Title

Tangrams 101: Effects of Tangible and Digital Play on Children’s Spatial Reasoning and Parental Spatial Language

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TANGRAMS 101: EFFECTS OF TANGIBLE AND DIGITAL PLAY ON CHILDREN'S SPATIAL REASONING AND PARENTAL SPATIAL LANGUAGE

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Nicola K. Antrilli

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Abstract

Tangrams 101: Effects of Tangible and Digital Play on Children's Spatial Reasoning and Parental Spatial Language

Nicola K. Antrilli

Understanding the experiences that shape the development of spatial reasoning is important, as it is related to academic achievement and participation in STEM fields (Newcombe, 2010). Play with puzzles, a common experience for many children, contributes to the development of spatial concepts, through hands-on experience manipulating spatially relevant objects and through the use of spatial language (Levine et al., 2012). However, these types of experiences may be changing as touchscreen devices become more commonly used for play, and there is very limited research that investigates this relationship.

This dissertation addresses the gap by comparing 6-year-olds' play with tangram puzzles using tangible or digital pieces. Specifically, I investigated whether playing with a tangible tangram set or one of two digital sets with different mechanics (e.g., tapping vs. twisting) would differentially affect children's spatial reasoning. In addition, I investigated whether parental use of spatial language would differ between tangram sets. Sixty parent-child dyads participated in the study and were randomly assigned to play tangram puzzles using one of three different forms: a traditional, tangible set (Tangible condition), a digital set where they rotated pieces using two-fingers and a twisting motion (Digital-Rotate condition), or a digital set where they rotated pieces by double tapping them (Digital-Tap condition). Children's spatial reasoning was measured before and after play. In addition, two independent raters coded parents’ use of spatial language during the play session.

The results revealed that children in the Tangible condition showed greater improvement than those in the Digital-Tap condition on items that required diagonal rotation. In addition, parents in the Digital-Tap condition used a higher proportion of deictic words than parents in the Digital-Rotate condition. Additional exploratory analyses examined children’s everyday use of touchscreen devices and revealed that children predominantly use devices by themselves, without the presence of their parents. Together, these findings add to the growing body of research that examines the impact of touchscreen use on child development and bears practical implications for the design and use of touchscreen games in early childhood.

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Tangrams 101: Effects of Tangible and Digital Play on Children's Spatial Reasoning and Parental Spatial Language

Spatial reasoning, or the ability to visualize, mentally generate, and manipulate information about the objects and spaces in our environment, is a vital part of navigating experiences in everyday life (Uttal et al., 2013). This often involves understanding the relations between objects or employing more abstract and analogical thinking. For many professions, the ability to mentally manipulate information in the environment is crucial, such as a city planner that designs a sewer system, or a mechanic that needs to know the precise placement of parts. However, the need for spatial reasoning is less evident when engaging in similar, albeit smaller scale, activities in everyday life. Tasks like walking through your house to get to the kitchen, describing to someone that the remote control is under the couch, and navigating a map all rely on the ability to orient yourself in space.

Beyond our daily lives, spatial reasoning has been strongly linked with science, technology, engineering and math (STEM) and professions associated with these fields (Coyle & Liben, 2018; Liben, 2009; Newcombe, 2010; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2014). This, perhaps, is not surprising given that work in these areas typically requires the understanding of complex spatial information such as seismic patterns and genetic structure. In particular, there has been a large amount of research supporting the link between early spatial reasoning and math achievement in adolescence (Cheng & Mix, 2014; Clements & Sarama, 2007; Gunderson, Ramirez, Beilock, & Levine, 2012; Verdine et al., 2014). For example, Gunderson et al. (2012) found that 1st and 2nd graders' performance on mental transformation tasks significantly predicted their improvement in linear number line knowledge over the course of the year. Additionally, mental rotation training has been shown to improve performance on math calculations in 6- to 8-year-old children (Cheng & Mix, 2014).

The strong links between spatial reasoning and math achievement have also been supported in children who are not yet at school age. For example, Verdine et al. (2014) found that 3-year-olds' performance on a spatial assembly task predicted a large proportion of the variability in their concurrent math skills. In their study, 3-year-olds were assessed on their spatial reasoning using the Test of Spatial Ability (TOSA) and then tested on their mathematical skills and executive function at age 4. Their results showed that spatial reasoning at age 3 and executive function at age 4 predicted 70% of the variance in mathematical skills and that spatial reasoning at age 3 predicted 27% of mathematical skills on its own. These findings provide evidence for an association between spatial skills and mathematics skills in early childhood. Further support from neurological research has shown that similar areas of the brain activate when engaging in spatial and mathematical processing, suggesting that they rely on a shared system (Göbel, Walsh, & Rushworth, 2001). Together, these findings highlight the relationship between spatial reasoning and STEM fields, which has pushed educators and policymakers to advocate for more spatial education in early schooling (National Research Council, 2006). Thus, it is important to examine how spatial reasoning develops both before and during schooling.

Hands-on Experience

A large body of research has highlighted the importance of hands-on experience on the development of spatial reasoning (Campos, Anderson, Barbu-Roth, Hubbard, Hertenstein, & Witherington, 2000; Gibson, 1988; Piaget & Inhelder, 1956). In particular, prior experience acting in and on the environment is argued to play a crucial role in motor, perceptual, and cognitive development. For example, when infants master the ability to sit up on their own, they are now able to freely explore and manipulate the objects that are in their immediate environment (Soska, Adolph, & Johnson, 2010). When they master the ability to crawl and walk, they can explore the world in a new and meaningful way, discovering information that was previously inaccessible to them (Schwarzer, Freitag, & Schum, 2013). Being able to explore the world in these newfound ways affords all kinds of interactions that help shape infants' and toddlers' perception of the world (Campos et al., 2000). Perhaps most famous, Piaget believed that our basic knowledge of the world stems from this type of sensorimotor experience (Piaget & Inhelder, 1956). Gibson (1988) expanded this idea by focusing on exploratory behavior from an ecological perspective, arguing that new affordances for action lead infants to actively update and refine their knowledge of the world.

Active exploration allows infants and young children to develop knowledge about how people and objects in the world operate in space around them. In particular, the association between actions and consequences on the spatial world has led many researchers to focus on mental rotation, the ability to mentally manipulate information about objects in our environment (Moore & Johnson, 2008). Previous research has found that these abilities emerge as early as 3 to 6 months of age (Möhring & Frick, 2013; Rochat & Hespos, 1996). For example, Rochat and Hespos (1996) found that 4-month-olds could track and anticipate the final orientation of an object after it passed through an occluder. This finding suggests that infants are capable of rudimentary forms of mental rotation when given relevant information, in this case, movement along a path. Möhring and Frick (2013) took this a step further to determine if infants can initiate mental transformations without the help of motion information. They examined whether 6-month-olds were able to correctly identify a familiar object in a new orientation from its mirror image, even after the object was hidden. Providing no prior motion cues, this task required infants to initiate mental rotation. They found that only infants that were given prior experience manipulating the object were able to correctly identify the familiar object from its mirror image. This suggests that infants are capable of initiating mental rotation by incorporating their prior experience acting on objects into this process.

With older infants, Frick and Wang (2014) examined mental rotation using a complex task with multiple objects and multiple actions, thus bring the task one step closer to resemble real-world situations. They found that 14-month-olds were able to correctly identify the final orientation of an object that was rotated under a cover, but only when they had prior experience rotating another object on a turntable. More recently, we have shown that the benefit of active experience on mental rotation is related to the integration of sensory information from multiple modalities, specifically visual and haptic information (Antrilli & Wang, 2016). In our study, 14-month-olds were given experience with a striped cylinder that was attached to a turntable. Half of them were given experience with a cylinder with vertical stripes, and the other half a cylinder with horizontal stripes. Notably, only the cylinder with vertical stripes provided discernable visual cues for rotation, whereas the cylinder with horizontal stripes provided few visual cues of rotation when acted upon. We found that only infants who were given experience with the cylinder with vertical stripes successfully identified the improbable rotation outcome. This suggests that the visual cues of rotation, produced from infants' action on the cylinder with vertical stripes but not with horizontal stripes, mediated the effects of action on mental rotation. Together, the findings suggest that hands-on experience alone may not be sufficient. Rather, it is the integration of information from multiple modalities, such as visual and motor information, that facilitates early mental rotation.

In addition to mental rotation, active exploration via self-produced locomotion facilitates early forms of spatial navigation (Campos et al., 2000; Clearfield, 2004; Kretch & Adolph, 2013; Kretch, Franchak, & Adolph, 2014). For example, Kretch and Adolph (2013) found that when infants were unsure about whether they would fall when crossing a narrow bridge, they would explore the drop off by reaching their hands into the gap to assess the probability of falling. Additionally, they would adjust their gait depending on the width of the bridge (i.e., put one foot directly in front of the other). Prior research has also shown that crawling and walking infants can use landmarks to navigate to a goal location in a large space if they have at least 6 weeks experience with the chosen form of locomotion (Clearfield, 2004). Interestingly, infants who were successful as crawlers were not immediately successful as walkers. It was not until they had at least 6 weeks of experience in this new form of locomotion that they were able to navigate to the goal location. This may not be surprising when you consider the vastly different perceptual experience between walking and crawling. When crawling, the majority of visual information that infants receive is of the floor, whereas when walking, infants typically spend more time looking straight ahead, thus providing walkers with a distinct visual experience from crawlers (Kretch et al., 2014). These experiences can lead to vastly different expectations of how to navigate the world. Together, these results highlight the importance of motor experience in learning to navigate a spatial world.

Spatial play in everyday life. Outside of controlled laboratory experiments, a majority of the information that infants and young children generate from active experience comes from play. For example, playing with blocks can provide information about balance, size, and shape. In addition to gaining knowledge via their hands-on experiences, children are often exposed to new information via their social and linguistic experiences when playing with adults (Tamis-LeMonda, Adolph, Lobo, Karasik, Ishak, & Dimitropoulou, 2008; Walle & Campos, 2014). For example, parents might highlight the names of certain shapes that are being used or created when playing with blocks. Similarly, parents might talk about how certain shapes are different from each other, thus providing young children with crucial information about the objects in their environment. Together, the combination of hands-on and social experiences during play helps shape young children’s expectations of the world.

Perhaps one of the most common forms of play that infants and toddlers experience is with shape sorters, which provide early exposure to and knowledge about basic shape names, properties, and categories (Clements, Swaminathan, Hannibal, & Sarama, 1999; Cross, Woods & Schweingruber, 2009). This type of play allows children to gain knowledge about the physical characteristics of basic geometric shapes, how they operate in space, and what their names are. Indeed, research has shown that by 25 months, children have a rudimentary knowledge of canonical shapes (i.e., triangles have 3 sides) and that by 30 months many children have advanced knowledge of canonical shapes (i.e., triangles are equilateral). At this age, they are also starting to apply them to atypical instances of shape categories (i.e., isosceles triangles are also triangles; Verdine, Lucca, Golinkoff, Hirsh-Pasek & Newcombe, 2016). However, 30-month-olds still struggle with identifying shapes that are embedded within a larger picture, such as identifying that a slice of pizza is also a triangle (Verdine et al., 2016). One possible reason for this difficulty is that common toys, such as shape sorters, typically consist of canonical shapes, thus limiting the exposure that young children have to non-canonical variants (Dempsey, Verdine, Golinkoff & Hirsh-Pasek, 2013). Thus, children may not need to accommodate new shape variants into existing schemas, and parents may implicitly relay less information about shape variants (e.g., that is a slice of pizza *and* a triangle) with traditional forms of these toys.

In older children, play with spatial materials tends to be more complex than with shape sorters and basic shapes. More complex play may include things such as building blocks (i.e., Legos) and puzzles, both of which are associated with children's current and future spatial reasoning (Casey, Andrews, Schindler, Kersh, Samper, & Copley, 2008; Ferrara, Hirsh-Pasek, Newcombe, Golinkoff, & Lam, 2011; Jirout & Newcombe, 2015; Levine, Ratliff, Huttenlocher, & Cannon, 2012). Playing with blocks and puzzles facilitates spatial reasoning by providing practice thinking about where objects go in relation to one another. For example, when building a castle with blocks, children might be exposed to different narratives, such as descriptive (i.e., put this block *on top* of that one) and metaphorical (i.e., this castle is *as big* as a mountain) language that ground spatial representations. This type of play experience with tangible materials is typical for many families with young children. At the same time, play has started to include the use of touchscreens for many children (Rideout, 2013; Shuler et al., 2012). Despite the increase in touchscreen use as a play medium, research that examines the impact on children's cognitive and social development is lacking (Cohen, Hadley, & Frank, 2011; Hirsh-Pasek, Zosh, Golinkoff, Gray, Robb, & Kaufman, 2015). One potential benefit of touchscreen devices is that they afford actions that can be intuitive, such as being able to move objects on the screen with your hands. In this way, touchscreens invite a form of interaction that somewhat mimics interaction with the physical world. Thus, touchscreens allow for a new kind of hands-on experience that makes for an interesting platform to examine the effects of play on spatial reasoning.

Previous research has argued that spatial reasoning is malleable and that it can be trained through practice with spatially relevant, tangible materials (Casey et al., 2008; Grissmer et al., 2013; Uttal et al., 2013). For example, Casey et al. (2008) had kindergarten children play with blocks or receive their regular education once a week over the span of 6 to 8 weeks before they were tested on a measure of spatial visualization and mental rotation. They found that playing with blocks improved kindergarteners' performance on the tasks relative to those who partook in their regular education. In a similar intervention, Grissmer et al. (2013) provided kindergarten and first-grade children with experience playing with spatial materials such as Legos and pattern blocks 4 times a week over a span of 28 weeks. They found that children's spatial reasoning and mathematical performance increased during this 28-week timespan. Further research has shown that block and puzzle play that occurs naturally in the home is related to children's long-term spatial reasoning. For example, children who were observed playing with puzzles during a series of home visits from ages 2 to 4 performed significantly better on a spatial-reasoning task at age 4.5 than children who did not play with puzzles (Levine et al., 2012). Among those who were observed playing with puzzles, the frequency of play was significantly related to task performance, suggesting that experience playing with and manipulating spatially relevant, tangible materials facilitates spatial reasoning over time.

