Diversity in spatial activities and parent spatial talk utterance length predict growth in preschoolers' spatial skills

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Submitted to the Graduate Faculty of the

Dietrich School of Arts and Sciences in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2022

UNIVERSITY OF PITTSBURGH

DIETRICH SCHOOL OF ARTS AND SCIENCES

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April 7, 2022

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Spatial cognition refers to a range of abilities related to visualizing, manipulating, and transforming objects and spaces. Previous research has shown that greater spatial cognition in childhood uniquely predicts later math skills and is linked to greater educational and occupational outcomes, especially in STEM fields. Additional research has shown that engaging in spatially related activities and play (e.g., puzzles, block building) positively influences spatial thinking and reasoning in children and adults, and increased exposure to spatial language is positively correlated with children's spatial word comprehension and performance on mental rotation and mapping tasks. In this study, we investigated potential origins of variability in preschool-aged children's spatial cognition (N=113, mean age=4 years 4 months) by examining how various measures of children's daily spatial activities as well as parental spatial language input during different activities with their child predicted growth in children's spatial skills from 4 to 5 years of age. More diversity in daily spatial activities was associated with greater growth in children's spatial skills. Moreover, parents who used longer spatial talk utterances during a spatial activity with their child had children with more growth in spatial skills, even when controlling for overall utterance length and verbosity. Finally, the diversity of spatial activities and parents' spatial utterance lengths were both unique predictors of growth in children's spatial skills suggesting that parental report of spatial activities and direct observations of parents' spatial language input capture

different and meaningful aspects of the home learning environment that supports children's spatial skill development.

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1.0 Introduction

Spatial cognition is a unique component of general intelligence as well as a predictor of math performance (LeFevre et al., 2010; Mix & Cheng, 2012). The term spatial cognition refers to a range of cognitive abilities related to visualizing, manipulating, and transforming the objects and spaces we encounter daily (Uttal et al., 2013). Some of these abilities are present in infancy and undergo a protracted development, extending to include more complex and abstract competencies over time. For example, one study has shown that infants with greater spatial abilities measured via their ability to discriminate between objects rotated in space vs mirrored objects are better at mentally transforming shapes at age 4 (Lauer & Lourenco, 2016). Moreover, children's spatial and patterning abilities can uniquely predict later math skills (Rittle-Johnson, Zippert, & Boice, 2019), and greater math ability is linked in turn to better health and medical decision-making (Reyna et al., 2009). In addition, greater spatial cognition in childhood is linked to greater educational and occupational outcomes, especially in STEM fields (Wai, Lubinski, & Benbow, 2009). Thus, spatial cognition acts as a foundational skill that impacts human capital outcomes throughout life. Despite its importance for many aspects of human life, the development of spatial skills has not received as much attention in research as other aspects of math, especially numeracy (Zippert & Rittle-Johnson, 2020).

While it is clear that spatial skills have a cascading effect on academic and occupational success, the origins of variability in spatial cognition are still unclear. Thus, the aim of the current study is to advance existing knowledge of how the home learning environment and parental support influences preschoolers' spatial skills by addressing three research aims. The first aim of the present study is to determine whether the frequency with which children engage in spatial activities (e.g., block play and puzzle play) or the diversity of their daily spatial activities is predictive of their growth in spatial ability from age 4 to age 5. The second aim examines whether the frequency or complexity of parent spatial talk, i.e., any conversations related to spatial properties or spatial relations, during spatial and non-spatial play activities predict the growth of preschoolers' spatial skills. The third aim of this study is to determine whether measures of spatial activities and spatial talk capture unique aspects of children's home learning environment.

1.1.1 Development of spatial skills in early childhood

Foundational spatial skills are present in infancy and undergo a protracted development throughout life. Studies have shown that already during the first eighteen months of life infants are able to perceive within-object spatial properties like differences in size (Cordes & Brannon, 2009), relative length of 2D visual forms (Dillon, Izard, & Spelke, 2020), as well as between-object properties like *above, below, on*, etc. (Casasola, 2005; Quinn et al., 1996). Moreover, using looking times, researchers found that infants between three and five months of age looked significantly longer at a familiar shape that had been rotated from its original position, indicating that they perceived the differences between the novel position and familiar position of the object long before they were able to understand or produce the necessary language to describe such spatial transformations (Moore & Johnson, 2011).

While preverbal infants may comprehend spatial concepts, language does play a role in shaping and refining children's spatial skills. By 18 months, children hearing a familiar spatial word describing support or containment (e.g., *on*, *in*, etc.) direct their attention to a scene matching the word presented. However, when the scenes are accompanied by other, non-spatial words, children are unable to form categorical spatial representations suggesting that they need the linguistic support to extract commonalities in spatial relations between objects (Casasola, 2005; Choi et al., 1999).

By the age of five, children's spatial skills start to include more abstract concepts like using a map to navigate an unfamiliar space (Jirout & Newcombe, 2014) and mentally folding and unfolding a piece of paper (Harris et al., 2013). Then in middle childhood (e.g., fifth grade), children are able to engage in classic perspective-taking tasks with some success (e.g., visualizing an environment from different vantage points; Newcombe & Frick, 2010; Rigal, 1996).

Very few studies have investigated individual differences in spatial skills with preschool-aged children (e.g., 3–5-year-olds; Bower et al., 2020; Verdine et al., 2014), and while a general understanding of developmental group differences exists, very little is known about individual differences in spatial skills and the environmental influences that may contribute to their growth. Given the dearth of knowledge regarding individual differences in spatial abilities in preschoolers, the current study aims to fill this gap.

1.1.2 The role of spatial activities for children's spatial skill development

While genetic influences seem to contribute to spatial cognition (McGee, 1979), spatial skills are malleable in both children and adults (Uttal et al., 2013). Even a small amount of training (e.g., formal curriculum, spatial video games, etc.) improves spatial skills at every ability level, and the rate of growth and the amount of training tend to be positively correlated (Baenniger & Newcombe, 1989; Bower et al., 2020; Cherney, 2008; Fernández-Méndez et al., 2018).

Importantly, the effects of training can have a lasting impact for months following the intervention and can be transferable to other spatial tasks (Newcombe & Frick, 2010; Newman et al., 2016).

Additional research has shown that engaging in spatially related activities and play (e.g., puzzles and block building) positively influences spatial thinking and reasoning in children and adults (Baenninger & Newcombe 1989; Baenninger & Newcombe, 1995; Casey et al., 2008; Cherney, 2008; Costa-Giomi, 1999; Doyle et al., 2012; Ozel et al., 2004; Weckbacher & Okamoto, 2012). For example, Levine and colleagues (2012) observed naturalistic play in 2- to 4-year-old children and their parents over a two-year span and found that those who played with puzzles outperformed those who did not on a mental transformation task. More importantly, the frequency and quality (a composite of difficulty, parental engagement, and parent spatial language) of puzzle play also predicted children's performance on the mental transformation task. Results from a study conducted by Jirout and Newcombe (2015) confirm that more frequent spatial play (i.e., puzzles, blocks, and board games) as reported by the parents is associated with stronger spatial skills in 4-7-year-olds.

Further longitudinal work showed that participation in spatial activities in childhood predicted spatially related problem-solving strategies as well as participation in spatial activities in adolescence (Peterson et al., 2020). Importantly, adolescent participation in spatial activities predicted their spatial ability. In sum, engagement in spatial activities is associated with better spatial skills throughout development.

1.1.3 Measurement of spatial activity

Most of the previously published research relied only on parent-reported frequencies of spatial activities. However, parent reports often vary in the range of activities surveyed as well as the time frame that parents report about.

Survey measures. Previous research using survey measures of parent-reported spatial activities usually asked about frequencies of activities over the span of one to four weeks using questionnaires with Likert scale response options like “never”, “rarely” (once or twice per week), “sometimes” (three to five times per week), and “often” (six or more times per week; Siegel-Hinson & McKeever, 2002; Jirout & Newcombe, 2015; Oostermeijer et al., 2014; Newcombe et al., 1983), or required parents to make a mark on a continuous line between “never” and “always” (Doyle et al., 2012). The current study employed a similar survey measure to capture the average frequency of children’s spatial activities over the span of one month. While these reports may average over day-to-day fluctuations in the frequency of children’s engagement in spatial activities, this method of reporting may introduce recall bias, memory errors, and inflated frequencies to appear more educationally oriented (Bachman et al., 2020). In addition, it does not consider the diversity of children’s spatial activities (i.e., how many different spatial activities children engage in). The present study seeks to reduce reporting bias by including an additional parent report from the previous day which will be used to examine the number of spatially relevant activities a child engaged in over the past 24 hours as a measure of diversity in children’s spatial activities.

