, A. D. (2011). OmniTouch: Wearable Multitouch Interaction Everywhere. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST)* (pp. 441–450). ACM. https://doi.org/10.1145/2047196.2047255

Harrison, C., & Hudson, S. E. (2009). Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST)* (pp. 121–124). New York, New York, USA: ACM Press. https://doi.org/10.1145/1622176.1622199

Harrison, C., Tan, D., & Morris, D. (2011). Skinput: appropriating the skin as an interactive canvas. *Communications of the ACM*, *54*(8), 111–118. https://doi.org/10.1145/1978542.1978564

Haugland, S. W. (1999). The Newest Software that Meets the Developmental Needs of Young Children. *Early Childhood Education Journal*, *26*(4), 245–254. https://doi.org/10.1023/A:1022915706904

Henze, N., Rukzio, E., & Boll, S. (2011). 100,000,000 taps: analysis and improvement of touch performance in the large. In *Proceedings of the International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI)* (pp. 133–142). New York, New York, USA: ACM Press. https://doi.org/10.1145/2037373.2037395

Hernandez, H. A., Graham, T. C. N., Fehlings, D., Switzer, L., Ye, Z., Bellay, Q., … Stach, T. B. (2012). Design of an exergaming station for children with cerebral palsy. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 2619–2628). New York, New York, USA: ACM Press. https://doi.org/10.1145/2207676.2208652

Hiniker, A., Sobel, K., Hong, S. (Ray), Suh, H., Irish, I., & Kientz, J. A. (2016). Hidden symbols: How informal symbolism in digital interfaces disrupts usability for preschoolers. *International Journal of Human-Computer Studies*, *90*, 53–67. https://doi.org/10.1016/j.ijhcs.2016.03.006

Hiniker, A., Sobel, K., Hong, S. R., Suh, H., Irish, I., Kim, D., & Kientz, J. A. (2015). Touchscreen Prompts for Preschoolers: Designing Developmentally Appropriate Techniques for Teaching Young Children to Perform Gestures. In *Proceedings of the International Conference on Interaction Design and Children (IDC)* (pp. 109–118). ACM Press. https://doi.org/10.1145/2771839.2771851

Hourcade, J. P. (2007). Interaction Design and Children. *Foundations and Trends® in Human-Computer*

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*Interaction*, *1*(4), 277–392. https://doi.org/10.1561/1100000006

Hourcade, J. P., Bederson, B. B., Druin, A., & Guimbretière, F. (2004). Differences in pointing task performance between preschool children and adults using mice. *ACM Transactions on Computer-Human Interaction*, *11*(4), 357–386. https://doi.org/10.1145/1035575.1035577

Hourcade, J. P., Mascher, S. L., Wu, D., & Pantoja, L. (2015). Look, My Baby Is Using an iPad! An Analysis of YouTube Videos of Infants and Toddlers Using Tablets. In *Proceedings of the Annual ACM Conference on Human Factors in Computing Systems (CHI)* (pp. 1915–1924). New York, New York, USA: ACM Press. https://doi.org/10.1145/2702123.2702266

Hourcade, J. P., Perry, K. B., & Sharma, A. (2008). PointAssist: Helping Four Year Olds Point with Ease. In *Proceedings of the International Conference on Interaction Design and Children (IDC)* (pp. 202–209). New York, New York, USA: ACM Press. https://doi.org/10.1145/1463689.1463757

Hurst, A., & Tobias, J. (2011). Empowering individuals with do-it-yourself assistive technology. In *Proceedings of the International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS)* (pp. 11–18). New York, New York, USA: ACM Press. https://doi.org/10.1145/2049536.2049541

Ibharim, L. F. M., Borhan, N., & Yatim, M. H. (2013). A field study of understanding child's knowledge, skills and interaction towards capacitive touch technology (iPad). In *Proceedings of the International Conference on Information Technology in Asia (CITA)* (pp. 1–5).