Spatial play with touchscreens. As access to touchscreen devices has risen over recent years, it has become increasingly common for children to have experience with and use these devices for play. Although research has documented the benefits of playing with spatially relevant, tangible materials on spatial reasoning, research on the effects of play with similar materials in a digital format is lacking. Research on related forms of device use such as e-books (Parish-Morris, Mahajan, Hirsh-Pasek, Golinkoff, & Collins, 2013) and electronic toys (Wooldridge & Shopka, 2012; Zosh, Verdine, Filipowicz, Golinkoff, Hirsh-Pasek, & Newcombe, 2015) has found that the features of these electronic devices can be distracting to parents and children, resulting in less varied language from parents while using these devices compared to non-electronic versions. For example, when using an electronic shape sorter, parents used less spatial language with their 2-year-olds in comparison to using a traditional shape sorter. This difference was likely due to increased talk about the features of the toy instead of the spatially relevant functions of the toy (Zosh et al., 2015). Along this vein, research with older children has shown that children learned more from computers when their parents provided guidance that focused on the content rather than the device (Flynn & Richert, 2015). Together, these findings point to an interesting trend where using an electronic device detracts from parents' focus on task-relevant content. This pattern has recently been extended to the use of touchscreen devices. Verdine et al. (2019) asked parents and their 3-year-old children to play a game using tangible geometric shapes that were canonical, a mix of canonical and non-canonical variants, or canonical shapes on a tablet. They found that parents used fewer overall words, fewer shape names, and fewer spatial words when playing with the tablet in comparison to the other conditions with tangible materials. This finding suggests that, like other forms of technology use, using a touchscreen device for play may result in a lower quality of parental interaction, such as the use of spatial language, than playing with their traditional counterparts.

Parental Talk

Prior research proposes that language plays a large role in the way that we think about and perceive the world (Gentner & Loewenstein, 2002; Jant, Haden, Uttal, & Babcock, 2014, Vygotsky, 1980). With this in mind, much of the research on the development of spatial reasoning points specifically to the influence of hearing parents use spatial language on children's short- and long-term spatial reasoning (Ferrara et al., 2011; Pruden, Levine & Huttenlocher, 2011; Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2014). At its core, research has argued that language provides a foundation for which relational cognition, and thereby abstract and spatial reasoning, can be learned (Gentner, 2016). In this view, language acts as a "cognitive tool kit" that allows us to represent and think about abstract concepts. Without language, we would not have the symbolic system necessary for this type of thinking. Indeed, research argues that language provides a system by which we ground relational thinking in embodied experiences (Gibbs, 2003), and extend it to concepts such as space, time, and humor (Gentner, Imai, & Boroditsky, 2002). For example, the concept of humor exists as relationships between an abstract concept (target domain) and concrete source domains that are grounded in spatialized, embodied actions (Samermit & Gibbs, 2016). In this view, children use their active experiences as the foundation on which they integrate newfound linguistic knowledge, helping them understand and ground relationships between abstract concepts.

Learning the language necessary to understand abstract concepts can be very challenging for young children. Children may initially learn through simple associations from exposure, such as *cow* goes with “*moo*” and *dog* goes with “*bark*." Children also learn from more nuanced mechanisms like direct interaction with parents. In particular, research has shown that children can infer that important conceptual information is being relayed from the descriptive language their parents' use (Cimpian & Markman, 2009). For example, play with spatial materials may encourage parents to describe different shapes (e.g., circles are round or triangles look like this), thus providing children with object labels that set the foundation for early conceptions of shapes. Children also learn via relational language, which supports children's abstract reasoning by inviting comparisons between familiar and unfamiliar concepts (Gentner, 2016; Gentner & Markman, 1997). For example, when children hear the same word used for multiple objects, such as labeling both an equilateral and isosceles triangle a triangle, it invites them to think about and identify the common relational pattern. By enacting this process of transfer, children now have a label for something they did not have before, which may make it easier for them to identify and transfer these concepts to future scenarios.

Given research showing that children learn language through exposure and direct instruction (Cimpian & Markman, 2009), it is important that we understand the situations in which parental use of spatial language is most likely to occur. Research has found that children tend to be exposed to spatial language more often when playing with spatial than non-spatial materials with their parents (Ferarra et al., 2011;

Pruden et al., 2011). For example, parents produced significantly more spatial language when working with their 3- to 5-year-old children towards a shared goal during block play, in comparison to when they were given preassembled structures to play with or when they played freely (Ferrara et al, 2011). A second experiment revealed that regardless of the play context (goal-oriented, preassembled, or free play), the mere act of playing with blocks elicited a greater proportion of spatial language from parents when compared to play that did not involve construction toys (Ferrara et al., 2011). These findings provide strong evidence that play with spatially relevant toys elicits parental use of spatial language.

Previous research supports the importance of parental use of spatial language for children's spatial reasoning (Ferarra et al., 2011; Pruden et al., 2011). For example, over a series of home visits from ages 2 to 4, Pruden et al. (2011) found that parental use of spatial language during play activities was a significant predictor of performance on a spatial task at age 4.5. They also found that parents' and children's use of spatial language was positively correlated and that children's spatial vocabulary was also predictive of their spatial reasoning at age 4.5. This finding supports the argument that having the language to conceptualize abstract spatial concepts is beneficial to children's ability to understand them. Together, these findings suggest that mere exposure to puzzles during playtime can have a long-term impact on spatial reasoning, likely due to practice engaging in spatial thinking via manipulating tangible materials and to the spatial language heard from parents.

Whether or not parents use the same quality of spatial language when playing with touchscreens is still unclear. To my knowledge, only one study has examined this and found that parental use of spatial language was lower when playing on a touchscreen than with tangible materials (Verdine et al., 2019). However, in their study the touchscreen device audibly labeled the names of shapes whenever they were touched, resulting in children hearing the same total amount of spatial words as those who played with tangible materials. Thus, parents' lower use of spatial language may have been due to the touchscreen's production of spatial words, rather than something inherent about using the device itself. Given that children's play experiences with touchscreens are becoming increasingly common, it is timely to examine the effects on parental use of spatial language.

The Present Research

This dissertation examined 5- to 6-year-old's spatial reasoning after playing tangram puzzles using a tangible set or a digital set, as well as parental use of spatial language during play. This is the age when children in the U.S. have entered formal schooling, making it an important time to examine their experiences related to STEM. Whereas previous research points to the benefit of playing with tangible materials, such as blocks and puzzles, on spatial reasoning (Pruden et al., 2011), research on the effect of spatial play with digital materials is lacking. Thus, I aimed to fill this gap by comparing spatial reasoning after playing with tangram puzzles using tangible pieces to using digital pieces on a touchscreen. Research also shows that parents tend to use more spatial language during play with tangible materials (Ferrara et al., 2011) in comparison to play with electronic toys and touchscreens (Verdine et al., 2019; Zosh et al., 2015). Thus, I also compared parental spatial language during play using tangible pieces or digital pieces on a touchscreen.

Tangram puzzles, in particular, provide a good platform for exploration because they tap into children's knowledge and understanding of geometric shapes, such as the ability to categorize and name them, which play an important role in early spatial understanding (Cross et al., 2009). Tangrams provide hands-on experience manipulating common geometric shapes, as well as the opportunity to combine these shapes to explore other, non-canonical, shape categories. These instances of shape categories are an important part of children's early conceptual formation of shape (Fisher, Hirsh-Pasek, Newcombe, & Golinkoff, 2013; Verdine et al., 2019).

Parent-child dyads were randomly assigned to play tangram puzzles in one of three conditions: Tangible, Digital-Rotate or Digital-Tap. In the Tangible condition, they played with the physical pieces of a tangram set. In the Digital-Rotate condition, they played on a touchscreen and rotated pieces by using two fingers and a twisting motion. In the Digital-Tap condition, they also played on a touchscreen but they rotated pieces by tapping them twice. Given the beneficial impact of spatial play with tangible materials on spatial development (Levine et al., 2012), I hypothesized that children would perform higher on a spatial-reasoning task in the Tangible condition than in the Digital conditions.

There has been no research to my knowledge that specifically examines the relationship between *how* children play on touchscreens and their spatial reasoning.

Previous research suggests that spatial reasoning is influenced by hands-on experience in the physical world and that the integration of information from multiple modalities, such as vision and haptic experience, underlie performance on spatial-reasoning tasks (Antrilli & Wang, 2016). Along this line, it seems plausible that different ways of playing could differentially relate to spatial reasoning. In particular, playing in a way that resembles play with tangible materials, such as using two fingers and a twisting motion, may provide children with hands-on experience that more closely maps onto their existing concept of space. In turn, this might provide more useful information for later spatial reasoning. In contrast, when playing in a way that decouples familiar action from perception, such as tapping an object twice to make it rotate, children might not be able to integrate the information in a way that is useful for application in later spatial-reasoning tasks. Thus, I hypothesized that children in the Digital-Rotate condition would perform higher on a spatial-reasoning task than children in the Digital-Tap condition.

For parental use of spatial language, if parents respond similarly to play with touchscreens as in prior research (Verdine et al., 2019; Zosh et al., 2015), it is likely that they will use less spatial language in the Digital conditions than in the Tangible condition. Thus, I hypothesized that parents in the Tangible condition would use a higher proportion of spatial language than in the Digital conditions. In addition, *how* children play touchscreen games may differently impact the language their parents use when playing with them. For example, parents may use language that focuses more on the tablet mechanism when tapping an object to rotate it (e.g., "keep tapping it") in comparison to using two fingers and a twisting motion (e.g., "twist it just a little bit more"). Using an action that is less similar to traditional, tangible forms of interaction, may elicit language that is more device focused, similar to what has been shown in prior research (see Zosh et al., 2015). Thus, I hypothesized that parents in the Digital-Rotate condition would use a higher proportion of spatial language than parents in the Digital-Tap condition.

Finally, I conducted two exploratory analyses to 1) examine whether a relationship between numerical competency and spatial reasoning exists, as has been widely established in prior research (Cheng & Mix, 2014; Verdine et al., 2016), and 2) explore children's experience using touchscreen applications. In everyday life, outside of controlled and observational experiments, it is less clear whether collaborative play with touchscreens is happening. Are parents playing games with their children, or is touchscreen time thought of as solitary playtime? The exploratory analyses begin to address the questions about children's everyday use of touchscreens for play.

Method

Participants

Sixty children (mean age = 5.85 years; range = 5.15 years to 6.67 years) and their parent, typically the mother (90%), participated in the study. The parent-child dyads were randomly assigned to one of three conditions: Tangible (*n* = 20), Digital-Rotate (*n* = 20), and Digital-Tap (*n* = 20). The majority of families (91.7%) participated in a research lab at UC Santa Cruz, with a small subset (8.3%)

participating in the study at home in Los Angeles, California (*n* = 5). Participants were recruited from an existing database, local library groups, word of mouth, or various children's events in the area. Overall, children in the sample came from a variety of ethnic and racial backgrounds (see Table 1), including participants who identified as European-American (52%), Hispanic (10%), Asian/Pacific Islander (5%), mixed race (32%), or other (1%). Parents were also asked to report their annual household income, with over half of the sample reporting income to be over $75,000 per year (55%, see Table 1). Children received a set of tangrams as a gift for their participation. Parents were offered travel reimbursement but were not otherwise compensated for their participation. An additional 4 parent-child dyads participated in the study but were not included, due to speaking a different language (*n* = 1), or distraction that led to unusable data (*n* = 3).

Parent Questionnaires

Parents completed three questionnaires designed to determine if there were any preexisting differences in child characteristics and spatial experiences. First, parents filled out a questionnaire that gathered basic demographic information, including their highest level of education and their annual household income (see Appendix A). Next, parents filled out two questionnaires, described in the following sections, to gather information about potential individual differences in children's use of spatial language and their experience with various digital and non-digital activities.

Spatial Language Checklist. This checklist comprised an extensive list of words taken from a spatial language coding manual (Cannon, Levine, &

Huttenlocher, 2007) and a preposition word list developed by abcteach.com (2001-2008). In total, the Spatial Language Checklist consisted of over 200 words related to spatial thought (See Appendix B). Parents were asked to check only the words that their child says to eliminate the need to guess whether or not they understand the word.

Activities Survey. The Activities Survey (adapted from Antrilli & Wang, 2018) was designed to gather parental reports on children's overall experience with spatial activities and their exposure to and use of screen technology, including daily TV time and time spent using a touchscreen for games (see Appendix C). To assess children's experience with spatial and digital activities, parents were asked to rate to what degree their child participates in several activities on a scale from 1 (less than once a month) to 6 (more than twice a week). This includes things such as playing with blocks, practicing math, and dance, as well as things such as to which degree their child "watches TV on a TV set," and "plays games on a tablet/iPad." If applicable, parents were asked to report the degree to which their child uses applications of a certain genre, such as "drawing," "music," and "games just for fun." Additionally, as an exploratory assessment of children's social experience during touchscreen time, parents were given the opportunity to list any specific applications their child uses, asked to rate how often their child plays on those apps (frequently, often, or rarely), and who they usually play with (always solitary, usually solitary, usually with someone, or always with someone). Finally, parents were asked to rate their own experience with digital technologies.

Materials

***I Spy* book.** Children and their parents were given *I Spy Gold Challenger: A Book of Picture Riddles* (Marzollo & Wick, 1998) to go through to establish a baseline measure of parental use of spatial language. This book is comprised of a series of scenes that are accompanied by a list of hidden objects. The goal of this book is to find the location of the hidden objects and was chosen for the following reasons: 1) The scenes depicted in the book present a wide range of objects that allow tailoring discussion in a multitude of ways. This resembles the vast amount of visual information that children and parents encounter in their everyday lives and thus may elicit more natural behaviors and speech; and 2) The act of searching for objects on the page invites, but does not necessitate, the use of spatial language. For example, one scene depicts a cluttered toy chest and asks to find the following objects: "I Spy a turtle, four ladders, and SAND, Three baseball gloves, and a picture of land; Four birdies of blue, nine bowling pins, A balloon, a mask, and two swim fins" (Figure 1). It is both possible to identify a found object by pointing to it on the page (no spatial language), or by verbally describing its location using spatial language such as "the ladder is *on top* of the truck." Choosing a measure that invited, but did not necessitate spatial language, provided a more accurate assessment of parents' baseline usage of spatial language.

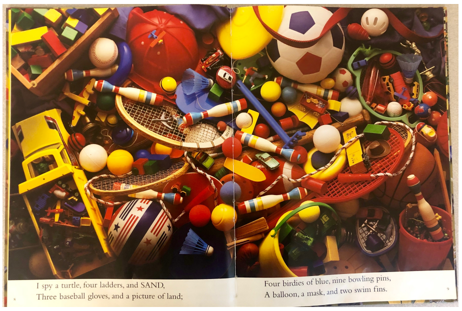

Figure 1. One page from the *I Spy* book (Marzollo & Wick, 1998). Children and parents were told to go through this book however they normally would at home.

Tangrams – Tangible Condition. The tangible version of the tangram set consisted of seven shapes, including two large triangles, one medium triangle, two small triangles, one square, and one parallelogram, which were used to complete a puzzle when placed together in the correct way (Figure 2). The puzzles depicted things like a swan, a cat, and a house. Each puzzle was presented on a separate base that was created from foam board (12in x 8.75in) and had been covered in contact paper. There were a total of ten bases that were numbered to indicate the order in which parents and children should complete them. The first two puzzles had the position of each piece outlined, while the remaining puzzles were made more difficult by including only the outline of the global picture.