Time diaries. Time diaries have been used to capture the duration of activities that parents and children engage in during a previous day (Bachman et al., 2020). Adapted from the American Time

Use Survey (ATUS; U.S. Bureau of Labor Statistics, 2016), time diaries require participating parents to record every activity that they and their child participated in over a period of 24 hours the day prior to the interview. This minute-by-minute account provides insight into how families typically allocate their time, and how informal educational activities are woven into daily life. Previous studies have employed time diaries to examine how American children spend their time using broad categories (e.g., play, reading, etc.; Fiorini & Keane, 2014; Hofferth & Sandberg, 2001); however, no prior study has expanded this tool to measure and investigate children's engagement in spatial activities.

Within the context of time diary interviews, parents can also be asked a series of questions to determine whether their child engaged in specific academically related activities (Academic Stimulation Activities; ASA) on the previous day (Bachman et al., 2020). Adding ASA to the time diary protocol can cue any memory of specific activities that parents may have forgotten such as building with blocks during a long play session. In fact, a previous report showed that less than 20% of parents reported engaging in math-related activities during the time diary interview, but 96% of them reported engaging in at least one math-related activity when asked about specific ASA (Bachman et al., 2020). Thus, the present study will capture diversity in children's engagement in spatial activities by using parents' responses to ASA questions to determine whether children engaged with four different spatial activities on two separate days, and whether engaging in a diversity of such activities is related to spatial skills.

1.1.4 The role of parent spatial talk for children's spatial skills

Parent spatial talk frequency. Parent reports may be subject to biases or influenced by parents' desire to depict a more academically oriented home environment (Bachman et al., 2020). Direct observations of parents' behaviors and especially their use of spatial language during interactions with their children may be a more direct measure of parental spatial input that can occur within the context of spatial activities as well as in the context of non-spatial activities. Prior studies have used naturalistic or semi-structured activities to promote and observe frequencies of spatial talk during parent-child play (Ferrara et al., 2011; Polinsky et al., 2017). Like spatial activities, the quality and quantity of spatial language children hear varies by household characteristics including interactional style, opportunities for engagement in spatially relevant discussions, and stimuli (i.e., toys) present (Cartmill et al., 2010; Ho et al., 2018; Lee & Wood, 2020; Pruden et al., 2011; Verdine et al., 2017). Importantly, increased exposure to spatial language is positively correlated with children's spatial word comprehension (Kisa et al., 2019) and performance on mental rotation and mapping tasks (Casasola et al., 2020; Loewenstein & Gentner, 2005).

Children who are exposed to a broader range of spatial words are able to transfer their understanding to other situations (Casasola et al., 2020). Results from a study with children between the ages of 14 and 46 months demonstrated that the frequency with which parents employ spatial words at 14 months is predictive of children's productive spatial language and spatial problem-solving at 46 months (Pruden, Levine, & Huttenlocher, 2011). Furthermore, Bower and colleagues (2020) showed that children who received feedback during spatial assembly training outperformed children in the control group who did not receive feedback. Similarly, Polinsky and colleagues (2017) found that when parents were prompted to discuss spatial concepts with their four-year-old children in a museum setting both the parents' and children's spatial talk frequencies increased, as did the children's subsequent performance on a spatial task.

Together, these findings provide empirical evidence to support the association between parents' spatial language use and children's spatial ability. However, previous literature on parent spatial talk has focused only on spatial language frequency and does not compare spatial or non-spatial contexts in which spatial language is employed and whether the context impacts children's spatial capabilities. The present study seeks to address this gap by investigating whether children's spatial skills are influenced by parent spatial talk during spatial and non-spatial activities.

***Parent Spatial Utterance Length*.** In addition to the frequency of parents' talk about specific concepts, the complexity of parents' talk may also impact children's opportunities to learn about these concepts. While *spatial* utterance length has not been examined yet, utterance complexity, measured by mean utterance length (MUL), has been used in several studies to examine the association between the quality of parental speech and early childhood development (Daneri et al., 2019; Hoff, 2003). In a longitudinal study investigating the impact of aspects of maternal language input on two-year-olds' vocabulary the only attribute of mothers' speech that significantly predicted children's vocabulary ten weeks later was MUL (Hoff, 2003). Furthermore, maternal speech complexity as indexed by MUL measured when children were 36 months old mediated the relation between developmental risks associated with socioeconomic status and children's executive functioning at 48 months (Daneri et al., 2019). Thus, it is reasonable to investigate whether spatial mean utterance length is predictive of preschoolers' spatial skills and whether effects are context specific, i.e., whether spatial talk occurred during spatial vs. non-spatial activities.

1.1.5 Research Aims

While the relation between children's spatial activities and parent spatial talk frequencies on children's spatial abilities has been investigated (Casasola et al., 2020; Ferrara et al., 2011; Jirout and Newcombe, 2015; Levine, et al., 2012;), there are notable methodological gaps in the literature. Thus, the first aim of the present study was to use parent reports of monthly spatial activities as measured on a questionnaire, as well as diversity in daily spatial activities measured during time diaries to examine how they relate to growth in preschoolers' spatial skills. Second, previous research measuring spatial talk during parent-child activities has focused exclusively on the frequency of utterances related to spatial concepts, ignoring the length of parents' spatial utterances and the context in which this talk was measured. Therefore, the second aim of the present study was to examine the effect of parent spatial talk frequency and spatial utterance length during spatial and non-spatial play activities on preschoolers' growth of spatial skills. Finally, the present study investigates the unique contributions of measures of children's spatial activities and parent spatial talk in spatial and non-spatial play contexts to growth in children's spatial ability. Thus, this investigation seeks to answer the following questions:

Research Question #1 (RQ1): Does the frequency or diversity of children's spatial activities as reported by parents on a questionnaire and daily time diaries at age 4 significantly predict their growth in spatial ability from age 4 to age 5? We hypothesize that both frequency and diversity of children's spatial activities at age 4 will significantly predict growth in children's spatial ability one year later.

Research Question #2 (RQ2): Does the frequency or length of parent spatial utterances during spatial and non-spatial play activities predict the growth of preschoolers' spatial skills?

Given results of previous investigations, we hypothesize that parents' spatial talk frequency during semi-structured play opportunities at T1 will predict children's spatial skills at T2. However, due to the exploratory nature of the present study we do not have any a priori hypotheses about how parent spatial utterance length will relate to children's spatial ability.

Research Question #3 (RQ3): Do spatial activities and spatial talk capture unique aspects of children's home learning environment? A previous study investigated the relation between children's math skills and two measures of the home numeracy environment: a questionnaire and naturalistic observational talk data from 44 parent-child dyads over two play sessions (Mutaf Yildiz, et al., 2018). The results showed that parent questionnaire responses and observational numeracy talk data were not related to each other, but rather the questionnaire data were positively related to children's math ability and the observational talk data were negatively related to children's math ability. From this, we hypothesize that parent reports of children's spatial activity and parent spatial talk will not capture the same aspects of the home learning environment, but may both be predictive of children's spatial abilities. However, it is unclear whether we may observe opposite effects in the relations between parent input measures and child outcomes as seen in the study by Mutaf Yildiz et al. (2018) given our focus on spatial skills rather than numeracy.

1.2 Methods

1.2.1 Participants

Data were drawn from a longitudinal study of 113 socioeconomically diverse parent-child dyads living in the greater metropolitan area of a major Northeastern university. Participating children were 51% female and, on average, 4 years, 4 months (*SD* = 0.3, range = 4.0 - 4.9) at the first time point (T1), and 5 years, 5 months (SD= 0.3, range= 5.1 – 5.9). On average, there was an average delay of 12 months and 21 days (*SD*= 23 days) between data collection at T1 and T2. Families were recruited via an online research participant registry, social media outlets, and childcare centers. Children with a diagnosed cognitive disability or motor impairments were excluded, and all participating children were required to be native English speakers. Parents provided written informed consent prior to any data collection in accordance with a protocol approved by the local Institutional Review Board.