Inkpen, K. M. (2001). Drag-and-drop versus point-and-click mouse interaction styles for children. *ACM Transactions on Computer-Human Interaction*, *8*(1), 1–33. https://doi.org/10.1145/371127.371146

Jaimes, A., & Sebe, N. (2007). Multimodal human-computer interaction: a survey. *Computer Vision and Image Understanding*, *108*(1–2), 116–134. https://doi.org/10.1016/j.cviu.2006.10.019

Joiner, R., Messer, D., Light, P., & Littleton, K. (1998). It is best to point for young children: a comparison of children's pointing and dragging. *Computers in Human Behavior*, *14*(3), 513–529. https://doi.org/10.1016/S0747-5632(98)00021-1

Kähkönen, M., & Ovaska, S. (2006). Initial observations on children and online instructions. In *Proceeding of the International Conference on Interaction Design and Children (IDC)* (pp. 93–96). New York, New York, USA: ACM Press. https://doi.org/10.1145/1139073.1139098

Kanda, T., Hirano, T., Eaton, D., & Ishiguro, H. (2004). Interactive Robots as Social Partners and Peer Tutors for Children: A Field Trial. *Human-Computer Interaction*, *19*(1), 61–84. https://doi.org/10.1207/s15327051hci1901&2_4

Kane, S. K., Morris, M. R., & Wobbrock, J. O. (2013). Touchplates: low-cost tactile overlays for visually impaired touch screen users. In *Proceedings of the International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS)* (p. Article No. 22). New York, New York, USA: ACM Press. https://doi.org/10.1145/2513383.2513442

Khalilbeigi, M., Lissermann, R., Kleine, W., & Steimle, J. (2012). FoldMe: interacting with double-sided foldable displays. In *Proceedings of the International Conference on Tangible, Embedded, and Embodied Interaction (TEI)* (pp. 33–40). New York, New York, USA: ACM Press. https://doi.org/10.1145/2148131.2148142

Kielty, J. (2019). Android v iOS market share 2019. Retrieved February 5, 2019, from https://deviceatlas.com/blog/android-v-ios-market-share

Lahey, B., Girouard, A., Burleson, W., & Vertegaal, R. (2011). PaperPhone: understanding the use of bend gestures in mobile devices with flexible electronic paper displays. In *Proceedings of the Annual ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 1303–1312). New York, New York, USA: ACM Press. https://doi.org/10.1145/1978942.1979136

Light, J. C., & Drager, K. D. R. (2002). Improving the Design of Augmentative and Alternative Technologies for Young Children. *Assistive Technology*, *14*(1), 17–32. https://doi.org/10.1080/10400435.2002.10132052

MacKenzie, I. S. (1992). Fitts' Law as a Research and Design Tool in Human-Computer Interaction. *Human–Computer Interaction*, *7*(1), 91–139. https://doi.org/10.1207/s15327051hci0701_3

Manjiviona, J., & Prior, M. (1995). Comparison of Asperger syndrome and high-functioning autistic children on a Test of Motor Impairment. *Journal of Autism and Developmental Disorders*, *25*(1), 23–39. https://doi.org/10.1007/BF02178165

Mayer, R. (2001). *Multimedia Learning*. New York: Cambridge University Press.

McKnight, L., & Cassidy, B. (2010). Children's Interaction with Mobile Touch-Screen Devices. *International Journal of Mobile Human Computer Interaction*, *2*(2), 18 pp. https://doi.org/10.4018/jmhci.2010040101

McKnight, L., & Fitton, D. (2010). Touch-screen Technology for Children : Giving the Right Instructions and Getting the Right Responses. In *Proceedings of the International Conference on Interaction Design and*

*Children (IDC)* (pp. 238–241). ACM Press. https://doi.org/10.1145/1810543.1810580

Mignot, C., Valot, C., & Carbonell, N. (1993). An experimental study of future "natural" multimodal human-computer interaction. In *INTERACT '93 and CHI '93 Conference Companion on Human Factors in Computing Systems* (pp. 67–68). New York, New York, USA: ACM Press. https://doi.org/10.1145/259964.260075