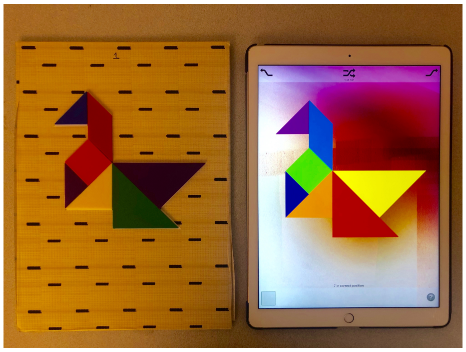

Figure 2. Side by side Images of the first tangram puzzle children and parents completed using the tangible version (left) and the digital versions (right).

Tangrams – Digital Conditions. The digital version of the tangram set was presented on an Apple iPad Pro (10.5in display; 12in x 8.75in total size) using the application "101 Tangrams." Children and their parents were asked to play the digital puzzles using one of two different mechanics to turn the pieces: two-finger rotate and tap (Figure 3). Like the tangible version, this app used seven shapes including two large triangles, one medium triangle, two small triangles, one square, and one parallelogram. The app allowed for the correct placement of each piece to be outlined, or for only the outline of the global picture. Children and parents were presented with individual outlines for the first two puzzles, and only the global outline for the remaining puzzles. The pieces appeared at the bottom of the screen and changed their size to match the puzzle when selected. The sizes of the pieces in both the Tangible and Digital conditions were identical. To move the pieces you have to place one finger on the shape and then drag it to the desired location. In the Digital-Rotate condition, children and parents were instructed to use two fingers and a twisting motion to rotate each piece. In the Digital-Tap condition, they were instructed to quickly tap the piece twice to make it rotate 90 degrees until it was in the desired orientation.

Two finger rotate
Free rotate the pieces to fit the correct position.

One finger double tap
Rotate the pieces clockwise to fit the correct position. Also is used to mirror a piece.

Figure 3. This image depicts the mechanism of play for the Digital-Rotate (left) and Digital-Tap (right) condition.

Design

The present study utilized a 3x2 mixed design with condition (Tangible, Digital-Rotate, Digital-Tap) as a between-subjects variable and type of play (baseline or spatial play) as a within-subjects variable (Figure 4). The baseline tasks were identical for children and parents in all conditions, where they were asked to go through an *I Spy* book for 10 minutes. After *I Spy*, all children completed 16 trials of a spatial task to establish a baseline level of spatial reasoning. For spatial play, children and parents were randomly assigned to play tangram puzzles for 10 minutes[1] in one of three ways: Tangible, Digital-Rotate, or Digital-Tap. After spatial play, children completed the final 16 trials of the spatial task and a measure of numerical competency. The entire session took approximately 45 minutes.

Figure 4. The order of tasks for children and parents in the study.

Procedure

After providing informed consent, participants were escorted to an adjacent room and seated at a small wooden table (26in by 17.5in). An experimenter was present to demonstrate but sat at the opposite side of the room during play. In the event of a technical issue with the iPad, the experimenter returned to the table to

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[1] After 10 minutes, children and parents were allowed to continue working on their current puzzle until completed or until a total of 15 minutes had elapsed.

troubleshoot. Two video recorders were present in the room to capture the child and parent's interactions with the games and their language production.

Baseline tasks. All participants were asked to go through an *I Spy* book for 10 minutes. They were told, "Today we're really interested in seeing how parents and children collaborate on tasks. Try to imagine that you're at home and not in this room right now. We want you to go through this book however you normally would at home. There's no right or wrong way, we're really just interested in how you and your child work together."

After *I Spy*, children were asked to complete 16 items[2] of the Children's Mental Transformation Task (CMTT) to establish baseline levels of spatial reasoning (Levine, Huttenlocher, Taylor, & Langrock, 1999). The CMTT assesses children's ability to mentally transform two pieces of a shape to make it whole (see Figure 5). Half of the items required a 45-degree rotation along a horizontal (horizontal rotation) or a diagonal plane (diagonal rotation), whereas the other half required a translation along a horizontal (horizontal slide) or a diagonal plane (diagonal slide). Based on the original procedure, children were told, "Look at the pieces. Now, look at these shapes. If you put the pieces together, they will make one of these shapes. Point to the shape the pieces make." Each child received 16 trials. During this time, the parent sat at a nearby table to complete the demographic questionnaire while their child worked on their own. Children were randomly assigned to one of eight different orders of the task.

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[2] Previous research suggests that an abridged version of this task using as few as 10 items is suitable to identify variability in spatial ability (Levine et al., 2011; Ping et al., 2011).

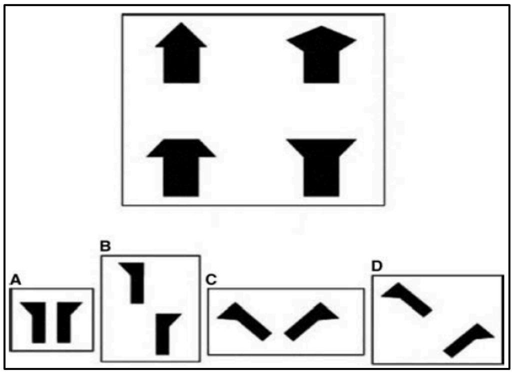

Figure 5. Images for each problem type of the children's mental rotation task are presented here: A) Horizontal slide, B) Diagonal slide, C) Horizontal rotation, D) Diagonal rotation. Image taken from Levine, Ratliff, Huttenlocher, & Cannon, 2012.

Spatial play. Parents were asked to rejoin their child at the table for spatial play where they were randomly assigned to the Tangible, Digital-Rotate, or Digital-Tap condition. In each condition, the dyads were asked to complete up to 10 puzzles[3] during the play session (Figure 6). The tangram puzzles in each condition were identical to each other and presented in a set order. Similarly, the initial placement and orientation of the pieces were the same for each puzzle. In the Tangible condition, they were given the following instructions: "Just like earlier, we're really interested in seeing how parents and children collaborate on tasks. Try to imagine that you're at home and not in this room right now. There's no right or wrong way, we're really just interested in how you and your child work together. Now, we want you to work together with your child to complete the following puzzles. The goal is to use the pieces to make the shape. In order to complete the shape, you may have to rotate the pieces." After explaining the instructions, the experimenter demonstrated how to

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[3] Pilot data indicated that parents and children tend to complete from 3-7 puzzles in the time allotted.

rotate one piece. All children were able to successfully rotate a piece. After demonstration, the experimenter reminded the parent, "We want you to work together to finish the puzzle."

In the two Digital conditions, they used an Apple iPad Pro for the same puzzles, with identical instructions to the Tangible condition except on how to rotate the pieces. In the Digital-Rotate condition, they were told: "To move a piece, you use one finger and drag it. To rotate a piece, you have to place two fingers on them and twist them." In the Digital-Tap condition, they were told: "To move the pieces you use one finger and drag it. To rotate a piece, you have to use one finger and tap it twice." After the instructions, the experimenter demonstrated how to rotate one piece. All children were able to successfully rotate a piece. After demonstration, the experimenter reminded the parent, "We want you to work together to finish the puzzle." The experimenter then went to the opposite side of the room and let the parent and child start working on their own. After each puzzle, the experimenter returned to the table to get the next one set up and reminded the dyad to "keep on working together."

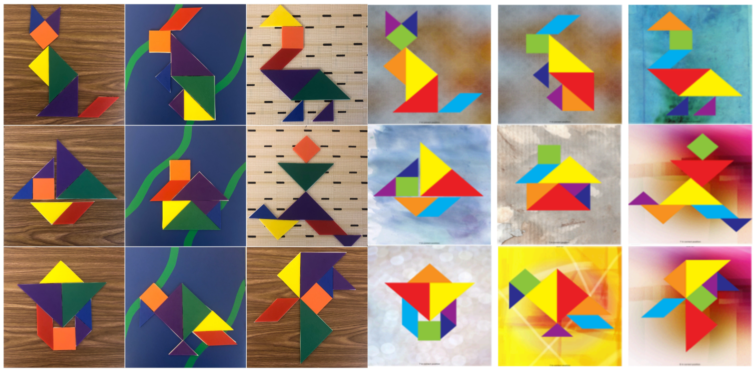

Figure 6. Images of the remaining tangram puzzles children and parents completed using the tangible version (left) and the digital version (right).

The first two puzzles were presented with the outline of each puzzle piece for all conditions. This was done to familiarize children and parents with the task. The remaining puzzles were presented without the outline of each piece, leaving only the outline of the global image. Pilot data suggested that removing the outline of each piece made the puzzles challenging for children this age; thus, each puzzle problem started with some of the pieces already in the correct position. For example, Puzzle 3 (the first puzzle without individual outlines) was presented to the dyad with 4 of the 7 pieces already in place; Puzzle 4 started with 3 of the 7 pieces in place; Puzzle 5 started with 2 of the 7 pieces in place, and so on until none of the pieces were started for them. The same pieces were started in place for each dyad.

Post-play tasks. After spatial play, the experimenter removed the tangram materials and replaced them with a binder that contained the stimuli for the CMTT (Levine et al., 1999). The experimenter then went through the remaining 16 trials with the child. During this time, the parent sat at a nearby table to complete the Activities Survey and Spatial Language Checklist and was told that their child should work on their own.

Children then completed the Jordan Number Sense Screener (JNSS), a task designed as a tool for educators and psychologists to screen early numerical competency in K-1 children (Jordan & Glutting, 2017). The screener consists of six subcategories: (1) counting skills, where children are asked to identify the number of stars on a sheet of paper and count to 10, (2) number recognition, or children's ability to name the numbers 13, 37, 82, and 124, (3) number comparisons, where children are asked to compare numbers, such as indicating which number is bigger, (4) nonverbal calculation, including simple addition and subtraction, (5) story problems, including oral addition and subtraction problems presented in a story context (*Jill has 2 pennies. Jim gives her 1 more penny. How many pennies does Jill have now?*), and (6) number combinations, including oral addition and subtraction problems with no context (*how much is 2 and 1*?). Following the provided script, the experimenter administered the six different subsections. The JNSS took approximately 10 minutes to complete.

Coding

CMTT. Two trained research assistants independently kept track of the final picture that the child pointed to on each trial. Children were then given one point for every correct response for a total possible score of 16 points during each assessment. In the case of a disagreement, a third coder watched the video recording to establish reliability of 100%. Difference scores from baseline to post-play for each type of problem (horizontal slide, diagonal slide, horizontal rotation, diagonal rotation) were also recorded for each participant.

JNSS. Children were given one point for each correct response, resulting in a total possible score of 29 points. Individual scores were then converted to standardized scores using the JNSS User Guide. Scores from 4 participants were not included in analyses because they were still in pre-school (*n* = 3) or unable to finish the task (*n* = 1).

Spatial language. Trained research assistants transcribed videotaped recordings of the parents' speech during the *I Spy* and tangram play sessions. The transcripts were then analyzed for spatial language using "A System for Analyzing Children and Caregivers Language about Space in Structured and Unstructured Contexts" (Cannon et al., 2007) which was specifically designed to assess spatial language use in everyday situations. This extensive system codes for target words and phrases based on eight different spatial categories: (1) *Spatial dimensions,* including words and phrases that describe the size of people, objects and spaces (e.g., big, small); (2) *Shapes,* including words that described traditional shapes and spaces (e.g., circle, triangle); (3) *Locations and directions,* including words and phrases that are about the position of objects, people, and space (e.g., towards, on); (4) *Orientations and transformations,* including words and phrases that are about the orientation of objects and people in space (e.g., upside down, rotate); (5) *Continuous amount,* including words and phrases that are about continuous quantities (e.g., whole, fraction); (6) *Deictics,* including phrases that specify a spatial or temporal location from the viewpoint of a speaker or listener in a given context (e.g., here, somewhere); (7) *Spatial features and properties,* including words and phrases that are about the features of people, objects, spaces and their properties (e.g., border, edge); (8) *Pattern,* including words and phrases that signify that someone is talking about a spatial pattern (e.g., pattern, repeat). And finally, an additional category, ***movements,*** was created to capture language that parents used spatially to talk about how pieces should move in space. This included words such as scooch, slide, and spin.

Words that do not fall under these categories were not counted as spatial language. However, there were certain situations in which words that fall under these categories were used in a non-spatial manner. Following the coding system, these words were excluded from the total count of spatial language. Uses of spatial terms in a non-spatial manner can be seen via homonyms, metaphor, names, and other spatially ambiguous uses. For example, the use of the word "in" was not counted as spatial language when used as follows: "the duck is in the page." However, the word "in" was counted when used in the following way: "the duck is *in* the house."

The data analysis software program NVivo was used to generate counts for words identified in all eight categories defined by the spatial language coding manual and the additional category generated by the experimenter. Using this software streamlined the coding procedure and reduced the chance of missing instances of spatial language. Each word was counted, regardless of whether or not it has been previously said. For example, the word "triangle" would count each time that it was said. The number of words spoken within each category was identified and highlighted within the original text using the text search function of the NVivo program. Two trained researchers ensured that all of the identified words were indeed used in a spatial manner and independently coded 20% of the NVivo output to establish reliability. Inter-coder reliability was measured using intraclass correlation coefficient (ICC) and yielded high measures of agreement (ICC = .987, 95% CI [.974, .994], Cronbach's α = .987). Each *I Spy* and tangram play session was transcribed and then coded for spatial language using the system above. The total number of words was also coded to calculate a ratio of spatial to non-spatial language. Using a ratio provided a more accurate account of spatial language use as it accounted for differences in parental talkativeness. Spatial language from one participant was not included in analyses due to video file corruption.

Predictions

There were two sets of main predictions. First, I predicted that children would achieve a higher score on the post-play CMTT in the Tangible condition than in the Digital conditions, and in the Digital-Rotate condition than in the Digital-Tap condition. Second, I predicted that parents would use a greater proportion of spatial language during the tangram play session in the Tangible condition than in the Digital conditions, and in the Digital-Rotate condition than in the Digital-Tap condition.

Results

Preliminary Analyses

Parent surveys. A series of 1-way ANOVAs were run to test for any group differences of pre-existing characteristics. The results indicated no between-group differences involving children's pre-existing use of spatial language, children's prior experience with spatial activities (such as soccer, playing with blocks, and math) and digital activities (such as watching TV and playing game applications), parental use of applications, and parental education (all *p*s > .05). These variables were thus excluded in the main analyses.

Age. A Pearson correlation was used to determine whether child age was related to the main dependent variables—CMTT performance and parental use of spatial language. The analysis revealed a significant correlation between age and the baseline CMTT ($r = .42$, $p < .01$) and post-play CMTT ($r = .34$, $p < .01$) performances. Therefore, child age was used a covariate for the subsequent analyses involving CMTT performance. No significant correlation was found between age and the proportion of spatial language parents used during tangram play ($r = -.22$, $p > .05$); thus, age was not included as a covariate for the subsequent analyses involving parental use of spatial language.