1.2.2 Procedures

All data for T1 were collected in person over the span of two home visits and two phone calls. Due to the COVID-19 pandemic, all data for T2 were collected via videoconferencing. Families without the required technology were loaned a laptop with a built-in webcam and a mobile Wi-Fi hotspot.

1.2.3 Time 1 (T1) procedures

Child assessments and semi-structured tasks for parent-child dyads were administered over the span of two home visits. All three of the semi-structured observations were administered at the first visit in the same order (book, puzzle, and grocery task, see below for details) before any other assessments were given. These semi-structured interactions were timed and video recorded. Researchers provided each parent-child dyad with age-appropriate toys and instructed participants to play like they normally would with these toys for about 5-8 minutes. Researchers then left the room to reduce distraction. If siblings were present, they were cared for by research assistants in a different area of the house.

After the semi-structured observations, the participating parent moved to a new location with one researcher to complete a battery of assessments and paperwork. The second researcher administered a series of tests with the child to measure various aspects of math ability and executive functioning. Task orders were counterbalanced between children, but in both cases the Geometric Sensitivity task was administered prior to the Children's Mental Transformation Task (see below for details).

Additional T1 data were collected in the form of an online survey and two time diaries that parents completed over two phone calls on separate days.

1.2.4 Time 2 (T2) procedures

Children completed an assessment battery online using video conferencing software. Assessments were divided into three calls to keep testing sessions between 15 and 30 minutes each. Within each session, task order was consistent (i.e., the Geometric Sensitivity task always occurred second during one session, and the Children's Mental Transformation Task occurred last in another), but the order of testing sessions was counterbalanced between children.

All materials were incorporated into PowerPoint slides that were shown to participants through a shared screen function, and researchers recorded children's responses during administration. Parents were invited to sit with their children during the sessions but were instructed to let their children answer all questions independently. All tasks were designed so that children could complete the sessions without parental assistance once the call was begun. To keep children engaged with the tasks, children were shown a brief animation after each task and allowed to move a piece of a virtual "sticker book" (e.g., images of animals could be placed in different locations on a jungle background). Additionally, at the end of the three testing sessions, children selected a small prize to be mailed to their homes as a thank-you for participating.

1.2.5 Measures

1.2.6 Children's spatial skills

Children's Mental Transformation Task (CMTT). The CMTT is a measure of children's mental transformation skills, specifically two-dimensional mental transformations, including horizontal and diagonal translations and rotations (Levine, et al. 1999). Participating children completed this task at both time points. Participants were presented with two shape pieces and asked to identify the shape that those pieces would create if they were put together from a set of four response options (see Figure 1). Task administration started with two practice trials, where researchers gestured to the prompt and said, "Look at these pieces. Now, look at these pictures. If you put these two pieces together, they will make one of the pictures. Point to the picture the pieces make." On the sixteen regular test trials the experimenter said only, "Point to the picture these pieces make." Corrective feedback was provided for the practice items, but not for the subsequent test trials. Children received one point for every correct answer (*range*=0-16) and the proportion correct was used as the dependent measure on the task (*range*=0.13-0.94, M = 0.49, SD=0.16). Past research with a 10-item version of the task demonstrates that this is a reliable measure of mental transformation skills, with split-half reliability of r = .55 (Ehrlich, Levine, & Goldin-Meadow, 2006; Levine et al., 1999). Children who completed fewer than 13 trials (80%) were recoded as missing. At T1, six (5%) of the observations were coded as missing.

Similar administrative methods were employed at T2, though some variation was necessary to adapt the task to the videoconferencing context. Children were introduced to the task with four cartoon animals (e.g., a dog, a cat, a bird, and a fish) and told that each animal was going to try to determine what shape these two pieces would make if put together. Children first saw the two shape pieces, followed by each of the four response options, and indicated verbally which animal had found the correct shape. The remainder of the task was exactly identical to T1. At T2, 18 (16%) of the observations were coded as missing. Across both time points two participants were missing values for both T1 and T2.

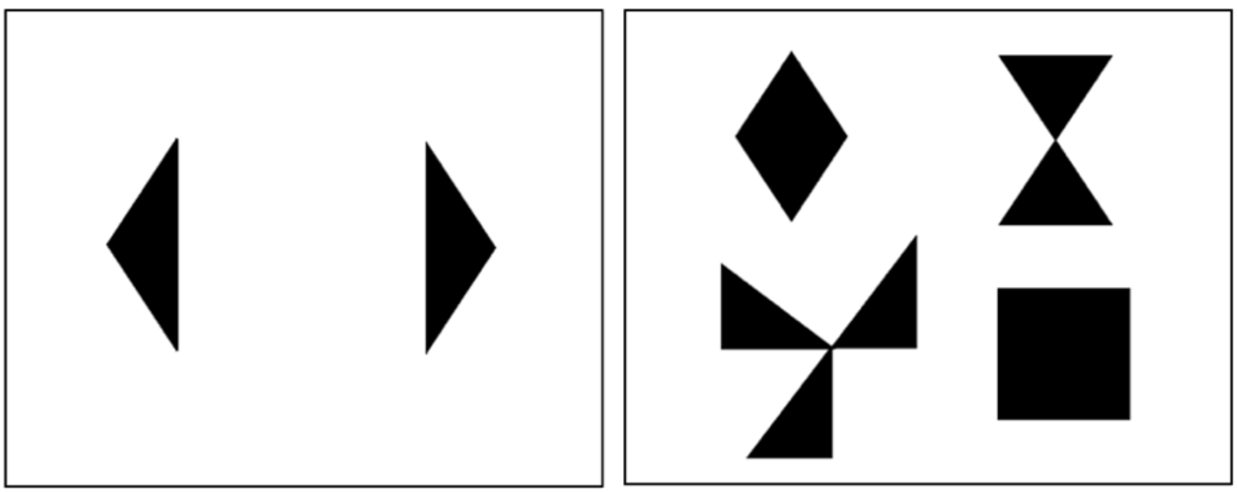

Figure 1 Children's Mental Transformation Task

Geometric Sensitivity (GS). The Geometric Sensitivity test (Dehaene, Izard, Pica, & Spelke, 2006; Dillon, Kannan, Dean, Spelke, & Duflo, 2017) was developed to measure children's ability to perceive differences in spatial relations and geometric properties of 2D visual displays. Children completed this task at both time points. Each display features six different images, five of which share a geometric property that is not present in the sixth image (see Figure 2). Children are asked to point to the picture that does not belong. Displays include geometric properties like distance, length, angles, symmetry, topology, straight lines, and parallelism. Four practice trials with feedback were included, followed by twelve test trials without feedback. Children received one point for every correct response (*range*=0-12) which was then converted to proportion correct (*range*=0.0-0.92, *M* = 0.36, *SD*=0.19). Scores were recoded to missing if the child completed fewer than 10 trials. At T1, four (3%) of the observations were coded as missing.

One year later at T2, the GS task was administered in a similar manner with some adaptations for videoconferencing. Children were first shown the six images on a single screen and asked to identify which was different from the rest. Then, different colored arrows with letters A through F pointing to the six images were displayed on the screen, and children were instructed to say either the color or the letter in the arrow pointing to the image that was different. At T2, 17 (15%) of the observations were coded as missing.

Composite scores of participants' spatial skills were created for T1 and T2 respectively by averaging CMTT and GS scores at each timepoint. Three participants (2.7%) were coded as missing at both timepoints.