Mitra, S., & Acharya, T. (2007). Gesture Recognition: A Survey. *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews), 37*(3), 311–324. https://doi.org/10.1109/TSMCC.2007.893280

Mora-Guiard, J., Crowell, C., Pares, N., & Heaton, P. (2016). Lands of Fog: helping children with Autism in social interaction through a full-body interactive experience. In *Proceedings of the ACM SIGCHI Conference on Interaction Design and Children (IDC)*. https://doi.org/10.1145/2930674.2930695

Mott, M. E., Vatavu, R.-D., Kane, S. K., & Wobbrock, J. O. (2016). Smart Touch: Improving Touch Accuracy for People with Motor Impairments with Template Matching. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 1934–1946). New York, New York, USA: ACM Press. https://doi.org/10.1145/2858036.2858390

Nacher, V., Jaen, J., & Catala, A. (2017). Evaluating Multitouch Semiotics to Empower Prekindergarten Instruction with Interactive Surfaces. *Interacting with Computers*, *29*(2), 97–116. https://doi.org/10.1093/iwc/iww007

Nacher, V., Jaen, J., Navarro, E., Catala, A., & González, P. (2015). Multi-touch gestures for pre-kindergarten children. *International Journal of Human-Computer Studies*, *73*, 37–51. https://doi.org/10.1016/j.ijhcs.2014.08.004

Nakagawa, Y., Kamimura, A., & Kawaguchi, Y. (2012). MimicTile: a variable stiffness deformable user interface for mobile devices. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 745–748). New York, New York, USA: ACM Press. https://doi.org/10.1145/2207676.2207782

NIDCD Information Clearinghouse. (2010). *Speech and Language Developmental Milestones, NIH Publication No. 13-4781*. Retrieved from https://www.nidcd.nih.gov/health/speech-and-language

Nikkila, S., Patel, G., Sundaram, H., Kelliher, A., & Sabharwal, A. (2012). Wind runners: designing a game to encourage medical adherence for children with asthma. In *Extended Abstracts of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 2411–2416). ACM. Retrieved from http://dl.acm.org/citation.cfm?id=2223811

Nilsson, S., Arvola, M., Szczepanski, A., & Bång, M. (2012). Exploring place and direction. In *Proceedings of the 24th Australian Computer-Human Interaction Conference on - OzCHI '12* (pp. 411–419). New York, New York, USA: ACM Press. https://doi.org/10.1145/2414536.2414601

Oviatt, S. (1999a). Mutual disambiguation of recognition errors in a multimodel architecture. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 576–583). New York, NY, USA: ACM. https://doi.org/10.1145/302979.303163

Oviatt, S. (1999b). Ten myths of multimodal interaction. *Communications of the ACM, 42*(11), 74–81. https://doi.org/10.1145/319382.319398

Oviatt, S. (2000). Taming recognition errors with a multimodal interface. *Communications of the ACM*, *43*(9), 45–51. https://doi.org/10.1145/348941.348979

Oviatt, S., Arthur, A., & Cohen, J. (2006). Quiet interfaces that help students think. In *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST)* (pp. 191–200). New York, New York, USA: ACM Press. https://doi.org/10.1145/1166253.1166284

Oviatt, S., Coulston, R., & Lunsford, R. (2004). When do we interact multimodally?: cognitive load and multimodal communication patterns. In *Proceedings of the ACM International Conference on Multimodal Interaction (ICMI)* (pp. 129–136). ACM. https://doi.org/10.1145/1027933.1027957

Palisano, R., Rosenbaum, P., Walter, S., Russell, D., Wood, E., & Galuppi, B. (2008). Development and reliability of a system to classify gross motor function in children with cerebral palsy. *Developmental Medicine & Child Neurology*, *39*(4), 214–223. https://doi.org/10.1111/j.1469-8749.1997.tb07414.x