Gender. It is worth noting that there was a large gender imbalance in this study, with many more boys (n = 38) than girls (n = 22) participating. Thus, gender was not included in the main analyses. However, previous research on spatial reasoning has shown mixed results on the relationship between gender, spatial reasoning, and parental use of spatial language (Levine et al., 2012; Verdine et al., 2019); therefore, I examined gender in the exploratory analyses.

Jordan Number Sense Screener (JNSS). A Pearson correlation revealed that JNSS standardized scores were positively correlated with CMTT baseline ($r = .54$, $p < .01$) and post-play ($r = .54$, $p < .01$) performance across conditions, a result consistent with previous findings on the relationship between spatial reasoning and mathematical performance (Cheng & Mix, 2014; Verdine et al., 2016). A 1-way ANCOVA was run with condition as a between-subjects variable, controlling for age, to examine whether JNSS performance differed across conditions. The analysis revealed that children in the Tangible ($M = 111.30$, $SD = 15.07$), Digital-Rotate ($M = 116.42$, $SD = 19.09$), and Digital-Tap ($M = 116.76$, $SD = 17.55$) conditions did not statistically differ on their JNSS performance, $F(2, 52) = .47$, $p = .63$, $\eta^2 = .018$. This result suggests that playing with tangrams using tangible or digital materials for 10 minutes did not immediately impact children's performance in the number sense task.

Children's Mental Transformation Task (CMTT)

Overall CMTT performance. My first hypothesis was that children in the Tangible condition would outperform those in the Digital-Rotate and Digital-Tap conditions on the CMTT post-play, and that performance would be higher in the Digital-Rotate than the Digital-Tap condition. To test this, I used 1-way ANCOVA with condition (Tangible, Digital-Rotate, Digital-Tap) as a between-subjects variable, and baseline CMTT performance and child age as covariates. The results indicated that children in the Tangible ($M = 11.15$, $SD = 3.12$), Digital-Rotate ($M = 11.90$, $SD = 3.21$), and Digital-Tap ($M = 11.25$, $SD = 2.84$) conditions did not significantly differ on their post-play CMTT performance, $F(2, 57) = .06$, $p = .95$, $\eta^2 = .002$ (Figure 7). This result indicates that overall performance was not related to the type of tangram set or the mechanics of the touchscreen version of the game (see Table 2). Additionally, baseline CMTT performance was a significant predictor of post-play performance, ($F(1, 58) = 12.97$, $p < .01$, $\eta^2 = .191$), indicating that children who scored higher at baseline tended to score higher at post-play.

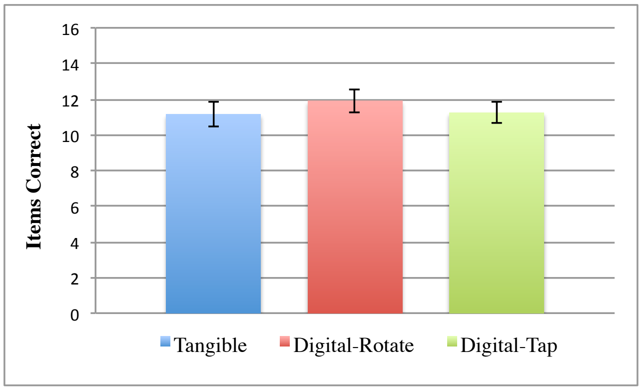

Figure 7. The number of correct items on the post-play CMTT. Error bars represent standard error.

CMTT performance by category. As mentioned before, CMTT consists of four categories of problems: horizontal rotation, diagonal rotation, horizontal slide, and diagonal slide. Some of these categories are more challenging than others. Among these categories, horizontal and diagonal rotation items have been shown to be more difficult for children than translational items such as horizontal and diagonal slide (Ehrlich, Levine, & Goldin-Meadow, 2006). Rotation items were rotated 45^{o} outward from the line of symmetry (horizontal rotation) or rotated 45^{o} outward from the line of symmetry and separated diagonally (diagonal rotation). These items may be more difficult as they require both translational and rotational thinking. To examine the effect of tangram play on performance of a given category, I created a difference score for each category by subtracting the baseline score from the post-play score.

I examined whether any differences emerged when combining results from both Digital conditions, thus honing in on potential effects between tangible and digital play. A series of independent t-tests were run to assess whether any differences between the Tangible and Digital Conditions emerged for each item type of the CMTT. Children in the Tangible condition (M = 18.75%, SD = 37.94%) showed significantly more improvement than children in the combined Digital conditions (M = -3.75%, SD = 24.38%) on diagonal rotation items, *t*(58) = 2.78, *p* < .01. No other effects were observed. A 1-way ANCOVA with condition (Tangible, Digital-Rotate, Digital-Tap) as the between-subjects variable, controlling for age, was used to examine this finding between the three main conditions.

Positive results were obtained for one problem category, diagonal rotations: The analysis indicated a significant effect of condition, *F*(2, 57) = 3.90, *p* = .03, η^2 = .12 (Figure 8). Post-hoc comparisons using the Bonferroni correction revealed that children in the Tangible condition (*M* = 18.75%, *SD* = 37.94%) showed greater improvement on diagonal rotation items than children in the Digital-Tap (*M* = -6.25%, *SD* = 27.95%) condition (*M* difference = 24.9%, *SE* = 9.4%, *p* = .03, 95% CI of the difference [1.6%, 48.2%]). However, there was no statistically significant difference between the Tangible and Digital-Rotate conditions (*M* = -1.25%, *SD* = 20.64%; *p* = .12) or between the Digital-Rotate and Digital-Tap conditions (*p* = 1.0). The greater improvement in performance in the Tangible than the Digital-Tap condition suggests that manually rotating and flipping tangible pieces resulted in an immediate benefit on problems that required diagonal rotation, but tapping tangram pieces on a touchscreen did not. No significant differences were found for any other problem category.

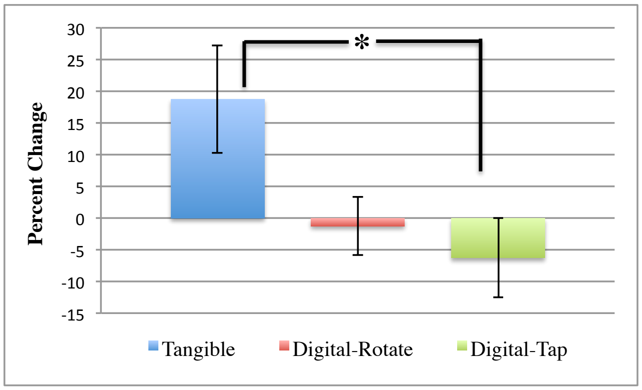

Figure 8. The percent change for diagonal rotation items from baseline to post-play CMTT. Error bars represent standard error. * denotes $p < .05$.

Parental Use of Spatial Language

Overall use of spatial language. I hypothesized that parents in the Tangible condition would use a higher proportion of spatial language than parents in the Digital-Rotate and Digital-Tap conditions, and that parents in the Digital-Rotation condition would use a higher proportion of spatial language than those in the Digital-Tap condition. A 1-way ANCOVA with condition (Tangible, Digital-Rotate, Digital-Tap) as the between-subjects variable, controlling for parental use of spatial language during *I Spy*, revealed that parents in the Tangible (M = 11.11%, SD = 3.23%), Digital-Rotate (M = 10.27%, SD = 3.76%), and Digital-Tap (M = 10.37%, SD = 3.49%) conditions did not statistically differ on the proportion of spatial language during tangram play, $F(2, 56) = .06$, $p = .94$, $\eta^2 = .002$ (Figure 9). Although no significant between-group difference was observed, the descriptive data (see Table 3) of parental use of spatial language helped inform about parent-child conversation in the context of touchscreen play.

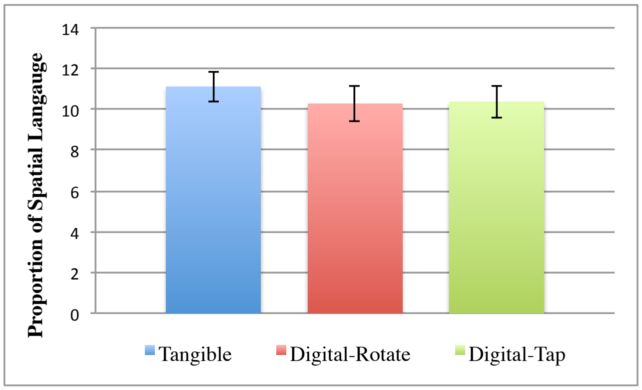

Figure 9. The proportion of spatial words parents used during the tangram play session. Error bars represent standard error.

Parental use of spatial language by category. Next, I examined parental talk during children's tangram play on a given category of spatial language[4]. Recall that coding was done in nine categories such as shapes, orientation and transformation, and deictics (see Table 4 for descriptives). A series of 1-way ANCOVA with condition (Tangible, Digital-Rotate, Digital-Tap) as the between-subjects variable, controlling for parental use of spatial language by category during *I Spy*, revealed a marginal effect for orientation and transformation tokens ($F(2, 56) = 2.47$, $p = .09$, $\eta^2 = .08$), and a significant effect for deictic tokens ($F(2, 56) = 3.76$, $p = .03$, $\eta^2 = .12$). Parents' use of deictic tokens during *I Spy* was a significant predictor of their deictic tokens during Tangram play ($p = .02$), suggesting that some parents may be predisposed to using deictic tokens more than others.

Post-hoc comparisons using the Bonferroni correction (Figure 10) revealed that parents in the Tangible condition ($M = .99\%$, $SD = .65\%$) used a marginally higher proportion of orientation and transformation words than those in the Digital-

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[4] Pattern was not included due to infrequent use. Only 10 words about pattern were identified in total across both the *I Spy* task and during tangram play.

Tap (*M* = .61%, *SD* = .65%) condition (*M* difference = .47%, *SE* = .21%, *p* = .09, 95% CI of the difference [-.05, .98]), but not the Digital-Rotate (*M* = .93%, *SD* = .89%) condition (*M* difference = .20%, *SE* = .22%, *p* = 1.0, 95% CI of the difference [-.33, .73]. For deictic tokens, parents in the Digital-Tap (*M* = 2.74%, *SD* = 2.06%) condition used a significantly higher proportion of deictic tokens than those in the Digital-Rotate (*M* = 1.51%, *SD* = .94%) condition (*M* difference = 1.26%, *SE* = .46%, *p* = .03, 95% CI of the difference [.12, 2.39]). The difference between the Digital-Tap condition and the Tangible condition (*M* = 2.39%, *SD* = 1.20%) was not significant, (*M* difference = .69%, *SE* = .48%, *p* = .46, 95% CI of the difference [-.49, 1.86].

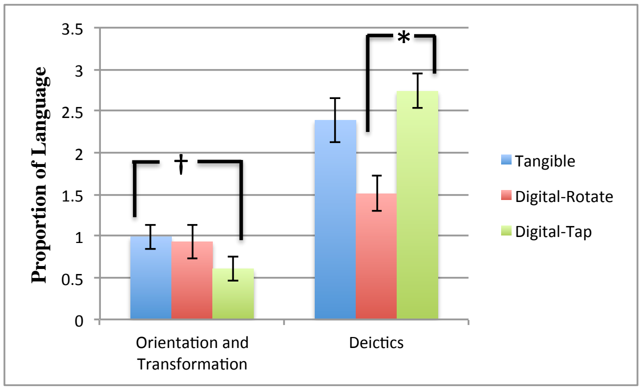

Figure 10. The proportion of spatial words parents used about orientation and transformation and deictics during the tangram play session. Error bars represent standard error. * denotes $p < .05$. † denotes $p < 0.1$.

Parental use of spatial language and CMTT. Stepwise regressions were conducted to determine the predictive power of age and the eight subcategories of parental use of spatial language during tangram play on post-play CMTT performance. The analysis revealed that age and words about spatial features and properties significantly predicted 17.9% of the variance in CMTT post-play performance, $R^2 = .21$, $F(2, 56) = 7.33$, $p < .001$. Age was a positive predictor of children's CMTT performance ($\beta = -1.52$, std $\beta = -.31$, $p = .01$), confirming the correlation results suggesting that older children performed better on the task. Surprisingly, parents' use of words about spatial features and properties ($\beta = -1.52$, std $\beta = -.31$, $p = .01$) was a negative predictor of CMTT performance. This result suggests that children who heard more spatial language in these two categories tended to perform worse on the CMTT. I will discuss this surprising result in the Discussion.

Exploratory Analyses

Gender. To assess potential gender differences, I used a 1-way ANCOVA identical to those used in the main analyses with the addition of gender (male, female) as a between-subjects variable. The analyses revealed no significant main effect of gender or interaction involving gender for CMTT performance. Analyses conducted for parental use of spatial language revealed no significant condition by gender interaction. However, they did reveal a marginal main effect of gender for total use of spatial language during the tangram play session, with girls ($M = 11.87\%$, $SD = 2.98\%$) tending to hear more than boys ($M = 9.88\%$, $SD = 3.53\%$), $F(1, 58) = 3.01$, $p = .09$, $\eta^2 = .06$. A series of independent t-tests revealed that this effect is driven by parents using a marginally higher proportion of words about orientation and transformation with girls ($M = 1.06\%$, $SD = .74\%$) than boys ($M = .72\%$, $SD = .72\%$) during tangram play ($t(57) = -1.70$, $p = .10$). This finding contradicts previous work showing that parents use more spatial language with boys than girls (Verdine et al., 2019), suggesting that this type of play might elicit different responses from parents.

This would be a potentially interesting finding to examine in future research. However, given the small sample of girls in this study, these effects should be treated with caution and confined to the present context.

Children's prior use of spatial language and CMTT. A Pearson correlation was used to examine any relationships between the spatial words that parents reported their children using and performance on the CMTT. The results revealed significant positive correlations between children's reported spatial language use and both baseline ($r = .34$, $p = .01$) and post-play ($r = .29$, $p = .03$) CMTT performance. This result is in line with previous findings that children's own spatial language use was related to their performance on spatial-reasoning tasks (Pruden et al., 2011), which highlights the importance of spatial vocabulary.

Prior digital activities and CMTT. Prior work has highlighted negative consequences of technology use—particularly watching TV—on cognitive function (Zimmerman & Christakis, 2007). The present study thus sought to investigate whether similar relationships would be found between technology use and the main dependent measures. Reponses on the Activities Survey were converted to a binary variable to more accurately assess their relationship to the main dependent variables in this study. Responses ranging from 1 (Less than once a month) to 3 (Twice a month) were recoded as 1 (Infrequent) and responses ranging from 4 (Once a week) to 6 (More than twice a week) were recoded to 2 (Frequent). This was done to compare children who have weekly experience participating in different digital activities to those who do not engage in them as often.

Point Biserial correlations were run to examine any relationships between prior participation with digital activities and baseline CMTT performance. Baseline CMTT performance was used because it provides the best reflection of the relationship between their prior activities and spatial reasoning. The analysis revealed significant negative correlations between baseline CMTT performance and exposure to playing games on a smartphone (r = -.35, p < .01), playing puzzle applications (r = -.40, p < .01), playing drawing applications (r = -.30, p = .02), watching TV on a tablet (r = -.30, p = .02) and watching TV on a smartphone (r = -.31, p = .02). These findings suggest that certain types of digital activity negatively relate to performance on this task.