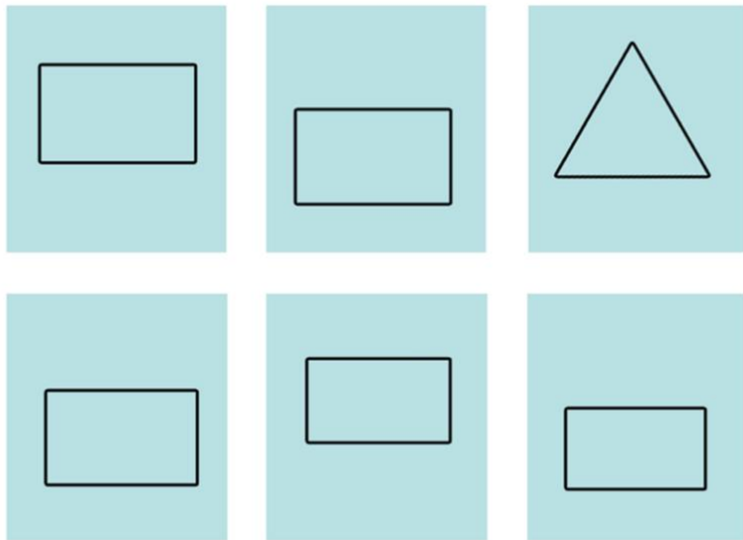

Figure 2 Test of Geometric Sensitivity

1.2.7 Spatial activity frequency & diversity

At T1 parents completed a questionnaire regarding the frequency with which their child engaged in a variety of activities over the span of one month (LeFevre et al., 2009). Spatially relevant activities included five items pertaining to the frequency of block building (blocks and Legos), puzzle play, making collections of like objects (i.e., patterning or grouping items with similar features), and sorting items by size, color, or shape. Parents responded using a Likert scale to indicate how often they observed their children engaging in an activity. Responses ranged from 1(*never*), 2 (*once or twice per month*), 3(*weekly*), 4 (*several times per week*), and 5 (*everyday*).

Time use diaries were completed by participating parents twice during T1: once tracking a workday (or weekday if not employed) and once tracking a non-workday (or weekend day). These data were collected over the phone by a research assistant or graduate student researcher in accordance with the American Time Use Survey (ATUS; U.S. Bureau of Labor Statistics, 2016). Specific prompts and clarifying questions were employed by interviewers to ensure consistent, quality data collection and to extract a level of detail that parents might otherwise have left out of their account (Phipps & Vernon, 2009). Calls were recorded and later coded to account for each minute of the day.

After the time use data were collected, the researcher asked a series of questions to determine if academic stimulation activities (ASA) occurred the previous day. This yes/no response indicates the variety of children's spatial play rather than the frequency or extent of time spent playing. See Appendix A for the complete list of ASA items and activity codes.

A spatial frequency score was created by averaging parents' Likert scale responses on the questionnaire. A daily spatial diversity score was created by averaging the number of spatial activities that parents responded "yes" to during the ASA section of the time diary on workdays and non-workdays.

Semi-structured observations. Parent-child dyads were observed as they participated in three semi-structured observation tasks designed to elicit a variety of math talk like number and spatial talk (Elliott, Braham & Libertus, 2017; Lee, Hodgins, & Wood, 2019; Ramani et al., 2015). However, participants were not informed that the study focused on math to avoid any priming effects. Participants were provided with age-appropriate toys and instructed to play like they normally would with these toys. To record these interactions, researchers set up a tripod and digital camera and left the room to avoid distracting participants.

The wordless picture book, *Fox's Fun Day*, used in the first task was specifically created for the project to ensure that it was equally novel for all dyads and to reduce any reading skill differences among parents. Each page introduced a new set of animals arriving at a fox's birthday party, a bird moves its location, the sun and sky change, and patterns emerge. After sharing the book, participants were instructed to complete a puzzle task that was specifically chosen to elicit high frequencies of spatial talk. For this task they were given a magnetic whiteboard, colorful, magnetic shapes, and a picture of an animal consisting of eighteen pieces and told to use the pieces to make the picture. Twenty-three more shape pieces than were needed to complete the puzzle were included as a foil. Dyads were told they had about five minutes to create the picture with the pieces. The grocery store task, which was always the last semi-structured task, involved parent-child dyads playing with plastic food, a shopping basket, and a toy cash register.

All semi-structured observations were video recorded, then transcribed verbatim at the utterance level. An utterance was defined as any language input from an individual speaker that is bounded by a silence of at least two seconds, a speaker transition, or a grammatical closure (e.g., a terminal punctuation mark such as a period; Pan et al., 2004). Once a video was transcribed, coders determined if spatial talk occurred by running a script to search for a list of potential spatial words (see Appendix B for search terms). Spatial terms were defined as any word that describes features or locations of 2D and 3D objects and spaces, excluding elements that are measurable but are not part of 2D/3D space (e.g., time & weight). Coders then read through the utterances identified as potentially including a spatial term and coded the content based on guidelines adapted from Cannon, Levine, and Huttenlocher's (2012) system for analyzing language about space (see Appendix B). Twenty percent of spatial talk transcriptions for each task were double-coded and reliability among coders was determined using Cohen's kappa (*range*=87-94, *M*=91).

Spatial talk frequencies for parents and children were calculated by adding the number of spatial utterances during each task. The parent spatial talk utterance length was determined by finding the mean length of all spatial utterances. The book and grocery tasks elicited less spatial talk, so spatial talk frequencies and utterance lengths from those tasks were combined to create measures of spatial talk during non-spatial activities. Spatial talk frequencies and utterance lengths during the puzzle task were used as measures of spatial talk during spatial activities. Four dyads had incomplete data for the puzzle task (3%), and four dyads had missing data for the other tasks (3%). Two dyads (1.6%) had missing data for both the puzzle and other tasks.

1.2.8 Covariates

1.2.8.1 Child age at T1

Age was measured by calculating the number of days from the participant's date of birth to the date of the first home visit, then dividing by 30 to determine children's age in months.

1.3 Data Analysis Plan

To address the aims of the present study all analyses were conducted in R version 4.1.0 (2021 – 05 – 18) and STATA version 16.1. To determine whether the frequency or diversity of spatial activities predict growth in preschoolers' spatial skills, two multiple regression analysis were conducted. First, to examine whether the frequency of children's spatial activities predict spatial ability one year later, children's spatial skills at T2 were regressed onto the spatial activity frequency composite taken from the questionnaire and covariates (child age and child spatial skills at T1). Next, children's spatial skills at T2 were regressed onto the spatial activity diversity composite drawn from ASA questions and covariates.

To address whether the frequency or length of parent spatial utterances predict growth of preschoolers' spatial skills, two separate multiple regression analyses were conducted. First, to determine if the *frequency* of parent spatial talk predicts growth of preschoolers' spatial skills, child spatial skills at T2 were regressed onto the total number of parent spatial utterances during the spatial activity (i.e., the puzzle task), total number of parent spatial utterances during the non-spatial activities (i.e., book and grocery tasks), and covariates (total parent utterances during the spatial activity, total parent utterances during the non-spatial activities, child age at T1, and child spatial skills at T1. Second, to investigate whether parents' *spatial utterance length* predicts children's spatial skills at T2, child spatial skills at T2 were regressed onto mean parental spatial utterance length during the spatial and nonspatial activities, as well as overall mean parent utterance length during the spatial and non-spatial activities, child age at T1 and child spatial skills at T1.

Finally, to determine whether spatial activities and spatial talk were unique aspects of the home learning environment correlations were used to determine the strength of the relation between the child's frequency and diversity of spatial activities and parent spatial talk variables. To further determine whether spatial activities and spatial talk were unique predictors of children's growth in spatial skills, in the final model we included only the predictor variables of spatial activities and spatial talk that were significant in previous models in the same regression model while including appropriate covariates.

Of the 113 participants, 95 (84%) had complete data for every variable. Cases with complete and missing data were compared to detect significant differences in age, socioeconomic status (SES), and spatial skills at T1 and T2. No significant differences between children with complete and missing data were found regarding age or spatial skills at either time point; however, there was a significant difference in SES. Children with missing data had lower SES composite scores (M=-.32, SD=.17) than children with complete data (M=.18, SD=.08, t(123)=-3.12, p=.002). All planned analyses were conducted using only the 95 complete cases as well as the largest sample size possible for a given analysis. The pattern of results was the same and the results reported below reflect those for the largest sample size possible.

1.4 Results

1.4.1 Descriptive statistics

Table 1 shows parents' reports of the frequency with which children engaged in spatial activities over the span of one month. On average, parents reported their children engaging in spatial activities between weekly and several times per week, except for making collections of like objects which was reported as occurring between only once or twice per month and once per week.