Pemberton, L., & Winter, M. (2009). Collaborative augmented reality in schools. In *Proceedings of the International Conference on Computer Supported Collaborative Learning (CSCL) - Volume 2* (pp. 109–111). International Society of Learning Sciences. Retrieved from https://dl.acm.org/citation.cfm?id=1599540

Perry, J., Klopfer, E., Norton, M., Sutch, D., Sandford, R., & Facer, K. (2008). AR gone wild: two approaches to using augmented reality learning games in Zoos. *Proceedings of the International Conference for the Learning Sciences (ICLS) - Volume 3*. International Society of the Learning Sciences. Retrieved from https://dl.acm.org/citation.cfm?id=1600034

Perry, K. B., & Hourcade, J. P. (2008). Evaluating one handed thumb tapping on mobile touchscreen devices. In *Proceedings of Graphics Interface* (pp. 57–64). Windsor, Ontario: Canadian Information Process Society. Retrieved from https://dl.acm.org/citation.cfm?id=1375725

Phillips, B., & Zhao, H. (1993). Predictors of Assistive Technology Abandonment. *Assistive Technology*, *5*(1), 36–45. https://doi.org/10.1080/10400435.1993.10132205

Piaget, J. (1983). Piaget's Theory. In P. Mussen (Ed.), *Handbook of Child Psychology*. New York, NY, USA: Wiley & Sons.

Radu, I., Guzdial, K., & Avram, S. (2017). An Observational Coding Scheme for Detecting Children's Usability Problems in Augmented Reality. In *Proceedings of the ACM International Conference on Interaction Design and Children (IDC)* (pp. 643–649). New York, New York, USA: ACM Press. https://doi.org/10.1145/3078072.3084337

Radu, I., MacIntyre, B., & Lourenco, S. (2016). Comparing Children's Crosshair and Finger Interactions in Handheld Augmented Reality. In *Proceedings of the ACM International Conference on Interaction Design and Children (IDC)* (pp. 288–298). New York, New York, USA: ACM Press. https://doi.org/10.1145/2930674.2930726

Read, J. C., MacFarlane, S., & Casey, C. (2003). "Good enough for what?": acceptance of handwriting recognition errors by child users. In *Proceedings of the International Conference on Interaction Design and Children (IDC)* (pp. 155–155). New York, New York, USA: ACM. https://doi.org/10.1145/953536.953565

Robinson, S., Coutrix, C., Pearson, J., Rosso, J., Torquato, M. F., Nigay, L., & Jones, M. (2016). Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 3793–3805). New York, New York, USA: ACM Press. https://doi.org/10.1145/2858036.2858097

Rosenbloom, L., & Horton, M. E. (1971). The Maturation of Fine Prehension in Young Children. *Developmental Medicine & Child Neurology*, *13*(1), 3–8. https://doi.org/10.1111/j.1469-8749.1971.tb03025.x

Rust, K., Malu, M., Anthony, L., & Findlater, L. (2014). Understanding child-defined gestures and children's mental models for touchscreen tabletop interaction. In *Proceedings of the International Conference on Interaction Design and Children (IDC)* (pp. 201–204). New York, New York, USA: ACM Press. https://doi.org/10.1145/2593968.2610452

Santrock, J. W. (2006). *Life-Span Development* (10th ed.). McGraw-Hill.

Schwesig, C., Poupyrev, I., & Mori, E. (2003). Gummi: user interface for deformable computers. In *Extended Abstracts of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 954–955). New York, New York, USA: ACM Press. https://doi.org/10.1145/765891.766091

Seow, S., & C., S. (2005). Information Theoretic Models of HCI: A Comparison of the Hick-Hyman Law and Fitts' Law. *Human-Computer Interaction*, *20*(3), 315–352. https://doi.org/10.1207/s15327051hci2003_3

Shaw, A. (2017). Human-Centered Recognition of Children's Touchscreen Gestures. In *Proceedings of the ACM International Conference on Multimodal Interaction (ICMI)* (pp. 638–642). ACM Press. https://doi.org/10.1145/3136755.3137033