Prior digital activities and parental use of spatial language. Point Biserial correlations were run to examine any relationships between participation in digital activities and parental use of spatial language during tangram play. The analysis revealed a significant negative correlation between parental overall use of spatial language and playing games on a touchscreen (r = -.29, p = .03). This finding suggests that parents tended to use more spatial language during play when their child had less experience using a touchscreen.

Application use. To explore children's experience with touchscreens, parents were asked to list any touchscreen applications that their child uses, how often they use them (frequently, often, or rarely), and who they typically play with (always solitary, usually solitary, usually with someone, or always with someone). In the following section, I highlight a few of the findings.

What types of apps are children playing? The genre of each application that children were reported to play at home was determined by its categorization on the Apple App Store, resulting in 10 distinct categories of apps: Educational, Action Games, Strategy Games, Simulation Games, Arcade Games, Puzzles, General Entertainment, Books, Music, and Other. Of these categories, the top 3 most played consisted of Educational (31%), Action Games (12%) and General Entertainment (20%). ***How often do children play with the applications?*** Overall, parents reported a range of frequency in children's use of applications, with the most common response being "often" (54.48%). Of all the app categories, only 4 of them had a higher proportion of children that used them "frequently": Arcade Games (56.3%), General Entertainment (48.3%), Books (100%), and Music (100%). ***Who are they playing with?*** Of the apps listed, parents reported high amounts of "usually solitary" (52.1%) and "always solitary" (28.8%) play. This result indicated that for this sample, children tended to spend a large proportion of touchscreen time by themselves (80.9%). Interestingly, parents reported that only 5.5% of the apps were played "always with someone," suggesting that it was rare for app use to be a joint activity (Figure 11). Of the 10 categories, only Educational (4.8%), Action Games (7.1%), Simulation Games (11.1%) and General Entertainment (14.8%) included reports that children always used these apps with someone.

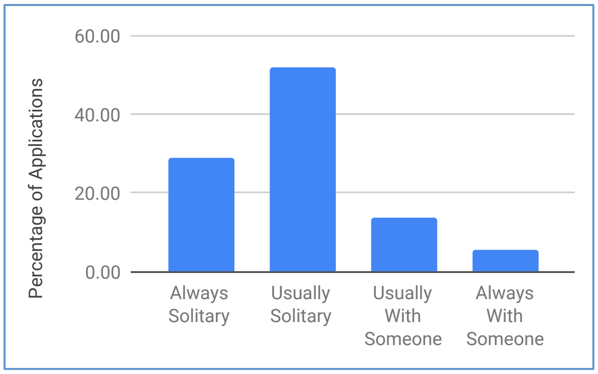

Figure 11. This graph depicts whom children played different touchscreen applications with. The majority of applications were used always (28.8%) or usually (52.1%) for solitary play.

Discussion

Previous research has highlighted the benefits of playing games like puzzles and blocks (Casey et al., 2008; Levine et al., 2012) and exposure to spatial language (Gentner, 2016; Pruden et al., 2011) on children's developing spatial reasoning. Here, I aimed to contribute to this line of research by comparing children's play with tangram puzzles using a tangible or digital set. Specifically, I asked whether children's performance on a spatial-reasoning task would be higher after playing with a tangible tangram set than with a digital set and whether the mechanics of the digital set would differentially affect performance. My second question asked whether parents differed in their use of spatial language when children play tangrams with a tangible set in comparison to a digital set and whether the mechanics of the digital set would differentially affect their language use.

Spatial Reasoning

The first goal of this study was to compare 5- to 6-year-olds' spatial reasoning after they played tangram puzzles in one of three ways: with tangible pieces

(Tangible condition), on a touchscreen where they rotated pieces using two fingers and a twisting motion (Digital-Rotate condition), or on a touchscreen where they rotated pieces by double tapping them (Digital-Tap condition). A significant difference in children's performance was observed on diagonal rotation items of the CMTT, but not on other aspects of the task.

Effects on diagonal rotation. The result indicated greater improvement on diagonal rotation items by children in the Tangible condition than those in the Digital-Tap condition. I speculate that this finding is related to the different visual cues provided across the two conditions. The visual information received in the Tangible and Digital-Tap conditions were quite different, as the tap mechanic did not allow for incremental rotation. For example, after double tapping a puzzle piece, it would immediately switch orientation by 90° clockwise in a set order. In contrast, both the Tangible and Digital-Rotate condition allowed children to rotate pieces incrementally both clockwise or counterclockwise, thus providing much more visually salient cues of rotation than in the Digital-Tap condition. So, even though children in all three conditions received visual information and hands-on experience that let them learn about how their actions affected the game, the difference in visual information may have influenced how they integrated information from those modalities.

Indeed, previous research stresses the importance of integrating visual information and motor experience to facilitate spatial reasoning in both the short- (Antrilli & Wang, 2016; Frick & Wang, 2013) and long-term (Casey et al., 2008).

Here, the benefits of interacting with tangible pieces that allowed for more visually salient rotation information may be why children in the Tangible condition showed more improvement on diagonal rotation items than children in the Digital-Tap condition. Similarly, the added benefit of being able to pair one's action with visual information from rotating pieces in a 3D plane might explain why children in the Tangible condition showed a slightly higher, although non-significant, improvement than those in the Digital-Rotate condition. It is possible then, that both differences in hands-on experience and visual information played a role in CMTT performance.

Recent research with adults supports the benefit of tangible interfaces on spatial planning (Schneider, Jermann, Zuffery, & Dillenbourg, 2011; Schneider, Wallace, Blikstein, & Pea, 2013). For example, Schneider et al. (2011) had adults use either a tangible or multitouch interface to design the floor plan for a warehouse with the caveat that they needed to include the maximum number of shelves and the most efficient route possible. The tangible user interface (TUI) allowed participants to physically manipulate objects on a 3D layout of the warehouse, whereas the multitouch interface was entirely on a touchscreen. Their results showed that those who interacted with the TUI created more successful floor plans for the warehouse. One potential reason is that the participants in the TUI group explored more possible layouts than those in the multitouch group. This is likely due to the increased familiarity with the physical objects and the relative ease with which they could be manipulated. Similarly, hands-on experience can increase both infants' and adults' ability to make connections between the objects at hand (Baldwin et al., 1993; Soska et al., 2010). In this way, tangible materials promote exploration and present a better opportunity spatial planning, both of which have been supported as beneficial to learning across the lifespan. In the present study, we may be seeing a similar benefit of tangible experience for diagonal rotation items. For example, by being able to pick up and turn pieces along multiple axes in the Tangible condition, children could explore the pieces in multiple orientations that were not possible in the Digital conditions. Thus, like adults, it is possible that children benefit from the opportunity to more thoroughly explore their spatial environment. Future research could examine this by having children play tangram puzzles on a touchscreen that allows for incremental rotation along multiple axes, or play tangram puzzles on a touch screen where they must use tangible tangram pieces.

The difference between the Digital-Rotate and Digital-Tap conditions was not significant, suggesting that different game mechanics may not impact spatial reasoning in the short-term. This is surprising given that in the Digital-Tap condition the effect of one's action is less controllable in comparison to the Digital-Rotate condition. For example, even though children knew that tapping a piece would make it turn, they did not have full control of the immediate outcome (i.e., they could only rotate it clockwise). Instead, they had to tap until it reached the desired orientation. One possibility is that children were able to quickly learn and anticipate the rotational outcomes as a result of their taps. A second possibility is that children in the Digital-Tap condition were benefitting from this style of rotation via a different mechanism, such as epistemic action. Epistemic actions are actions done to gain information about a problem to more easily uncover a solution (Kirsh & Maglio, 1994). In this view, epistemic actions facilitate or prime cognition by reducing cognitive load (Maglio, Wenger, Copeland, 2003). For example, in Tetris it is faster to simply rotate a piece until it fits the desired space, thereby externalizing spatial reasoning to vision, instead of engaging in mental rotation. For children in this study, they may have been enacting a similar type of action by tapping a puzzle piece until it seemed like it would fit, rather than thinking in advance about or consciously registering what its final orientation should be. This, in turn, would reduce their cognitive load needed to complete the puzzle, and thereby free up resources for later use. It may also mean that the children were externalizing spatial reasoning to their visual system and thus, not processing it in a way that would transfer to the CMTT. Future research is needed to understand the different mechanisms at play for different types of game mechanics during touchscreen use, and the effect of epistemic actions in children's spatial reasoning transfer.

Negative results in other aspects of spatial performance. Other than diagonal rotation, children's performance on other aspects of the spatial-reasoning task did not differ significantly across conditions. This finding suggests that for the children in this sample, playing a puzzle game on a touchscreen, regardless of the game mechanics, did not affect their overall short-term spatial reasoning in comparison to using traditional, tangible materials.

There are several possibilities for why this result was found. First, it may be that the affordances offered by touchscreen devices liken the experience to play with tangible materials. Previous research has highlighted the positive impacts of play with tangible, spatially relevant materials, on young children's spatial reasoning (Grissmer et al., 2013), whereas it is less clear whether playing similar games on a touchscreen results in similar effects. Although research on touchscreen use is growing, much of the research to date on the consequences of technology use for early cognition has focused on TV watching (Lillard, Drell, Richey, Boguszewski, & Smith, 2015; Lillard & Peterson, 2011). However, watching TV is a vastly different experience than using a touchscreen, perhaps making any links between touchscreen use and cognition incomparable to TV. For example, touchscreens afford engagement and interaction in ways that TV watching cannot, such as adapting difficulty and contingently responding to action, both of which are crucial elements that support learning (Hirsh-Pasek et al., 2015). Thus, despite reported negative consequences of TV watching on cognition in the short- and long-term (Lillard et al., 2015; Nathanson, Aladé, Sharp, Rasmussen, & Christy, 2014), it is possible that touchscreen use would not follow this trend.

Furthermore, work in our lab with 2.5-year-olds suggests that potential negative consequences derived from touchscreen use are related to *how* children play rather than the mere *act* of using a touchscreen device for play (Antrilli & Wang, 2018). In particular, social interaction during touchscreen use was associated with higher scores on a measure of cognitive function. In the present study, we see a similar effect, where using a touchscreen device for play with their parents resulted in no significant between-group differences on a measure of spatial reasoning. This may indicate that using a touchscreen for play, where there is a reciprocal response (e.g., responding directly to one's action) from the game and social interaction with their parent, alleviates any potential differences between technology use and traditional forms of play on cognition.

A second possibility is that the tactile experience of playing on the touchscreen allowed children to think about and understand how their actions caused an outcome in a similar way to play with the tangible pieces. For example, in the Tangible condition, to complete the puzzle children had to pick up a piece, turn it to the correct orientation, and then put it down in the correct place. In the Digital conditions, children had to touch a puzzle piece to move it (e.g., pick it up), twist or double-tap the piece to turn it to the correct orientation (e.g., turn it), and then drag it (e.g., put it down) to the correct place. It is possible that by drawing attention to the causal nature of their actions on either a tangible or digital tangram piece, any integration of visual cues and motor actions similarly affected children's short-term spatial reasoning, regardless of condition. In this view, the findings suggest that spatial reasoning may be impacted by the integration of visual and motor information, even if the type of visual information (e.g., 2D vs. 3D) and their motor experiences (e.g., tangible piece vs. digital piece) are different.

Finally, it is possible that providing children with only 10 minutes of play with tangram puzzles was not enough to elicit differences in task performance between the conditions. Previous research that found links between play with spatial materials and spatial reasoning primarily points to the benefits of long-term exposure.

For example, Casey et al. (2008) found that spatial reasoning increased after a 6 to 8-week intervention. Similarly, Levine et al. (2012) reported that puzzle play over a 2-year span was related to subsequent spatial reasoning. As for short-term impact, research that has shown immediate effects provided children with training that closely translated to their outcome measures (Ping, Ratliff, Hickey, Levine, 2011). Thus, although children in the present study were playing a spatially relevant game, they may have not had enough time for any effects to materialize. Given that touchscreen use is only becoming more prevalent in early childhood, future research is needed to see how long-term use with spatially relevant games (e.g., puzzles, Minecraft) affects spatial reasoning.

Parental Talk

The second goal of this study was to compare parental use of spatial language during play with tangram puzzles between each condition. I hypothesized that parental use of spatial language would be greater in the Tangible than Digital conditions, and greater in the Digital-Rotate than Digital-Tap condition. A significant difference was observed on parental use of deictic words between the two digital conditions.

Different usage of deictic words across digital conditions. I found that parents in the Digital-Tap condition tended to use a higher proportion of deictic words than parents in the Digital-Rotate condition. This finding was counter to my prediction that parents would use a higher proportion of spatial language in the Digital-Rotate than in the Digital-Tap Condition. One possibility is that the mechanic of tapping to rotate encouraged children to play using only a single finger, positioning their hand in a gesture akin to pointing, which then primed language for joint attention from parents. Pointing gestures are argued to set the stage for early linguistic communication and future language learning (Goldin-Meadow, 2007) by orienting children to objects in their environment. For example, when pointing gestures are accompanied by talk they signal crucial information about what is being attended to as well as the features and properties relevant to this interaction.

Previous research also suggests that pointing plays an important role as part of a larger system of joint attention and shared intentionality in younger children (Tomasello, Carpenter, & Liszkowski, 2007). When coupled with a pointing gesture, deictic language can identify what is being pointed to as well as providing relevant information about location (Goodwin, 2003), thus helping to coordinate spatial attention to what is present in the visual field. In this way, the pointing-like mechanic of tapping may have primed parents to use more deictic words to orient their child to what was in front of them. For example, in the present study, children's pointing gestures as a function of the game mechanic may have primed parents to use deictic terms such as "here" and "there" to direct their child's attention to the relevant space. In this way, parents' use of deictic words may be the result of pointing being a situated practice that implicitly facilitates parents' use of locative deictic words. Future research is needed to examine how different game mechanics influence parents' use of deictic words during play.

Similar usage of spatial language. In contrast to my hypothesis, overall parental use of spatial language did not statistically significantly differ between any of the conditions. There has been very little research that has shown what parents say when they and their children play spatial games with digital materials. Here, even though my hypothesis was not supported, the results meaningfully contribute to our understanding of parental use of spatial language in everyday situations.