Table 1

Spatial activity frequency descriptive statistics

Activity	*M*	*SD*
Puzzles	3.02	1.23
Building (blocks)	3.72	1.15
Building (Legos)	.3.66	1.29
Sorting	3.66	1.27
Making collections of like objects	2.58	1.39
Activity frequency composite	3.33	.84

Note: The range for all activities was 1 (never) – 5 (everyday)

Table 2
Spatial activity diversity descriptive statistics

Activity	***M***	***SD***	
Puzzles (workday)	11	32	.
Puzzles (non-workday)	19	39	.
Building (workday)	29	46	.
Building (non-workday)	39	49	.
Sorting (workday)	17	38	.
Sorting (non-workday)	25	43	.
Making collections (workday)	05	23	.
Making collections (non-workday)	08	28	.
Activity diversity composite	75	69	.

Table 2 shows how many parents responded "yes" when asked if they observed their child participating in one of the listed spatial activities. Overall, about 75% of parents reported that their child had participated in at least one of the four activities during the previous day with building activities being the most frequently reported.

Finally, Table 3 shows the descriptive statistics of parent spatial utterance lengths for the spatial and non-spatial activities. Parents' mean spatial utterance lengths in spatial and non-spatial activities were longer than overall utterance lengths by an average of about 2 words. Additionally, spatial utterance lengths in the spatial activity were slightly shorter than the non-spatial activities, while overall utterance length was nearly the same in both contexts.

Table 3

Descriptive statistics of parent spatial and overall utterance length across tasks

Category & Task	*M*	*SD*	Min	Max
Puzzle Task				
Spatial utterance length	6.7	1.29	3.57	10.86
Overall utterance length	4.61	.88	2.85	9
Book & Grocery Tasks (combined)				
Spatial utterance length	7.09	1.58	3.64	14.13
Overall utterance length	4.51	.75	2.71	7.94

Spatial activity frequency predicting spatial skill growth (RQ1). The first aim of the present study was to determine if children's spatial activity frequency or diversity is predictive of their growth in spatial ability from age 4 to age 5. Regression analyses indicate that frequency of spatially relevant activities is not predictive of children's spatial skills but rather diversity of spatial activities at age 4 is predictive of children's spatial ability one year later even while controlling for age and spatial ability at age 4 (Table 4). The standardized beta coefficients show that a change of one standard deviation in diversity of daily spatial activity at T1 is associated with a change of .18 standard deviations of children's spatial skills at T2.

Table 4

Regression models predicting children's spatial skills at T2 from children's spatial activities

	Children's spatial skills at T2: Frequency model	Children's spatial skills at T2: Diversity model
Predictor	**B (SE)**	**B (SE)**
Spatial activities	.18* (.08)	-.03 (.09)
Child spatial skill at T1	.48*** (.09)	.52*** (.09)
Child age at T1	.17 (.09)	.13 (.08)
Constant	.16	-.04
F (3,86)	13.77***	15.13***
R^2	.30	.32

Notes: **p<.05, ** p<.01, *** p<.001*

Frequency or length of spatial utterances predicting spatial skill growth (RQ2). The second aim examines whether the frequency or mean spatial utterance length of parents' spatial talk during semi-structured tasks predicts preschoolers' spatial skills at T2 controlling for spatial skills at T1. As can be seen in Table 5, the *frequency* of parent spatial talk did not significantly predict children's spatial skills at T2, in contrast, parent spatial utterance length was a significant predictor of children's spatial skills at T2 even when controlling for spatial skills at T1. Importantly, the length of parent spatial utterances during a spatial activity (i.e., the puzzle task) was significant, whereas utterance length across the two non-spatial activities was not. Furthermore, the strength of the relation between spatial utterance length during spatial play and children's skills was quite strong. A one standard deviation change in parent spatial utterance length during puzzle play at T1 corresponded with a .46 standard deviation change in children's spatial skills at T2.

Table 5
Regression models predicting children's spatial skills at T2 from parent spatial utterances

	Children's spatial skills at T2: Frequency model	Children's spatial skills at T2: Length
Predictor	**B (SE)**	**B (SE)**
Parent spatial utterance: puzzle	-.15 (.01)	.43** (.14)
Parent spatial utterance: other	-.13 (.01)	.16 (.09)
Overall spatial utterance: puzzle	.20(.01)	-.21 (.12)
Overall spatial utterance: other	.14 (.02)	-.30 (.10)
Child spatial skill at T1	.55*** (.09)	.41*** (.09)
Child age at T1	.09 (.09)	.21 (.09)
Constant	.19(.41)	.21(.40)
F(6,86)	7.52***	11.32***
R^2	.29	.40

Notes: *p<.05, ** p<.01, *** p<.001

Spatial activities and spatial talk as unique aspects of the home learning environment (RQ3). The third aim of the present study was to investigate whether children's spatial activities and parents' spatial talk capture similar aspects of the home learning environment and whether those measures of the home learning environment that independently predicted growth in preschoolers' spatial skills in RQ1 and RQ2 continue to predict growth in children's spatial skills when controlling for other each other.

Table 6

Correlations between measures of spatial activity and parents' spatial talk at T1

Variable	**1**	**2**	**3**	**4**	**5**
1.Frequency of spatial activities					
2. Diversity of spatial activities	.23**				
3. Puzzle spatial talk frequency	.07	.11			
4. Other spatial talk frequency	.11	.001	.53***		
5. Puzzle spatial utterance length	-.18	.04	.01	.05	
6. Other spatial utterance length	-.19*	.09	.07	.04	.48***

Table 6 shows Pearson's correlations between all measures of spatial activities and spatial talk. As can be seen, only parent reports of children's spatial activity frequency are correlated with parent spatial utterance length during non-spatial tasks. The lack of correlation among the other parent talk and activity measures suggest that they capture different aspects of the home learning environment.

Regression results revealed that both diversity of spatial activities and parent spatial utterance lengths during the spatial task remain significant predictors of children's spatial skills at T2 when included in the same model (Table 7), and importantly that the strength of their association with children's spatial skills at T2 remained unchanged. These results indicate that the diversity of children's daily spatial activities and parents' spatial utterance lengths during a spatial activity are unique contributors to growth in children's spatial skills.

Table 7

Regression model results examining spatial utterance length and frequency of spatial activities as simultaneous predictors of children's spatial skills at T2

Variable	B (SE)
Spatial utterance length: puzzle	.48*** (.13)
Overall utterance length: puzzle	-.27* (.12)
Diversity of spatial activities	.18* (.09)
Child spatial skills at T1	.36*** (.09)
Child age at T1	.19* (.09)
Constant	-.52
F(4,87)	15.11***
R^2	.38

Notes: **p<.05, ** p<.01, *** p<.001*

1.5 Discussion

The first aim of the present study was to use parent report of spatial activities as measured via questionnaire and academic stimulation questions, a novel extension of time diary interviews, to measure the frequency and diversity of preschoolers' daily spatial activities and examine how it relates to growth in their spatial skills. Our results support that children's spatial activity diversity, but not frequency, at age four are predictive of their growth in spatial skills between age 4 and age five.

Second, the present study expanded on previous research that investigated only the relation between parent spatial talk frequencies and children's spatial abilities by investigating how both parent spatial talk frequencies and utterance lengths within spatial and non-spatial play contexts influenced preschoolers' spatial skill growth over the span of one year. Our results did not support our initial hypothesis that more frequent spatial utterances employed by parents would be predictive of children's growth in spatial skills. Instead, we found that parent spatial utterance length within spatial play contexts was predictive of children's growth in spatial ability from age 4 to age 5.

Finally, the present study investigated the unique contributions of children's spatial activities and parent spatial talk measured in spatial and non-spatial play contexts to growth in children's spatial ability. Both parent spatial utterance length during the spatial activity at T1 and the diversity of children's daily spatial activities at T1 remained significant predictors of children's spatial skills one year later when included in the same model.

1.5.1 Spatial activities predicting spatial skills

Several studies have shown a relation between the frequency with which children engage in spatially relevant activities and their subsequent spatial ability. Levine et al. (2012) demonstrated that more frequent puzzle play in children between the ages of 24 and 46 months predicted their performance on a mental transformation task administered when children were 4.5 years old. Jirout and Newcombe (2015) who used a large, diverse cross-sectional data set showed that spatial play with blocks, puzzles, and board games in children between the ages of 2 and 7 years old is also positively associated with their concurrent spatial skills. The present study extended these previous findings by demonstrating that parent reports of their children's spatial activity diversity were significantly predictive of children's spatial skill growth from age 4 to 5. Importantly, to derive our measure of spatial activity diversity we asked parents about the occurrence of spatially relevant activities their child was engaged in during the previous day as part of a complete recollection of their activities during the past 24 hours. This method is more likely to accurately reflect children's engagement in spatial activities since parents only have to recall the activities of the previous day. However, it may be more susceptible to the idiosyncrasies of the two days we asked parents to report on and is limited by the specific activities we probed.