Siek, K. A., Rogers, Y., & Connelly, K. H. (2005). Fat Finger Worries: How Older and Younger Users Physically Interact with PDAs. In *Proceedings of the IFIP TC13 Conference on Human-Computer Interaction (INTERACT)* (pp. 267–280). Springer, Berlin, Heidelberg. https://doi.org/10.1007/11555261_24

Smyth, M. M. (1989). Visual control of movement patterns and the grammar of action. *Acta Psychologica*, *70*(3), 253–265. https://doi.org/10.1016/0001-6918(89)90025-5

Statista. (2018a). Gaming devices used by children in the United States in 2015. Retrieved March 13, 2018, from https://www.statista.com/statistics/466760/devices-gaming-children-usa/

Statista. (2018b). Number of smartphone users worldwide from 2014 to 2020 (in billions). Retrieved March 13, 2018, from https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/

Strickland, D., Marcus, L. M., Mesibov, G. B., & Hogan, K. (1996). Brief report: Two case studies using virtual reality as a learning tool for autistic children. *Journal of Autism and Developmental Disorders*, *26*(6), 651–659. https://doi.org/10.1007/BF02172354

Thomas, J. R. (1980). Acquisition of motor skills: information processing differences between children and adults. *Research Quarterly for Exercise and Sport*, *51*(1), 158–173. https://doi.org/10.1080/02701367.1980.10609281

Valderrama Bahamóndez, E. del C., Kubitza, T., Henze, N., & Schmidt, A. (2013). Analysis of children's handwriting on touchscreen phones. In *Proceedings of the International Conference on Human-Computer Interaction with Mobile Devices and Services* (pp. 171–174). New York, New York, USA: ACM Press. https://doi.org/10.1145/2493190.2493222

Vatavu, R.-D., Anthony, L., & Brown, Q. (2015). Child or Adult? Inferring Smartphone Users' Age Group from Touch Measurements Alone. In J. Abascal, S. Barbosa, M. Fetter, T. Gross, P. Palanque, & M. Winckler (Eds.), *Human-Computer Interaction – INTERACT 2015. INTERACT 2015. Lecture Notes in Computer Science, vol 9299* (pp. 1–9). Springer, Cham. https://doi.org/10.1007/978-3-319-22723-8_1

Vatavu, R.-D., Anthony, L., & Wobbrock, J. O. (2012). Gestures as point clouds: a $P recognizer for user interface prototypes. In *Proceedings of the ACM International Conference on Multimodal Interaction (ICMI)* (pp. 273–280). New York, New York, USA: ACM Press. https://doi.org/10.1145/2388676.2388732

Vatavu, R.-D., Cramariuc, G., & Schipor, D. M. (2015). Touch interaction for children aged 3 to 6 years: Experimental findings and relationship to motor skills. *International Journal of Human-Computer Studies*, *74*, 54–76. https://doi.org/10.1016/j.ijhcs.2014.10.007

Vinter, A., & Meulenbroek, R. (1993). The role of manual dominance and visual feedback in circular drawing movements. *Journal of Human Movement Studies*, *25*, 11–37.

VisionSystems Design. (2012). Camera makes Puffersphere interactive. Retrieved May 23, 2016, from http://www.vision-systems.com/articles/print/volume-17/issue-1/departments/snapshots/camera-makes-puffersphere-interactive.html

Weinland, D., Ronfard, R., & Boyer, E. (2011). A survey of vision-based methods for action representation, segmentation and recognition. *Computer Vision and Image Understanding*, *115*(2), 224–241. https://doi.org/10.1016/J.CVIU.2010.10.002

Wobbrock, J. O., Kane, S. K., Gajos, K. Z., Harada, S., & Froehlich, J. (2011). Ability-Based Design. *ACM Transactions on Accessible Computing*, *3*(3), 1–27. https://doi.org/10.1145/1952383.1952384