Previous research on parental language during play has shown that, even though parents use more spatial language during play with spatial materials (Ferrara et al., 2011; Pruden et al., 2011), the quality and quantity of their language use is lower when using electronic toys and tablets (Zosh et al., 2015, Verdine et al., 2019). In these reports, parents' language shifted from content to properties of the device, causing an overall decrease in the quality of their language use. There are a few possibilities as to why similar effects were not seen in the present study. First, it is possible that by kindergarten age many children already have experience using touchscreen devices. If they were familiar with the basic principles of how to use the device, children may not have required as much device-focused language from parents, who could instead focus more of their attention on the content of the game. This may be true to some extent, as over half of the children in the Digital-Rotate (55%) and Digital-Tap (60%) conditions were reported to play games on a touchscreen on a weekly basis. Furthermore, in the Digital conditions, parental overall use of spatial language showed a marginal negative association with children's experience using a touchscreen to play games ($r = -.27$, $p = .096$). This suggests that parents tended to use less spatial language when their child had more experience with using touchscreens to play games, supporting the idea that parents use less language when their child is more familiar with the device. Understanding how children's prior experience with touchscreens affects their parents’ use of language during play would be an interesting avenue for future research.

A second possibility is that the intuitive nature of the game mechanics in both Digital conditions elicited more parental use of spatial language, making their language use comparable to use in the Tangible condition. For example, in the Digital-Rotate condition children were able to manipulate puzzle pieces in a very similar way to if they were using tangible pieces. This similarity may have made it easier for children to operate, and therefore led parents to use more content than device focused language. In the Digital-Tap condition, it may be that the mechanic of tapping to rotate pieces was easily and rapidly learned, thereby negating the need for parents to spend time talking about the device, and instead allowed them to focus on content. There is some support in favor of the ease of playing this way, as children in the Digital-Tap condition tended to complete more puzzles (*M* = 5.00, *SD* = 1.03) than those in the Digital-Rotate condition (*M* = 3.82, *SD* = 1.38). If this is the case, then parents may be inclined to use more content focused language during touchscreen use if their child can intuitively and easily understand how to play, no matter what the game mechanics are. Future research is needed to examine how children's expertise with touchscreen devices and the applications they use are related to the language their parents use during play.

Parental Talk and Spatial Reasoning

In the present study, hearing spatial language, specifically words about spatial features and deictics, negatively predicted performance on the CMTT across all conditions. Previous research has indicated that preschool-aged children perform better on spatial search tasks when hearing words that highlight a specific location (e.g., middle) in comparison to less specific, deictic words (e.g., there; see Loewenstein & Gentner, 2005). In the present study, deictic words contributed the highest proportion of words used by parents in the Digital-Tap (2.65%) and Tangible (2.32%) conditions, and the third highest in the Digital-Rotate condition (1.54%). Thus, it could be that even though children heard spatial language from a variety of categories, the prevalence of deictic words negated any potential benefits to subsequent performance on the CMTT.

Nonetheless, it is surprising that hearing a higher proportion of spatial language would negatively predict CMTT performance, as one might expect that hearing any spatial language is better than hearing none. One possibility is that parents may have had the impression that their child was struggling with the tangram puzzles and required assistance in completing them. This may have resulted in a higher proportion of spatial language as parents tried to assist their child. The increased use of spatial language, then, may be parents reacting to individual differences in their child's spatial reasoning abilities, where some children required more spatial language to compensate for their perceived performance. However, no significant correlations were found between the number of puzzles completed and parental use of spatial language during tangram play (*r* = -.05, *p* = .69), suggesting that this may not be the case.

Another possibility could be that in general, parents used more spatial language with children who were less familiar with puzzles. Indeed, the results indicated a significant negative correlation between children's experience using a touchscreen to play puzzle applications and parents' proportion of words that were about continuous amount (*r* = -.33, *p* = .01). In other words, children who had experience playing puzzle applications on a weekly basis tended to hear a lower proportion of spatial language within that category. This, at least in some respects, suggests that parents may have used more spatial language during puzzle play when their child had less experience with similar types of games. In this way, parents may be using spatial language as a tool when their child has little experience with similar spatial materials.

Finally, it is possible that individual differences in children's pre-existing use of spatial language played a larger role in CMTT performance than the language heard from their parents during play. This may be likely given the relatively short amount of time they were given to play. This theory is somewhat supported given the positive associations between parents' reports of the spatial words that their children use in their everyday lives and CMTT performance. This finding is in line with previous research showing that children's spatial language use is related to spatial reasoning (Pruden et al., 2011). Additionally, their findings also report that children's use of spatial language use is positively related to their parents' use, which indicates that children who hear more spatial language tend to use more spatial language themselves (Prudent et al., 2011). In this view, it seems likely that children are learning and adapting their conceptions of spatial relationships through prolonged exposure to spatial language. Hearing this type of language over time may be especially important, as research has argued that at its core, language provides a symbolic system that allows us to think about these types of abstract spatial relationships (Gentner, 2016). In the present research, even though hearing spatial language during play did not relate to spatial reasoning in the short term, playing tangram puzzles was associated with a significantly higher proportion of parental use of spatial language across all conditions (*M* all tangram play = 10.74%, *M* all baselines = 5.60%, t(55) = 10.66, $p < .001$). It is possible then, that with continued exposure to playing these types of games, children will learn and incorporate more spatial language into their vocabularies, regardless of whether they play using tangible or digital pieces.

Exploratory Results

Number sense. The first exploratory question I asked was whether children's performance on a measure of numerical competency would differ depending on whether they played tangible or digital tangram puzzles. There was a significant correlation with the JNSS and their baseline and post-play CMTT scores. This indicates that there is a strong relationship between math and spatial reasoning scores, which has been repeatedly shown in the literature (Gunderson et al., 2012; Verdine et al. 2014). However, children’s performance on the task did not differ across conditions. One possibility is that the amount of time spent playing tangrams may not have been long enough for such spatial reasoning to transfer. A second possibility is that the type of spatial reasoning may have been too different between the tasks for analogical transfer. Tangrams require location and mental rotation reasoning, which would prove beneficial for equation equivalence problems. However, the number sense task does not require them to solve mathematical equations through spatial transformations of equations. Prior research has shown that long-term mental rotation training is beneficial for mathematical reasoning (Cheng & Mix, 2014). However, the children were slightly older and they used math equations that were primarily solved through equivalence transformations (e.g., 4 + ___ = 7; move the 7 over to the left side to get 7 – 4 = 3). Here, it is likely that the mental rotation involved in tangrams may have transferred some benefit to math equivalence transformations, but not tasks such as the Children's Number Sense battery.

Children's everyday use of touchscreens. I attempted to explore children's everyday use of touchscreen applications by way of this study. First, I found that the most common games that children used were educational games (31%), based on the categorization in Apple's Application store. This finding is consistent with prior research (Rideout, 2017; Shuler et al., 2012) and to be expected, as parents are likely more comfortable providing their children with touchscreen time if they also feel that there is an educational benefit. The next two most common categories were general entertainment (20%) and action (12%). Research has not conclusively demonstrated benefits from children's use of educational apps (Fisch, 2016), or whether the mechanics learned from app use can result in an adequate transfer of knowledge (Barnett, 2014). Given that children who use touchscreens are likely to have experience with educational and non-educational applications, it is important that future researchers account for the type of app when linking effects of touchscreen use to developmental outcomes, and to further assess their efficacy in knowledge transfer.

Second, I gathered data on the frequency of children's everyday use of application: frequently, often, or rarely. In general, children's overall use of applications was reported as "often" (54%), suggesting that application use is allowed but not without moderation. Of the categories reported, arcade games (56.3%), general entertainment (48.3%), books (100%) and music (100%) were the only ones that parents reported a high proportion of frequent use. This provides us with a snapshot for which type of applications, at least for children in this sample, are more likely to be frequently used. Future research is needed to examine potential relationships between frequency of use for different types of applications and developmental outcomes, as the quality of child engagement and transfer may differ across app types.

Finally, I asked parents to report with whom their child typically plays each respective application. Of the applications named, parents reported that 80.9% of children's application use was usually or always by themselves, indicating that joint play was somewhat rare in this sample. Although most touchscreen applications provide an inherent level of contingency, which is argued to increase engagement and learning, it is likely that this form of device-based contingency is only beneficial to a certain degree (Hirsh-Pasek et al., 2015). In addition, research on TV watching has pointed out benefits of co-viewing, as it encourages engagement and facilitates learning in ways that are typically not possible from the device alone (American Academy of Pediatrics, 2018; Hirsh-Pasek et al., 2015; Uhls & Robb, 2017). Similarly, when co-playing a game with their child, parents may call attention to on-screen objects and ask dialogic questions, inviting questions and discussions that are beneficial to learning (Blumberg et al., 2019; Hirsh-Pasek et al., 2015). However, such co-playing did not typically occur in this sample. This finding is in line with recent research that indicates children's app use is predominantly solitary (Griffith & Arnold, 2019). However, in their sample, parental behavior (including warmth, engagement, playfulness, and support for autonomy) during their child's play with educational apps predicted higher levels of engagement and affect. This suggests that the effect of educational applications on children's cognition, though potentially beneficial, may not be seen if parents do not engage in joint play with their child. Thus, it is critical that we continue to examine touchscreen use as a social context for learning and cognitive development.

Concluding Remarks

In sum, the findings from this dissertation found partial differences between conditions for both children's spatial reasoning and parental use of spatial language during play. For spatial reasoning, a greater improvement on diagonal rotation items was found for children in the Tangible condition than those in the Digital-Tap condition. This finding suggests that play with tangible puzzle pieces, as compared to digital ones with a constrained method of rotation, has a short-term impact on one aspect of children's spatial reasoning. This difference may be due to the difference in visual cues garnered by each method of play, which has been related to mental rotation in prior work (Antrilli & Wang, 2016). It was surprising that no differences were found for other aspects of spatial reasoning. Much of the past work on the relationship between spatial play and spatial reasoning has focused on long-term effects (Pruden et al., 2011). Thus, one limitation of this study is that the parent-child dyads only played for 10 minutes in a single sitting. It is possible that other differences would emerge if they were able to play multiple times over a longer period.

With regards to parental use of spatial language, the findings from this dissertation found that parents in the Digital-Tap condition tended to use a higher proportion of deictic words than parents in the Digital-Rotate condition. This suggests that the mechanics of touchscreen games might differentially impact the linguistic experiences that children have during play. For example, the mechanic of using a single finger and tapping to rotate on-screen pieces might influence parents to use more deictic words because it positions children’s hand in a way that looks like pointing, which has been shown to elicit deictic language (Goodwin, 2003). It was surprising that no differences were found for other aspects of spatial language. Prior work has predominantly studied children who are younger than 3, an age group that tends to be the focus for researchers and practitioners regarding exposure to technology (Blumberg et al., 2019). In the present study, it is possible that no differences emerged in part because the children were older. At 5 years old they may be familiar with and capable of using touchscreens, thus allowing parents to focus more on content than on the device itself. Future research is needed to examine how parents' use of spatial language changes as a function of their child's expertise with touchscreens.

Although it was surprising that no differences were found between conditions for overall spatial reasoning or parental use of spatial language, the results of this dissertation provide evidence that how children play impacts certain aspects in these domains. The increasing use of touchscreen devices as a tool for learning at home and in schools, or even as an acceptable play medium, is rapidly shifting children's sociocultural context for cognitive development (Blumberg et al., 2019). Here, we are fortunate to be present for, and to be able to research, this shift in children's sociocultural context as it happens. Currently, the majority of research has focused on the impact of touchscreen use by focusing on the content. However, the findings from this dissertation suggest that *how* children are using touchscreens plays a potentially important role in their spatial reasoning as well as their parents' use of spatial language. Future research is thus needed to examine the impact of *how* children use touchscreens by focusing on the different affordances offered by game mechanics. As the use of touchscreens for play becomes more prevalent in our lives, it is important that we develop touchscreen games that incorporate meaningful interactions with the device and encourage parents to use more content-oriented language.

Table 1

Demographics and Annual Household Income

	Tangible	Digital-Rotate	Digital-Tap	Average
Ethnicity				
European-American	60%	55%	40%	51.67%
Hispanic	10%	10%	10%	10%
Asian/Pacific Islander	5%	5%	5%	5%
Mixed Ethnicity	20%	30%	45%	31.67%
Other (non-specified)	5%	0%	0%	1.67%
Education (Yrs.)				
Mother	16.20 (1.67)	15.9 (1.97)	15.94 (1.95)	16.02 (1.84)
Father	15.32 (1.86)	15.40 (2.46)	15.80 (2.14)	15.51 (2.14)
Income				
Over $100,000	36.84%	44.44%	42.11%	41.07%
$75,000 – $100,000	26.32%	0%	26.32%	17.86%
$50,000 – $75,000	5.26%	16.67%	5.26%	8.93%
$30,000 – $50,000	15.79%	16.67%	10.53%	14.29%
$15,000 – $30,000	10.53%	11.11%	10.53%	10.71%
Less than $15,000	5.26%	11.11%	5.26%	7.14%

Note. Standard deviations appear in parentheses next to means.

Table 2

CMTT Accuracy (out of 16) at Baseline and Post-play. Standard deviations appear in parentheses next to means.

	Tangible		Digital-Rotate		Digital-Tap	
	Baseline	Post-play	Baseline	Post-play	Baseline	Post-play
All	10.50 (2.16)	11.15 (3.12)	11.45 (2.67)	11.90 (3.21)	10.65 (3.07)	11.25 (2.84)
Boys	11.20 (6.19)	11.70 (5.10)	11.79 (2.58)	12.21 (3.04)	10.21 (3.29)	11.00 (3.23)
Girls	9.80 (2.30)	10.60 (4.03)	10.67 (2.94)	11.17 (3.76)	11.67 (2.42)	11.83 (1.72)

Table 3

Average and Range Language Use During Each Play Session. Standard deviations appear in parentheses

	Tangible	Digital-Rotate	Digital-Tap
I Spy			
Total Words	673.35 (235.71)	683.68 (163.69)	621.60 (203.77)
Range	297 - 1189	288 - 963	257 - 1084
Proportion Spatial	6.45 (1.81)	5.06 (2.14)	5.25 (1.97)
Tangram			
Total Words	560.55 (218.82)	541.47 (218.35)	529.35 (294.27)
Range	227 - 955	292 - 1045	112 - 1127
Proportion Spatial	11.11 (3.23)	10.41 (3.64)	10.23 (3.60)
Change in Proportion	4.66 (2.95)	5.12 (3.78)	5.18 (4.13)

Table 4

Parental Proportion of Spatial Language by Category During the Tangram Play Session. Values indicate: M (SD)

	Tangible		Digital-Rotate		Digital-Tap	
	I Spy	Tangram	I Spy	Tangram	I Spy	Tangram
Total	6.45 (1.81)	11.11 (3.23)	5.06 (2.14)	10.41 (3.64)	5.25 (1.97)	10.23 (3.60)
Shapes	.66 (.64)	1.31 (.92)	.56 (.41)	.76 (.99)	.60 (.45)	1.02 (1.39)
Spatial Dimensions	.64 (.46)	.68 (.48)	.73 (.40)	1.01 (.77)	.54 (.44)	.75 (.69)
Location and Direction	1.78 (1.14)	1.93 (.97)	1.53 (.93)	2.41 (1.19)	1.54 (.88)	1.89 (1.04)
Orientation and Transformation	.06 (.10)	.99 (.65)	.12 (.32)	.91 (.91)	.14 (.27)	.62 (.64)
Continuous Amount	.95 (.44)	1.50 (.65)	.64 (.44)	1.53 (1.22)	.85 (.56)	1.05 (.67)
Deictics	2.16 (1.20)	2.39 (1.20)	1.20 (1.23)	1.62 (.98)	1.31 (.96)	2.64 (2.10)
Spatial Features and Properties	.13 (.27)	.79 (.74)	.12 (.22)	.65 (.46)	.16 (.28)	.56 (.63)
Pattern	0 (0)	0 (0)	.01 (.04)	0 (0)	.02 (.09)	.01 (.09)
Movement	.06 (.10)	1.53 (.82)	.15 (.43)	1.52 (1.13)	.12 (.27)	1.70 (1.00)

Appendix A
Demographic Questionnaire

1. EDUCATION (parents)
Circle the highest grade completed (12 = high school, 16 = college graduate, 18 = advanced degree)

Parent 1 (Sex: M/F): 6 7 8 9 10 11 12 13 14 15 16 17 18

Parent 2 (Sex: M/F): 6 7 8 9 10 11 12 13 14 15 16 17 18

2. COLLEGE MAJOR (if applicable)

Parent 1 (Sex: M/F):
____

Parent 2 (Sex: M/F):
____

3. OCCUPATION
Please provide a brief description of your occupation using specific terms (e.g., computer technician, accountant, dental assistant).