Unexpectedly, our questionnaire measure of spatial activity frequency at age 4, which was like those used in previous studies (LeFevre et al., 2009), was not predictive of children's spatial skill at age 5. It is possible that the differing outcomes observed in the present study were due to focusing narrowly on only five spatial activities listed in the questionnaire predicting spatial skills, rather than a wider range of spatial activities or spatial skills measures that were more in line with the activities surveyed (e.g., building with 3D materials).

1.5.2 Length of spatial utterances but not frequency predicts spatial skill growth

Previous studies have demonstrated that more frequent spatial language exposure is positively related to children's spatial word comprehension, productive spatial language, and performance on various spatial measures (Cartmill, et al., 2021; Casasola et al., 2020; Kisa et al., 2019; Lowenstein & Gentner, 2005). Surprisingly, the results of the present study do not support these previous findings. This inconsistency may be due to a variety of factors including the use of differing outcome measures, who provided spatial language input and how it was measured, and different sample characteristics.

The present study is the only investigation into the relation between parent spatial language in naturalistic play scenarios with children at age four years, and children's subsequent growth in spatial ability one year later as measured by mental transformation and visual geometric deviation detection tasks. Several of the studies investigating the relation between spatial language input and children's spatial abilities used outcome measures of spatial vocabulary production and comprehension, showing that the more spatial language children hear the more spatial language they produce and comprehend themselves (Ferrera et al., 2011; Kisa et al., 2019). In addition to investigating children's spatial language production, Cartmill and colleagues (2021) also looked at the use of gesture accompanying spatial talk and found that children's learning was bolstered by parents' use of gesture during spoken instruction. The current investigation did not examine children's spatial language output or gesture as a factor of parental spatial language input, nor did our outcome measures rely on children's spatial vocabulary comprehension providing a possible explanation for the discrepancy between our results and these previous findings.

Similar to our study, other studies examining the link between adult spatial language input and preschoolers' spatial abilities have used outcome measures that do not rely on spatial language comprehension or production. However, they tap into different aspects of children's spatial abilities such as their relational mapping skills (Lowenstein & Gentner, 2005), their abilities to recreate spatial patterns (Pruden et al., 2011), or their mental rotation skills (Casasola et al., 2020). It is possible that differences in the aspects of spatial cognition measured in children may explain why these previous studies found associations between parents' spatial language frequency and children's spatial skills whereas we failed to find such an association.

Only one previous study by Levine and colleagues (2012) measured children's mental transformation skills in a similar way to our study and found an association between spatial language input and children's spatial skills. However, Levine and colleagues used the CMTT as a mental rotation measure of children's spatial ability and had several target pieces that were rotated by 45 degrees whereas none of our shapes were rotated thus requiring only mental transformation, not rotation. In addition to these differences in the CMTT, Levine and colleagues incorporated parent spatial language input into a composite predictor variable that also included measures of parent engagement and puzzle difficulty. These measurement differences could be the reason for the discrepancies between our results and theirs.

In addition to using different outcome measures, some of the previous investigations examining the relation between parent spatial language frequency and children's spatial ability included sample characteristics that differed from participants in the current investigation. Several studies included younger participants ranging in age from birth to 42 months (Bower et al., 2020; Clingan-Siverly et al., 2021; Kisa et al., 2019; Levine et al., 2012), or exclusively preschoolers enrolled in Head Start (Casasola et al., 2020). These differences could account for the divergent findings of the present study. Thus, future work should examine whether associations between parents' spatial talk frequency and children's spatial skills differ by age or other demographic differences.

While the present study was unable to replicate previous findings regarding associations between frequency of spatial language input and children's spatial abilities, the present study is the first to demonstrate that parents' spatial utterance length within the context of a spatial activity is a significant predictor of children's growth in spatial skills from age 4 to age 5. These findings offer insights regarding the relation between spatial language and children's spatial abilities. Perhaps parents' use of more complex spatial language within a spatial play context draws children's attention to relevant spatial content like features and relative sizes, which in turn facilitates more "robust encoding of spatial information" and "richer representations" of the concepts being learned (Pruden, et al., 2011, p. 1427). Pruden et al. (2011) further speculate that children with a broad spatial vocabulary expend less mental energy on mental rotation tasks because their vocabulary allows them to recognize specific features and develop a better mental picture. The present investigation used an untraditional, non-interlocking puzzle that included many shapes beyond the more common figures (e.g., rectangles, circles, and triangles) children encounter in daily life. This puzzle required a lot of conversation about location, orientations, and direction. Further work is needed to determine if these results are maintained in other spatial play scenarios like shape sorting or constructing with blocks where dialogue may focus more on spatial relations and features.

One unanticipated result was that parents' overall utterance lengths within the non-spatial tasks at age 4 was also significant in predicting children's growth in spatial skills. A possible explanation for this might be that more complex conversations about non-spatial topics may support the development of other cognitive skills that support growth in spatial skills. For example, previous research has shown that greater mean utterance lengths support children's vocabulary development (Hoff, 2003). Domain-general cognitive skills such as children's language skills in turn may support spatial learning, but further research is needed to fully understand the role that domain-general cognitive skills play for children's growth in spatial skills and to what extent parents' utterance length facilitates this development.

1.5.3 Spatial activities and spatial talk as unique aspects of the home learning environment

Past studies have examined factors within a child's home learning environment that are associated with their spatial abilities (Purpura et al., 2020; Zippert & Rittle-Johnson, 2020). The present study has added to the field by investigating two specific factors, diversity of daily spatial activity and parent spatial utterance length, within the home learning environment and demonstrated that each is a unique contributor to children's spatial abilities. One possible explanation of why spatial activity frequency and spatial utterance length may be unique predictors of children's spatial skill growth is that each reflects another aspect of the home learning environment that supports children's spatial skills development. More time spent on spatial activities increases children's familiarity with toys' spatial features and opportunities to practice spatial skills. More complex spatial language in a spatial play context may bolster children's attention to specific aspects of the spatial activity and their mental representations of spatial features. These results are particularly useful for practical applications as they suggest that parents should encourage their children to frequently engage in a variety of different spatial activities and engage in spatial play time with their children that fosters conversations about spatial concepts as well.

While the diversity of spatial activity and spatial utterance length during the puzzle task were not correlated to a meaningful degree, and unexpected negative correlation between spatial activity frequency and parent spatial utterance length during non-spatial tasks was observed. When we examined this relation further using partial correlations and controlling for children's age, we found that the correlation between children's activity frequency and parent spatial utterance length during non-spatial play was no longer significant. This suggests that the frequency of the spatial activities and the complexity of parents' spatial talk are both affected by age, but in opposite directions (e.g., younger children may be engaging more frequently in the activities reported, whereas parents' talk complexity increases as their children age).

1.6 Limitations and future directions

While the current results extend our knowledge of which environmental factors contribute to children's spatial skill development, a number of limitations need to be noted. One limitation is that the present study inquired about only five items on the survey, and the academic stimulation activity questions only asked about four activities: puzzle play, building play, sorting, and making collections. There are additional spatially relevant activities that young children regularly engage in like board games, spatial video games, and sports (Cherney, 2008; Doyle, 2012; Ho et al., 2018; Lee et al., 2019; Ozel et al., 2004, Verdine et al., 2014). In the future, it would be beneficial to include a broader range of spatial activity questions and evaluate which activities are more highly correlated to spatial skills than others.

The current study was also limited by the measures of children's spatial skills employed. Both measures were forced choice tasks that did not tap into spatial language comprehension or production. Future research should include other response formats and measures that tap into other aspects of children's spatial cognition (e.g., spatial language, 3D mental rotation of 3D objects, 2D and 3D match to sample assembly tasks).

Another area of opportunity for future investigations is to expand the qualitative aspects of parent-child interactions being considered. The current study only focused on frequency and mean utterance length of parents' spatial talk. Future studies could investigate whether children's spatial abilities are related to how parents scaffold conversations, parents' responses to children's questions and decisions during play, and whether spatial problem-solving interactions are parent-led or child-led.