Woodward, J., Shaw, A., Aloba, A., Jain, A., Ruiz, J., & Anthony, L. (2017). Tablets, tabletops, and smartphones: cross-platform comparisons of children's touchscreen interactions. In *Proceedings of the ACM International Conference on Multimodal Interaction (ICMI)* (pp. 5–14). New York, New York, USA: ACM Press. https://doi.org/10.1145/3136755.3136762

Woodward, J., Shaw, A., Luc, A., Craig, B., Das, J., Hall Jr., P., … Anthony, L. (2016). Characterizing How Interface Complexity Affects Children's Touchscreen Interactions. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)* (pp. 1921–1933). New York, New York, USA: ACM Press. https://doi.org/10.1145/2858036.2858200

Xiao, B., Girand, C., & Oviatt, S. (2002). Multimodal integration patterns in children. In *Proceedings of International Conference on Spoken-Language Processing (INTERSPEECH)* (pp. 629–632). Intl Speech Comm Assoc.

Yildirim, S., & Narayanan, S. (2009). Automatic Detection of Disfluency Boundaries in Spontaneous Speech of Children Using Audio–Visual Information. *IEEE Transactions on Audio, Speech, and Language Processing*, *17*(1), 2–12. https://doi.org/10.1109/TASL.2008.2006728

Yilmaz, A., Javed, O., & Shah, M. (2006). Object tracking: A survey. *ACM Computing Surveys*, *38*(4), Article No. 13. https://doi.org/10.1145/1177352.1177355

## Author Biography

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## Appendix A.

### MTAGIC Design Recommendations: Cumulative Lessons From Five Years of Study

*Lisa Anthony and the INIT Lab at the University of Florida*

| **Interaction** | **Recommendation** |
|---|---|
| ***Touch Interactions*** | Use timing and location of touches and interface widgets to identify and ignore holdover touches (corollary: improve interface responsiveness to prevent holdovers) (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Use consistent, platform-recommended target sizes (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Increase active area for interface widgets to allow slightly out-of-bounds touches to register and activate the intended widget (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Align targets to edge of screen, or count edge touches (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Provide salient visual feedback of accepted input to prevent holdovers (Woodward et al., 2016). |
| | Avoid small targets at the screen edges, especially in visually complex interfaces (Woodward et al., 2016). |
| | Consider the trade-off between visual saliency and response time when designing games or applications for speedy input (Woodward et al., 2016). |
| | Account for children's tendency to drag pens while touching targets (Woodward et al., 2017). |
| | For all devices, favor placing widgets closer to the child (Woodward et al., 2017). |
| | For the tabletop, space widgets farther apart for both children and adults (Woodward et al., 2017). |
| ***Gesture Interactions*** | Train age-specific recognizers to improve accuracy on kids' gestures (Anthony, Brown, et al., 2012; Anthony et al., 2014). |
| | Design gesture sets to avoid confusions caused by recognizer limitations (corollary: train recognizers specifically to problematic pairs) (Anthony, Brown, et al., 2012). |
| | Design gestures and gesture sets that make conceptual sense to children and are easy for them to execute (Anthony et al., 2014). |
| | Develop child-specific recognizers from the ground up (Anthony et al., 2014). |
| | Allow recognizers to learn over time and adapt to an individual child's gestures (Anthony et al., 2014). |
| | DO provide visual feedback for surface gesture interaction on mobile devices (Anthony, Brown, et al., 2013). |
| | DON'T include gestures unfamiliar to users (Anthony, Brown, et al., 2013). |
| | DO test new gesture sets with the target recognizer in advance (Anthony, Brown, et al., 2013). |
| | Train gesture recognizers for younger children (e.g., ages 5 to 7) with more examples (Woodward et al., 2016). |
| | Collect gesture data [for training] on whichever device is most convenient for the youngest children (e.g., ages 5 to 7) (Woodward et al., 2017). |
| ***Data Collection*** | Use gamification elements such as points, prizes, or game design patterns (Brewer et al., 2013). |
| | Personalize motivating elements to the individual child (Brewer et al., 2013). |
| | Avoid conducting sessions with children who know each other (Brewer et al., 2013). |
| | Consider a balance of distraction in controlled environments (Brewer et al., 2013). |

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## Appendix B.