Parent 1 (Sex: M/F):
____

Parent 2 (Sex: M/F):
____

4. INCOME (What is your family income per year? Please check one)

____ less than $15,000 ____ $15,000 - $30,000 ____$30,000 - $50,000

____ $50,000 - $75,000 ____ $75,000 - $100,000 ____ over $100,000

5. Child's Current Grade (circle one)

Pre-K K 1st grade

Appendix B
Spatial Language Checklist

Spatial Dimensions

- ☐ Big
- ☐ Little
- ☐ Small
- ☐ Large
- ☐ Tiny
- ☐ Enormous
- ☐ Huge
- ☐ Gigantic
- ☐ Teeny
- ☐ Itsy-bitsy
- ☐ Itty-bitty
- ☐ Long
- ☐ Short
- ☐ Tall
- ☐ Wide
- ☐ Narrow
- ☐ Thick
- ☐ Thin
- ☐ Skinny
- ☐ Fat
- ☐ Deep
- ☐ Shallow
- ☐ Full
- ☐ Empty
- ☐ Size
- ☐ Length
- ☐ Height
- ☐ Width
- ☐ Depth
- ☐ Volume
- ☐ Capacity
- ☐ Area (as in of a square)
- ☐ Measure

Shapes

- ☐ Circle
- ☐ Oval
- ☐ Ellipse
- ☐ Semicircle
- ☐ Triangle
- ☐ Square
- ☐ Rectangle
- ☐ Diamond
- ☐ Pentagon
- ☐ Hexagon
- ☐ Octagon
- ☐ Parallelogram
- ☐ Quadrilateral
- ☐ Rhombus
- ☐ Sphere
- ☐ Globe
- ☐ Cone
- ☐ Cylinder
- ☐ Pyramid
- ☐ Cube
- ☐ Rectangular prism
- ☐ Shape

Location and Direction

- ☐ At
- ☐ To
- ☐ From
- ☐ On
- ☐ Off
- ☐ In
- ☐ Out (of)
- ☐ Under
- ☐ Beneath
- ☐ Below
- ☐ Over
- ☐ Above
- ☐ Up
- ☐ Down
- ☐ (On) top
- ☐ Bottom
- ☐ High
- ☐ Low
- ☐ Column
- ☐ Vertical
- ☐ Left
- ☐ Right
- ☐ (In) front
- ☐ (In) back
- ☐ Ahead
- ☐ Behind
- ☐ Sideways
- ☐ Row
- ☐ Horizontal
- ☐ By
- ☐ Near
- ☐ Close
- ☐ Next to
- ☐ With
- ☐ Beside
- ☐ Far
- ☐ Away
- ☐ Beyond
- ☐ Further
- ☐ Past
- ☐ Against
- ☐ Together
- ☐ Separate
- ☐ Join
- ☐ Apart
- ☐ Between
- ☐ Among
- ☐ Middle
- ☐ Center
- ☐ About

- ☐ Throughout
- ☐ Along
- ☐ Lengthwise
- ☐ North
- ☐ South
- ☐ East
- ☐ West
- ☐ Around
- ☐ Through
- ☐ Across
- ☐ Opposite
- ☐ Aside
- ☐ Reverse
- ☐ Back (*verb*)
- ☐ Backward
- ☐ Forward
- ☐ Parallel
- ☐ Perpendicular
- ☐ Diagonal
- ☐ Down (as in "down the street")
- ☐ Up (as in "up the street")
- ☐ Location
- ☐ Position
- ☐ Direction
- ☐ Route
- ☐ Path
- ☐ Head
- ☐ Place
- ☐ Distance

Orientation and Transformation

- ☐ Upside down
- ☐ Right side up
- ☐ Upright
- ☐ Orientation
- ☐ Turn
- ☐ Flip
- ☐ Rotate
- ☐ Rotation

Continuous Amount

- ☐ Whole
- ☐ All
- ☐ Part
- ☐ Piece
- ☐ Section
- ☐ Bit
- ☐ Segment
- ☐ Portion
- ☐ Fragment
- ☐ Fraction
- ☐ Some
- ☐ A lot
- ☐ A little
- ☐ Much
- ☐ Enough
- ☐ Half
- ☐ Third
- ☐ Quarter
- ☐ Fifth
- ☐ Sixth
- ☐ Seventh
- ☐ Eighth
- ☐ Ninth
- ☐ Tenth
- ☐ None
- ☐ More
- ☐ Less
- ☐ Same
- ☐ Equal
- ☐ Inch
- ☐ Foot
- ☐ Mile
- ☐ Centimeter
- ☐ Meter
- ☐ Amount
- ☐ Room
- ☐ Space
- ☐ Area (as in "space")

Deictics

- ☐ Here
- ☐ There
- ☐ Where
- ☐ Anywhere
- ☐ Somewhere
- ☐ Nowhere
- ☐ Everywhere
- ☐ Wherever

Spatial Features and Properties

- ☐ Side
- ☐ Edge
- ☐ Border
- ☐ Line
- ☐ Round
- ☐ Curve
- ☐ Bump
- ☐ Bent/d
- ☐ Wave
- ☐ Lump
- ☐ Arc
- ☐ Sector
- ☐ Straight
- ☐ Flat
- ☐ Angle
- ☐ Corner
- ☐ Point
- ☐ Plane
- ☐ Surface
- ☐ Face
- ☐ Circular
- ☐ Rectangular
- ☐ Triangular
- ☐ Conical
- ☐ Spheric
- ☐ Elliptical
- ☐ Cylindric

☐ Shaped
☐ Shaped
☐ Horizontal
☐ Vertical
☐ Diagonal
☐ Axis
☐ Parallel
☐ Perpendicular
☐ Symmetry

Pattern

☐ Pattern
☐ Design
☐ Sequence
☐ Order
☐ Next
☐ First
☐ Last
☐ Before
☐ After
☐ Repeat (repetition)
☐ Increase
☐ Decrease

Prepositions

☐ During
☐ Except
☐ For
☐ Inside
☐ Instead of
☐ Into
☐ Like
☐ Of
☐ Onto
☐ Outside
☐ Since
☐ Toward
☐ Underneath
☐ Until
☐ Upon
☐ Within
☐ Without

Appendix C
Activities Survey

In an average month, please indicate the degree to which your child participates in each of the following activities. Next to each activity, there is a scale ranging from 1 (less than once a month) to 6 (daily). Please circle the number that best corresponds to your child's level of participation for each activity.

	Less than once a month	**Once a month**	**Twice a month**	**Once a week**	**Twice a week**	**More than twice a week**
Drawing	1	2	3	4	5	6
Play with connecting blocks (such as Legos)	1	2	3	4	5	6
Basketball	1	2	3	4	5	6
Dance	1	2	3	4	5	6
Gymnastics	1	2	3	4	5	6
Soccer	1	2	3	4	5	6
Swimming	1	2	3	4	5	6
Play with blocks	1	2	3	4	5	6
Painting	1	2	3	4	5	6
Play with puzzles	1	2	3	4	5	6
Musical Instrument	1	2	3	4	5	6
Addition/Subtraction	1	2	3	4	5	6
Geometry/Shapes	1	2	3	4	5	6
Being read to	1	2	3	4	5	6
Tangrams						

Reading	1	2	3	4	5	6
Please list any other activities you wish to share in the lines below.	**Less than once a month**	**Once a month**	**Twice a month**	**Once a week**	**Twice a week**	**More than twice a week**
____________________	1	2	3	4	5	6
____________________	1	2	3	4	5	6
____________________	1	2	3	4	5	6
____________________	1	2	3	4	5	6
____________________	1	2	3	4	5	6
____________________	1	2	3	4	5	6
	1	2	3	4	5	6

The following questions will ask about your child's experiences with digital technology. In an average month, please indicate the degree to which your child participates in each of the following activities. Next to each activity, there is a scale ranging from 1 (less than once a month) to 6 (daily). Please circle the number that best corresponds to your child's level of participation for each activity.

	Less than once a month	**Once a month**	**Twice a month**	**Once a week**	**Twice a week**	**More than twice a week**
Watch TV on a TV set	1	2	3	4	5	6
Watch TV on a Computer	1	2	3	4	5	6
Watch TV on a Tablet/iPad	1	2	3	4	5	6
Watch TV on a Smartphone	1	2	3	4	5	6
Play Games on a TV set (i.e. Xbox,	1	2	3	4	5	6

Playstation, etc.)

	Less than once a month 1	**Once a month 2**	**Twice a month 3**	**Once a week 4**	**Twice a week 5**	**More than twice a week 6**
Play Games on a Computer	1	2	3	4	5	6
Play Games on a Tablet/iPad	1	2	3	4	5	6
Play Games on a Smartphone	1	2	3	4	5	6

How often does your child use the following kinds of apps?

Puzzle Games	1	2	3	4	5	6
Math Games	1	2	3	4	5	6
Memory Games	1	2	3	4	5	6
Tangrams	1	2	3	4	5	6
Reading	1	2	3	4	5	6
Games that are just for fun	1	2	3	4	5	6
Drawing	1	2	3	4	5	6
Music	1	2	3	4	5	6
Apps Based on Character(s) known from a TV show or movie	1	2	3	4	5	6
Skype/FaceTime	1	2	3	4	5	6
View/Take Pictures	1	2	3	4	5	6
Does your child like playing with this device?			Yes	No		

Please use the following lines to list any digital games and/or applications that your child has experience with.	How often used? (circle one) F = frequently O = occasionally R = rarely			Do they play alone or with someone else? (circle one) 1 = Always solitary. 2 = Usually solitary. 3 = Usually with someone. 4 = Always with someone.			
______________________	F	O	R	1	2	3	4
______________________	F	O	R	1	2	3	4
______________________	F	O	R	1	2	3	4
______________________	F	O	R	1	2	3	4
______________________	F	O	R	1	2	3	4
______________________	F	O	R	1	2	3	4
______________________	F	O	R	1	2	3	4
______________________	F	O	R	1	2	3	4

The following questions are about **YOU.** How often do **YOU** use the following kinds of apps?

	Less than once a month	**Once a month**	**Twice a month**	**Once a week**	**Twice a week**	**More than twice a week**
Puzzle Games	1	2	3	4	5	6
Math Games	1	2	3	4	5	6
Memory Games	1	2	3	4	5	6
Tangrams	1	2	3	4	5	6
Reading	1	2	3	4	5	6
Games that are just for fun	1	2	3	4	5	6
Drawing	1	2	3	4	5	6
Music	1	2	3	4	5	6
Apps Based on Character(s) known from a TV show or movie	1	2	3	4	5	6

Skype/FaceTime	1	2	3	4	5	6
View/Take Pictures	1	2	3	4	5	6

References

ABCTeach.com. (2001-2008). Word list: prepositions. Retrieved from: https://www.abcteach.com/free/l/list_prepositions.pdf.

American Academy of Pediatrics (2018). Children and media tips from the American Academy of Pediatrics. Retrieved from: https://www.aap.org/en-us/about-the-aap/aap-press-room/news-features-and-safety-tips/Pages/Children-and-Media-Tips.aspx

Antrilli, N. K., & Wang, S. (2016). Visual cues generated during action facilitate 14-month-old infants' mental rotation. *Journal of Cognition & Development*, *17*, 418-429. doi:10.1080/15248372.2015.1058262.

Antrilli, N. K., & Wang, S. H. (2018). Toddlers on touchscreens: immediate effects of gaming and physical activity on cognitive flexibility of 2.5-year-olds in the US. *Journal of Children and Media*, *12*(4), 496-513. doi:10.1080/17482798.2018.1486332.

Baldwin, D. A., Markman, E. M., & Melartin, R. L. (1993). Infants' ability to draw inferences about nonobvious object properties: Evidence from exploratory play. *Child Development*, *64*(3), 711-728. doi: 10.1111/j.1467-8624.1993.tb02938.x.

Barnett, S. M. (2014). Virtual to real life—Assessing transfer of learning from video games. In F. C. Blumberg (Ed.), *Learning by Playing: Video Gaming in Education* (15-28). Oxford: Oxford University Press.

Barr, R. (2008). Attention and learning from media during infancy and early childhood. In S. L. Calvert & B. Wilson (Eds.), *Handbook on Children, Media, and Development* (pp. 143–165). Boston: Blackwell.

Blumberg, F. C., Deater-Deckard, K., Calvert, S. L., Flynn, R. M., Green, C. S., Arnold, D., & Brooks, P. J. (2019). Digital games as a context for children's cognitive development: Research recommendations and policy considerations. *Social Policy Report*, *32*(1), 1-33. doi: 10.1002/sop2.3.

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel broadens the mind. *Infancy, 1*, 149–219. doi:10.1207/S15327078IN0102_1.

Cannon, J., Levine, S., & Huttenlocher, J. (2007). A system for analyzing children and caregivers' language about space in structured and unstructured contexts. *Spatial Intelligence and Learning Center (SILC) Technical Report*.

Casey, B. M., Andrews, N., Schindler, H., Kersh, J. E., Samper, A., & Copley, J. (2008). The development of spatial skills through interventions involving block building activities. *Cognition and Instruction*, *26*(3), 269-309. doi:10.1080/07370000802177177.

Cimpian, A., & Markman, E. M. (2009). Information learned from generic language becomes central to children's biological concepts: Evidence from their open-ended explanations. *Cognition*, *113*(1), 14-25. doi:10.1016/j.cognition.2009.07.004.

Clearfield, M. W. (2004). The role of crawling and walking experience in infant spatial memory. *Journal of Experimental Child Psychology*, *89*(3), 214-241. doi:10.1016/j.jecp.2004.07.003.