Finally, the present study is limited by parent gender. The majority of participating parents were mothers, which does not allow us to draw any conclusions regarding potential gender differences in parent talk. Given well documented gender differences in spatial skills (Reilly & Neumann, 2013), further work is needed to investigate how mothers and fathers might differ in ways that they use spatial talk while playing with their children and how their spatial talk might differ in spatial and non-spatial contexts.

1.7 Conclusion

The current study aimed to advance existing knowledge regarding how engagement in spatial activities and parent verbal input influence children's spatial skill growth from age four to five. We found that diversity of engagement in spatial activities, not frequency, at age four was predictive of spatial ability at age five even when controlling for spatial ability at age four. Furthermore, we found that only length of spatial utterances, not their frequency, was predictive of children's growth in spatial abilities. Finally, we demonstrated that children's spatial activity frequency at age four as well as parents' spatial utterance lengths during a semi-structured puzzle play activity were significant and unique predictors of children's spatial skill growth. These findings highlight the importance of various aspects of the home learning environment for scaffolding children's spatial skills, which in turn are an important foundation for later STEM success.

Appendix A

Academic Stimulation Activity Questions

Using written numbers

Using number or arithmetic flashcards
Identifying names of written numbers
Playing with number fridge magnets
Printing numbers
Playing with calculators

Categorizing or counting

Counting objects
Sorting things by size, color, or shape
Making collections
Counting down
Learning simple sums

Using math while shopping or cooking

Talking about money when shopping
Measuring ingredients while cooking

Talking about dates or times

Using calendars and dates
Using a watch, clock, or timer
Having conversations about time
Timing child doing something

Books or activities that involve math

Using number activity books
Reading number storybooks
Paint by number activities
Connect the dot activities

Playing games that could involve math

Board games
Card games
Puzzles
Legos or construction sets

Using video or computer games

Using educational software
Playing other videogames

Reading a book or magazine

[If so] While you were reading, did you…

Ask questions about what is being read
Ask child reading or filling in words
Talk about what happened in the story
Point things in pics/ask child to point
Child pretend to read

Doing any work with letters or words

Playing rhyming games
Learning the names of the letters
Playing with alphabet toys at home
Pointing out letters or words
Pretending to read independently

Appendix B

Table B 1: Spatial utterance content codes

Code	Definition	Examples
Spatial dimensions	Describing the size of objects, people, and spaces	"We don't need the big purple one." "Can you get the shorter rectangle?"
Shapes	Describing the standard or universally recognized form of enclosed 2- or 3-D objects and spaces	"Now find the green square." "How many sides does a triangle have?"
Locations, directions, and orientations	Describing the relative position, orientation, or transformation of objects, people, or points in space	"Move towards the bottom." "That piece should be sideways."
Continuous amount	Describing the amount of continuous quantities within the spatial domain, including the extent of an object, space, or liquid	"That is one half of the giraffe's body." "That piece is the exact same as that one."
Deictics	Utterances that rely on place deictics or pro-forms	"If you move that piece there and this other piece here, they will be in the correct place."
Spatial features and properties	Describing the features and properties of 2- or 3-D objects, spaces, people, or the properties of their features	"We are looking for the one with a flat side and a curved edge."

Concept: Terms that refer to…	Words (includes –er, -est, -s, -ment(s) forms)
Spatial dimensions	
Unconstrained spatial dimensions like height, length, or both.	Big, little, small, large, tiny, enormous, huge, gigantic, teeny, itsy-bitsy, itty-bitty, giant, miniscule
Only horizontal or vertical extent	Long, short
Only vertical extent	Tall
Only horizontal extent	Wide, narrow, thick, thin, skinny, fat
Only vertical or horizontal extent of a 3D object/shape	Deep, shallow
Only internal extent of 3D object/shape	Full, empty, fill (in)
Superordinate of above	Size, length, height, width, depth, volume, capacity, area (as in of a square), measure
Shapes	
2D enclosed shapes that do not have any sides or angles or do not have all straight sides	Circle, oval, ellipse, semicircle
2D shapes with at least 3 straight sides and angles	Triangle, square, rectangle, diamond, pentagon, hexagon, octagon, parallelogram, quadrilateral, rhombus, polygon, star, column
PPEL specific shapes, including how participants describe features of shapes.	Zigzag, "L", heart, rainbow, dot, swoop (describing the yellow arch), squiggle (describing the zigzag) *If a child uses a word, they are familiar with (e.g., ball) rather than the technical name of a shape (e.g., sphere) that should be considered spatial language and coded as shape (this excludes referring to shapes as colors).
3D shapes	Sphere, globe, cone, cylinder, pyramid, cube, rectangular prism
Superordinate of above	Shape
Location, direction, and orientation	
The noun that follows the term (in the case of "from" the reference is to movement away from the noun)	At, to, from
Resting/ not resting tip a surface (including an invisible surface that is a boundary of a space like "on the side" and "on the bottom"	On, off
Within or outside of the boundaries of an area or confines of a volume	In, out (of)
Along a vertical axis (including intrinsic vertical axis of object/person)	Under, beneath, below, over, above, up, down, (on) top, bottom, high, low, column, vertical

Along a horizontal axis (in the case of front, back, left, and right this includes intrinsic horizontal axis of the object/person)	Left, right, (in) front, (in) back, ahead, behind, sideways, row, horizontal
Proximal/ distal to another point	By, near, close, next to, with, beside, far, away, beyond, further, past, against, together, separate, join, apart, touches/ing (when being used instead of next to or beside), connect, attach, meet (when used in the context of where two points come together/touch/connect), side (when used like "on that side of the fence" not like the flat edge of an object- see spatial features)
Defined with respect to the location of at least two other object/ people/ points	Between, among
An equal distance from the extremities of something	Middle, center
In the broad vicinity of another point	About, around, throughout
Defined with respect to the length of an object/ person/ point	Along, lengthwise
In a cardinal direction	North, south, east, west
From one side to another side of (or circumvents) another object/ person/ point	Around, through
On the (other) side of another object/ person/ point	Across, over, opposite, aside, reverse
Defined by the direction that an object/person/point/plane is oriented	Around, reverse, back (verb), backward, forward, parallel, perpendicular, diagonal, down (as in down the street), up (as in up the street)
The superordinate of above	Location, position, direction, way (when used in place of the word direction), route, path, head, place, distance
The orientation of an object or person	Upside down, right side up, upright, backward, forward
Superordinate of the above	Orientation
A transformation around an axis	Turn, flip, rotate, tilt, reverse
The superordinate of the above	Rotation
Continuous Amount	
An inexact part of a continuous object or space	Part (do not use in context of body part), piece, slice
An exact part of a continuous object or space	Half
Deictics	
The location of the speaker	Here
A location other than that of the speaker	There

A request for identification of a location	Where
No, any, some, or all location(s)	Anywhere, somewhere, nowhere, everywhere, wherever
Spatial features and properties	
The flat surface of an object	Side, edge, border, line, end (when used like "side")
Curvature of an object or the curved portion of an object	Round, curve, bump, bend, bent, wave, lump, arc, sector, squiggle/y, twist
Lack of curvature of an object	Straight, flat
The place where two or more sides of an object meet	Angle, corner, point
A surface of a 3D object	Plane, surface, face
Having the form of standard shapes or used with an object noun to describe the outline of a 2D or 3D shape or space (heart-shaped, star-shaped)	Circular, rectangular, triangular, conical, spherical, elliptical, cylindric, shaped
The orientation of an element of a 2D or 3D shape or space	Horizontal, vertical, diagonal, axis

References

Bachman, H. J., Elliott, L., Duong, S., Betancur, L., Navarro, M., Votruba-Drzal, E., & Libertus, M. (2020). Triangulating multi-method assessments of parental support for early math development. *Frontiers in Education, 5*:589514.

Baenninger, M., & Newcombe, N. (1989). The role of experience in spatial test performance: A meta-analysis. *Sex Roles*, *20*(5–6), 327–344. https://doi.org/10.1007/BF00287729

Baenninger, M., & Newcombe, N. (1995). Environmental input to the development of sex-related differences in spatial and mathematical ability. *Learning and Individual Differences*, *7*(4), 363–379. https://doi.org/10.1016/1041-6080(95)90007-1

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.