## Detailed Numerical Results

In the following tables, detailed means [and standard deviations] are provided for each study (one study per row). These data correspond to the graphs shown in Figures 5, 6, 7, and 8. Significant factors (at the $p < .05$ level) are denoted by a † in the tables for each study.

### B.1 Touchscreen Interaction Results

| **Study** | **Overall Misses** | **Target Size** | **Edge Padding** | **Location (Top, Center, Bottom)** | **Location (Left, Center, Right)** |
|---|---|---|---|---|---|
| **Abstract Interface Smartphone Study** (Anthony, Brown, et al., 2012; Anthony et al., 2014) | **Children:** 23% | V.Small: 56%[13%]<br>Small: 22%[14%]<br>Medium: 10%[ 6%]<br>Large†: 4%[ 4%] | Yes: 30%[12%]<br>No†: 18%[ 7%] | *not reported* | *not reported* |
| | **Adults:** 17% | V.Small: 50%[ 9%]<br>Small: 12%[ 9%]<br>Medium: 4%[ 5%]<br>Large†: 1%[ 3%] | Yes: 22%[ 5%]<br>No†: 12%[ 6%] | | |
| **Visual Feedback Smartphone Study** (Anthony et al., 2014) | *not reported* | **7 to 10:**<br>V.Small: 57%[11%]<br>Small: 31%[15%]<br>Medium: 12%[ 6%]<br>Large†: 4%[ 5%] | Yes: 37%[14%]<br>No†: 18%[ 7%] | *not reported* | *not reported* |
| | | **11 to 13:**<br>V.Small: 58%[11%]<br>Small: 17%[11%]<br>Medium: 11%[ 7%]<br>Large†: 3%[ 3%] | Yes: 29%[ 7%]<br>No†: 18%[ 7%] | | |
| | | **14 to 17:**<br>V.Small: 54%[14%]<br>Small: 21%[16%]<br>Medium: 11%[10%]<br>Large†: 3%[ 3%] | Yes: 27%[10%]<br>No†: 18%[10%] | | |
| | | **Adults:**<br>V.Small: 48%[11%]<br>Small: 12%[10%]<br>Medium: 3%[ 4%]<br>Large†: 1%[ 3%] | Yes: 20%[ 6%]<br>No†: 13%[ 6%] | | |
| **Interface Complexity Smartphone Study *(children only)*** (Woodward et al., 2016) | Abstract: 23%[6%]<br>Complex†: 24%[6%] | V.Small: 58%[11%]<br>Small: 25%[10%]<br>Medium: 9%[ 7%]<br>Large†: 4%[ 6%] | Yes: 31%[ 7%]<br>No†: 17%[ 8%] | Top: 24%[ 8%]<br>Center: 26%[ 6%]<br>Bottom† 19%[ 6%] | Left: 25%[ 7%]<br>Center: 22%[ 8%]<br>Right†: 24%[ 5%] |
| **Tablet Study *(children only)*** (Woodward et al., 2017) | Pen: 41%[10%]<br>Touch†: 32%[13%] | **Pen:**<br>V.Small: 62%[19%]<br>Small: 34%[17%]<br>Medium: 21%[14%]<br>Large†: 10%[10%] | **Both:**<br>Yes: 41%[15%]<br>No: 38%[13%]<br>*(no effect)* | **Both:**<br>Top: 50%[18%]<br>Center: 38%[12%]<br>Bottom† 31%[16%] | **Both:**<br>Left: 44%[16%]<br>Center: 39%[14%]<br>Right†: 35%[11%] |
| | | **Touch:**<br>V.Small: 72%[13%]<br>Small: 42%[14%]<br>Medium: 27%[15%]<br>Large†: 22%[12%] | | | |
| **Tabletop Study *(children only)*** (Woodward et al., 2017) | Overall: 62%[16%] | VS(.4in): 76%[15%]<br>SM(.6in): 61%[18%]<br>MD(.8in): 58%[19%]<br>LG(1in)†: 52%[19%] | Yes: 63%[14%]<br>No: 65%[18%]<br>*(no effect)* | Top: 64%[18%]<br>Center: 68%[15%]<br>Bottom 62%[15%]<br>*(no effect)* | Left: 67%[18%]<br>Center: 60%[16%]<br>Right: 64%[15%]<br>*(no effect)* |