Clements, D. H., & Sarama, J. (2007). Effects of a preschool mathematics curriculum: Summative research on the Building Blocks project. *Journal of Research in Mathematics Education*, 38, 136–163. Retrieved from http://www.jstor.org/stable/30034954.

Cheng, Y. L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development*, *15*(1), 2-11. doi:10.1080/15248372.2012.725186.

Clements, D. H., Swaminathan, S., Hannibal, M. A. Z., & Sarama, J. (1999). Young children's concepts of shape. *Journal for research in Mathematics Education*, *30*, 192-212. doi:10.2307/749610.

Cohen, M, Hadley, M, & Frank, M. Young children, apps, and iPads. Report from U.S. Department of Education Ready to Learn Program 2011. Retrieved from http://mcgrc.com/wp-content/uploads/2012/06/ipad-study-cover-page-re port-mcg-info_new-online.pdf.

Coyle, E. F. & Liben, L. S. (2018). Gendered packaging of a STEM toy influences children's play, mechanical learning, and mothers' play guidance. *Child Development*. doi:10.1111/cdev.13139.

Cross, C. T., Woods, T. A., & Schweingruber, H. (Eds.). (2009). *Mathematics Learning in Early Childhood: Paths toward Excellence and Equity.*

Washington, DC: The National Academies Press. Retrieved from http://www.eric.ed.gov/ERICWebPortal/recordDetail?accno=ED536446.

Dempsey, R., Verdine, B. N., Golinkoff, R. M., & Hirsh-Pasek, K. (2013). Sorting out spatial toys: Comparing traditional shape sorters to modern touchscreen applications. In *25th Annual Association for Psychological Sciences Convention, Washington, DC, US.*

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology*, *42*(6), 1259. doi:10.1037/0012-1649.42.6.1259.

Ferrara, K., Hirsh-Pasek, K., Newcombe, N. S., Golinkoff, R. M., & Lam, W. S. (2011). Block talk: Spatial language during block play. *Mind, Brain, and Education*, *5*(3), 143-151. doi:10.1111/j.1751-228X.2011.01122.x

Fisch, S. M. (2016). The capacity model, 2.0: Cognitive processing in children's comprehension of educational games. Paper presented at the Society for Research in Child Development Special Topic Meeting on Technology and Media in Children's Development. Irvine, CA.

Fisher, K. R., Hirsh-Pasek, K., Newcombe, N. S., & Golinkoff, R. M. (2013). Taking shape: Supporting preschoolers’ acquisition of geometric knowledge through guided play. *Child Development*, *84*(6), 1872–1878. doi.org/10.1111/cdev.12091.

Flynn, R. M., & Richert, R. A. (2015). Parents support preschoolers' use of a novel interactive device. *Infant and Child Development*, *24*(6), 624-642. doi:10.1002/icd.1911.

Frick, A., & Wang, S. (2014). Mental spatial transformations in 14- and 16-month-old infants: Effects of action and observational experience. *Child Development, 85*, 278-293. doi:10.1111/cdev.12116.

Gentner, D. (2016). Language as cognitive tool kit: How language supports relational thought. *American Psychologist*, *71*(8), 650. doi: 10.1037/amp0000082.

Gentner, D., Imai, M., & Boroditsky, L. (2002) As time goes by: Evidence for two systems in processing space → time metaphors, *Language and Cognitive Processes*, 17:5, 537-565. doi:10.1080/01690960143000317.

Gentner, D., & Loewenstein, J. (2002). Relational language and relational thought. In *Language, Literacy, and Cognitive Development* (pp. 101-138). Psychology Press.

Gentner, D., & Markman, A. B. (1997). Structure mapping in analogy and similarity. *American Psychologist*, *52*(1), 45. doi:10.1037/0003-066X.52.1.45.

Gibbs Jr, R. W. (2003). Embodied experience and linguistic meaning. *Brain and Language*, *84*(1), 1-15. doi:10.1016/S0093-934X(02)00517-5.

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology*, *39*, 1-42. doi:10.1146/annurev.ps.39.020188.000245

Göbel, S., Walsh, V., & Rushworth, M. F. (2001). The mental number line and the human angular gyrus. *Neuroimage*, *14*(6), 1278-1289. doi:10.1006/nimg.2001.0927.

Goodwin, C. (2003). Pointing as situated practice. In *Pointing* (pp. 225-250). Psychology Press.

Goldin-Meadow, S. (2007). Pointing sets the stage for learning language—and creating language. *Child Development*, *78*(3), 741-745. doi:10.1111/j.1467-8624.2007.01029.x

Griffith, S. F., & Arnold, D. H. (2019). Home learning in the new mobile age: Parent–child interactions during joint play with educational apps in the US. *Journal of Children and Media*, *13*(1), 1-19. doi:10.1080/17482798.2018.1489866.

Grissmer D., Mashburn A., Cottone E., Brock L., Murrah W., Blodgett J., Cameron C. (2013). The efficacy of minds in motion on children's development of executive function, visuo-spatial and math skills. Paper presented at the *Society for Research in Educational Effectiveness Conference*, Washington, DC.

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: the role of the linear number line. *Developmental Psychology*, *48*(5), 1229. doi:10.1037/a0027433.

Hirsh-Pasek, K., Zosh, J. M., Golinkoff, R. M., Gray, J. H., Robb, M. B., & Kaufman, J. (2015). Putting education in "educational" apps: lessons from the science of learning. *Psychological Science in the Public Interest*, *16*(1), 3-34. doi:10.1177/1529100615569721.

Jant, E. A., Haden, C. A., Uttal, D. H., & Babcock, E. (2014). Conversation and object manipulation influence children's learning in a museum. *Child Development*, *85*(5), 2029-2045. doi:10.1111/cdev.12252.

Jirout, J. J., & Newcombe, N. S. (2015). Building blocks for developing spatial skills: Evidence from a large, representative US sample. *Psychological Science*, *26*(3), 302-310. doi:10.1177/0956797614563338.

Jordan, N.C., & Glutting, J.J. (2017). *Number Sense Screener. Research Edition*. Baltimore, MD: Brookes Publishing Co.

Kirkorian, H. L., Pempek, T. A., Murphy, L. A., Schmidt, M. E., & Anderson, D. R. (2009). The impact of background television on parent–child interaction. *Child Development*, *80*(5), 1350-1359. doi:10.1111/j.1467-8624.2009.01337.x

Kirsh, D., & Maglio, P. (1994). On distinguishing epistemic from pragmatic action. *Cognitive Science*, *18*(4), 513-549. doi:10.1016/0364-0213(94)90007-8.

Kretch, K. S., & Adolph, K. E. (2013). Cliff or step? Posture-specific learning at the edge of a drop-off. *Child Development*, *84*(1), 226-240. doi:10.1111/j.1467-8624.2012.01842.x.

Kretch, K. S., Franchak, J. M., & Adolph, K. E. (2014). Crawling and walking infants see the world differently. *Child Development*, *85*(4), 1503-1518. doi:10.1111/cdev.12206.

Levine, S.C., Huttenlocher, J., Taylor, A. & Langrock, A. (1999). Early Sex Differences in Spatial Skill. *Developmental Psychology*, 35(4), 940-949.

Levine, S. C., Ratliff, K. R., Huttenlocher, J., & Cannon, J. (2012). Early puzzle play: a predictor of preschoolers' spatial transformation skill. *Developmental Psychology*, *48*(2), 530. doi:10.1037/a0025913.

Liben, L. S. (2009). The road to understanding maps. *Current Directions in Psychological Science, 18,* 310-315. doi:10.1111/j.1467-8721.2009.01658.x.

Lillard, A. S., Drell, M. B., Richey, E. M., Boguszewski, K., & Smith, E. D. (2015). Further examination of the immediate impact of television on children's executive function. *Developmental Psychology*, *51*(6), 792. doi:10.1037/a0039097.

Lillard, A. S., & Peterson, J. (2011). The immediate impact of different types of television on young children's executive function. *Pediatrics*, *128*(4), 644-649. doi:10.1542/peds.2010-1919.

Loewenstein, J., & Gentner, D. (1998). Relational language facilitates analogy in children. In *Proceedings of the Twentieth Annual Conference of the Cognitive Science Society* (Vol. 20, pp. 615-620). doi:10.1111/j.1467-7687.2011.01088.x.

Maglio, P. P., Wenger, M. J., & Copeland, A. M. (2003). The benefits of epistemic action outweigh the costs. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 25, No. 25).

Marzollo, J., & Wick, W. (1998). *I Spy: Gold Challenger. A Picture Book of Riddles.* Scholastic Inc., Cartwheel Books.

Möhring, W., & Frick, A. (2013). Touching up mental rotation: Effects of manual experience on 6-month-old infants' mental object rotation. *Child Development*, *84*, 1554-1565. doi:10.1111/cdev.12065.

Moore, D. S., & Johnson, S. P. (2008). Mental rotation in human infants: A sex difference. *Psychological Science*, 19, 1063–1066. doi:10.1111/j.1467-9280.2008.02200.x.

Nathanson, A. I., Aladé, F., Sharp, M. L., Rasmussen, E. E., & Christy, K. (2014). The relation between television exposure and executive function among preschoolers. *Developmental Psychology*, *50*(5), 1497. doi:10.1037/a0035714.

National Research Council. (2006). *Learning to think spatially: GIS as a support system in the K-12 Curriculum*. Washington, D.C.: National Academies Press. Retrieved from http://site.ebrary.com/id/10110308.

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator*, *34*(2), 29.

Parish-Morris, J., Mahajan, N., Hirsh-Pasek, K., Golinkoff, R. M., & Collins, M. F. (2013). Once upon a time: Parent–child dialogue and storybook reading in the electronic era. *Mind, Brain, and Education*, *7*(3), 200-211. doi:10.1111/mbe.12028.

Piaget, J., & Inhelder, B. (1956). *The child's conception of space* (F. J. Langdon & J. L. Lunzer, Trans.). London: Routledge and Kegan Paul. (Original work published 1948).

Ping, R., Ratliff, K., Hickey, E., & Levine, S. (2011). Using manual rotation and gesture to improve mental rotation in preschoolers. In *Proceedings of the Cognitive Science Society* (Vol. 33, No. 33).

Pruden, S. M., Levine, S. C., & Huttenlocher, J. (2011). Children's spatial thinking: does talk about the spatial world matter? *Developmental Science*, *14*(6), 1417-1430. doi:10.1111/j.1467-7687.2011.01088.x

Rideout, V. (2013). *Zero to eight: Children's media use in America 2013.* Retrieved from http://www.commonsensemedia.org.

Rideout, V. (2017). The common sense census: Media use by kids age zero to eight. *San Francisco, CA: Common Sense Media*, 263-283.

Rochat, P. & Hespos, S.J. (1996). Tracking and anticipation of invisible spatial transformations by 4- to 8-month-old infants. *Cognitive Development*, *11*, 3-17. doi:10.1016/S0885-2014(96)90025-8.

Samermit, P., & Gibbs, R. W. (2016). Humor, the body, and cognitive linguistics. *Cognitive Linguistic Studies*, *3*(1), 32-49. doi:10.1075/cogls.3.1.02sam.

Schneider, B., Jermann, P., Zufferey, G., & Dillenbourg, P. (2011). Benefits of a tangible interface for collaborative learning and interaction. *Learning*

Technologies, IEEE Transactions on, *4*(3), 222-232. doi:10.1109/TLT.2010.36

Schneider, B., Wallace, J. M., Blikstein, P., & Pea, R. (2013). Preparing for future learning with a tangible user interface: The case of neuroscience. *Learning Technologies, IEEE Transactions on*, *6*(2), 117-129. doi:10.1109/TLT.2013.15

Schwarzer, G., Freitag, C., & Schum, N. (2013). How crawling and manual object exploration are related to the mental rotation abilities of 9-month-old infants. *Frontiers in Psychology*, *4*, 97. doi:10.3389/fpsyg.2013.00097.

Shuler, C., Levine, Z., & Ree, J. (2012*). iLearn II: An analysis of the educational category of Apple's app store.* Joan Ganz Cooney Center. Retrieved from www.joanganzcooneycenter.org.

Soska, K. C., Adolph, K. E., & Johnson, S. P. (2010). Systems in development: Motor skill acquisition facilitates three-dimensional object completion. *Developmental Psychology*, *46*, 129-138. doi:10.1037/a0014618.

Tamis-LeMonda, C. S., Adolph, K. E., Lobo, S. A., Karasik, L. B., Ishak, S., & Dimitropoulou, K. A. (2008). When infants take mothers' advice: 18-month-olds integrate perceptual and social information to guide motor action. *Developmental Psychology*, *44*(3), 734. doi:10.1037/0012-1649.44.3.734.

Tomasello, M., Carpenter, M., & Liszkowski, U. (2007). A new look at infant pointing. *Child Development*, *78*(3), 705-722. doi:10.1111/j.1467-8624.2007.01025.x

Uhls, Y., & Robb, M. B. (2017). How parents mediate children's media consumption. InF. C. Blumberg & P. J. Brooks (Eds.), *Cognitive Development in Digital Contexts* (pp. 326– 343). New York, NY: Academic Press.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., et al. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, 139, 352–402. doi:10.1037/a0028446.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2014). Finding the missing piece: Blocks, puzzles, and shapes fuel school readiness. *Trends in Neuroscience and Education*, *3*(1), 7-13. doi:10.1016/j.tine.2014.02.005.

Verdine, B., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. (2017). Links between spatial and mathematical skills across the preschool years. *Society for Research in Child Development Monograph*, *82*(1).

Verdine, B. N., Lucca, K. R., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2016). The shape of things: The origin of young children's knowledge of the names and properties of geometric forms. *Journal of Cognition and Development*, *17*(1), 142-161. doi:10.1080/15248372.2015.1016610.

Verdine, B. N., Zimmermann, L., Foster, L., Marzouk, M. A., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. (2019). Effects of geometric toy design on parent–child interactions and spatial language. *Early Childhood Research Quarterly*, *46*, 126-141. doi:10.1016/j.ecresq.2018.03.015.

Vygotsky, L. S. (1980). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Walle, E. A., & Campos, J. J. (2014). Infant language development is related to the acquisition of walking. *Developmental Psychology*, *50*(2), 336. doi:10.1037/a0033238.

Wooldridge, M. B., & Shapka, J. (2012). Playing with technology: Mother–toddler interaction scores lower during play with electronic toys. *Journal of Applied Developmental Psychology*, *33*(5), 211-218. doi:10.1016/j.appdev.2012.05.005.

Zimmerman, F. J., & Christakis, D. A. (2007). Associations between content types of early media exposure and subsequent attentional problems. *Pediatrics*, *120*(5), 986-992.

Zosh, J. M., Verdine, B. N., Filipowicz, A., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2015). Talking shape: parental language with electronic versus traditional shape sorters. *Mind, Brain, and Education*, *9*(3), 136-144. doi:10.1111/mbe.1208.