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## B.2 Gesture Recognition Results

| Study | Recognizer Tested | User-Dependent (train / test same user) | | User-Independent (train / test diff. users) | | Correlation to Age | Other Tests |
|---|---|---|---|---|---|---|---|
| **Abstract Interface Smartphone Study** (Anthony, Brown, et al., 2012; Anthony et al., 2014) | $N-Protractor (Anthony & Wobbrock, 2012) | **Age†**<br>**Children:**<br>*(7 to 16)* | 81%[ 9%] | *not reported* | | *signif.:*<br>r=.59, p<0.01, N=30 | *no signif. effect of complexity* |
| | | **Adults:** | 90%[ 6%] | | | | |
| | | | | | | | |
| **Visual Feedback Smartphone Study** (Anthony, Brown, et al., 2013) | $N-Protractor (Anthony & Wobbrock, 2012) | **Age†:**<br>**7 to 10:** | 77%[ 8%] | *not reported* | | *not reported* | *not reported* |
| | | **11 to 13:** | 81%[ 8%] | | | | |
| | | **14 to 17:** | 88%[ 5%] | | | | |
| | | **Adults:** | 91%[ 6%] | | | | |
| (Anthony et al., 2014) | $P (Vatavu et al., 2012) | **Age†:**<br>**7 to 10:** | 84%[ 9%] | **Age†:**<br>**7 to 10:** | 70%[ 8%] | *signif.:*<br>r=.60, p<0.01, N=39 ($P) | *n/a* |
| | | **11 to 13:** | 92%[ 8%] | **11 to 13:** | 78%[ 6%] | | |
| | | **14 to 17:** | 96%[ 2%] | **14 to 17:** | 78%[ 8%] | | |
| | | **Adults:** | 97%[ 5%] | **Adults:** | 84%[ 7%] | | |
| | | | | | | | |
| **Interface Complexity Smartphone Study** (Woodward et al., 2016) | $P (Vatavu et al., 2012) | **Age†:**<br>**5 to 7:** | 79%[19%] | **Age†:**<br>**5 to 7:** | 65%[8 %] | *signif.:*<br>r=.52, p<.01, N=27 | *no signif. effect of complexity; signif. interaction between training examples and age* |
| | | **8 to 10:** | 88%[10%] | **8 to 10:** | 76%[ 8%] | | |
| | | **Adults:** | 96%[ 5%] | **Adults:** | 81%[ 8%] | | |
| | | | | | | | |
| **Tablet Study** (Woodward et al., 2017) | $P (Vatavu et al., 2012) | **Age†:**<br>**5 to 6:** | 69%[14%] | **Age†:**<br>**5 to 6:** | 47%[ 5%] | *not reported* | *no signif. effect of input modality* |
| | | **7 to 8:** | 83%[ 9%] | **7 to 8:** | 58%[ 5%] | | |
| | | **9 to 10:** | 89%[ 7%] | **9 to 10:** | 78%[ 4%] | | |
| | | | | | | | |
| **Tabletop Study** (Woodward et al., 2017) | $P (Vatavu et al., 2012) | **Age:**<br>**6 to 7:** | 64%[21%] | **Age:**<br>**6 to 7:** | 68%[13%] | *not reported* | *n/a* |
| | | **8 to 10:**<br>***(no effect)*** | 75%[18%] | **8 to 10:**<br>***(no effect)*** | 76%[11%] | | |
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