Casasola, M. (2005). Can language do the driving? The effect of linguistic input on infants' categorization of support spatial relations. *Developmental Psychology*, *41*(1), 183–192. https://doi.org/10.1037/0012-1649.41.1.183

Cartmill, E., Pruden, S., Levine, S. & Golden-Meadow, S. (2010). The role of parent gesture in children's spatial language development. Spatial Intelligence and Learning Center (SILC).

Casey, B. M. (2013). Individual and group differences in spatial ability. Waller, D., & Nadel, L. (Eds.). *Handbook of spatial cognition:* (pp. 128-134). Washington D.C: American Psychological Association.

Chatterjee, A. (2008). The neural organization of spatial thought and language. *Seminars in Speech and Language*, *17(*3), 226–238. https://doi.org/10.1055/s-0028-1082886

Cherney, I. D. (2008). Mom, Let Me Play More Computer Games: They Improve My Mental Rotation Skills. *Sex Roles*, *59*(11–12), 776–786. https://doi.org/10.1007/s11199-008-9498-z

Cherney, I. D., & Voyer, D. (2010). Development of a spatial activity questionnaire I: Items identification. *Sex Roles*, *62*(1), 89–99. https://doi.org/10.1007/s11199-009-9710-9

Choi, S., McDonough, L., Bowerman, M., & Mandler, J. M. (1999). Early sensitivity to language-specific spatial categories in English and Korean. *Cognitive Development*, *14*(2), 241–268. https://doi.org/10.1016/S0885-2014(99)00004-0

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155-159. doi:http://dx.doi.org.pitt.idm.oclc.org/10.1037/0033-2909.112.1.155

Cordes, S., & Brannon, E. (2009). Crossing the divide: Infants discriminate small from large numerosities. *Developmental Psychology*, *45*(6), 1583–1594. https://doi.org/10.1037/a0015666

Costa-Giomi, E. (1999). The effects of three years of piano instruction on children's cognitive development. *Journal of Research in Music Education*, *47*(3), 198–212. https://doi.org/10.2307/3345779

Daneri, M. P., Blair, C., Kuhn, L. J., & Investigators, F. K. (2019). Maternal language and child vocabulary mediate relations between socioeconomic status and executive function during early childhood. *Child Development*, *90*(6), 2001–2018. https://doi.org/10.1111/cdev.13065

Dehaene, S., Izard, V., Pica, P., & Spelke, E. (2006). Core knowledge of geometry in an Amazonian indigene group. *Science (New York, N.Y.)*, *311*, 381–384. https://doi.org/10.1126/science.1121739

Dillon, M. R., Izard, V., & Spelke, E. S. (2020). Infants' sensitivity to shape changes in 2D visual forms. *Infancy*, *25*(5), 618–639. https://doi.org/10.1111/infa.12343

Doyle, R. A., Voyer, D., & Cherney, I. D. (2012). The relation between childhood spatial activities and spatial abilities in adulthood. *Journal of Applied Developmental Psychology, 33*(2), 112–120. https://doi.org/10.1016/j.appdev.2012.01.002

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology*, *42*(6), 1259–1268. https://doi.org/10.1037/0012-1649.42.6.1259

Elliott, L., and Bachman, H. J. (2018). How do parents foster young children's math skills? *Child Development Perspectives. 12*, 16–21. doi: 10.1111/cdep.12249

Elliott, L., Braham, E. J., & Libertus, M. E. (2017). Understanding sources of individual variability in parents' number talk with young children. *Journal of Experimental Child Psychology, 159*, 1–15. https://doi.org/10.1016/j.jecp.2017.01.011

Fernández-Méndez, L. M., Contreras, M. J., & Elosúa, M. R. (2018). From what age is mental rotation training effective? Differences in preschool age but not in sex. *Frontiers in Psychology, 9*, 753. https://doi.org/10.3389/fpsyg.2018.00753

Ferrara, K., Hirsh-Pasek, K., Newcombe, N. S., Golinkoff, R. M., and Lam, W. S. (2011). Block talk: Spatial language during block play. *Mind Brain Education. 5*, 143–151. doi: 10.1111/j.1751-228x.2011. 01122.x

Fiorini, M., & Keane, M. P. (2014). How the allocation of children's time affects cognitive and noncognitive development. *Journal of Labor Economics*, *32*(4), 787–836. https://doi.org/10.1086/677232

Gershon, R.C., Wagster, M.V., Hendrie, H.C., Fox, N.A., Cook, K.F., Nowinski, C.J. NIH toolbox for assessment of neurological and behavioral function. *Neurology*. 2013 Mar 12;80(11 Suppl 3): S2-6. doi: 10.1212/WNL.0b013e3182872e5f. PMID: 23479538; PMCID: PMC3662335.

Harris, J., Newcombe, N. S., & Hirsh-Pasek, K. (2013). A new twist on studying the development of dynamic spatial transformations: Mental paper folding in young children: A new twist. *Mind, Brain, and Education*, *7*(1), 49–55. https://doi.org/10.1111/mbe.12007

Ho, A., Lee, J., Wood, E., Kassies., S., & Heinbuck, C. (2018). Tap, swipe, and build: Parental spatial input during iPad® and toy play. *Infant Child Development*, 27:e2061. https://doi.org/10.1002/icd.2061

Hoff, E. (2003). The specificity of environmental influence: Socioeconomic status affects early vocabulary development via maternal speech. *Child Development*, *74*(5), 1368–1378. https://doi.org/10.1111/1467-8624.00612

Hofferth, S. L., & Sandberg, J. F. (2001). How American children spend their time. *Journal of Marriage and Family*, *63*(2), 295–308. https://doi.org/10.1111/j.1741-3737.2001.00295.x

Jirout, J., & Newcombe, N. (2014). Mazes and maps: Can young children find their way? *Mind, Brain and Education*, *8*(2), 89–96. https://doi.org/10.1111/mbe.12048

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

Kısa, Y., Aktan-Erciyes, A., Turan, E., & Göksun, T. (2019). Parental use of spatial language and gestures in early childhood. *British Journal of Developmental Psychology*, 37(2), 149–167. https://doi.org/10.1111/bjdp.12263

Lauer, J. E., & Lourenco, S. F. (2016). Spatial processing in infancy predicts both spatial and mathematical aptitude in childhood. *Psychological Science*, *27*, 1291-1298. https://doi-org.pitt.idm.oclc.org/10.1177/0956797616655977

Lee, J., Hodgins, S., & Wood, E. (2019). Spatial learning and play with technology: How parental spatial talk differs across contexts. *Mathematical Learning and Cognition in Early Childhood*, 23–38. https://doi.org/10.1007/978-3-030-12895-1_3

LeFevre, J.-A., Skwarchuk, S.-L., Smith-Chant, B. L., Fast, L., Kamawar, D., & Bisanz, J. (2009). Home numeracy experiences and children's math performance in the early school years. *Canadian Journal of Behavioural Science / Revue canadienne des sciences du comportement, 41*(2), 55–66. https://doi.org/10.1037/a0014532

LeFevre, J.-A., Fast, L., Skwarchuk, S.-L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development*, *81*(6), 1753–1767. https://doi.org/10.1111/j.1467-8624.2010.01508.x

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), 530–542. https://doi.org/10.1037/a0025913

Lourenco, S., & Huttenlocher, J. (2008). The representation of geometric cues in infancy. *Infancy*, *13*(2), 103–127. https://doi.org/10.1080/15250000701795572

Loewenstein, J., & Gentner, D. (2005). Relational language and the development of relational mapping. *Cognitive Psychology*, *50*(4), 315–353. https://doi.org/10.1016/j.cogpsych.2004.09.004

McGee, M. G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin, 86*(5), 889–918. https://doi.org/10.1037/0033-2909.86.5.889

Mix, K. S., & Cheng, Y.-L. (2012). The relation between space and math. *Advances in Child Development and Behavior Volume 42*, 197–243. https://doi.org/10.1016/b978-0-12-394388-0.00006-x

Mix, K., Levine, S., Cheng, Y., Young, C., Hambrick, D., Ping, R., & Konstantopoulos, S. (2016). Separate but correlated: The latent structure of space and mathematics across development. *Journal of Experimental Psychology. General, 145*(9), 1206–1227. https://doi.org/10.1037/xge0000182

Mix, K., Hambrick, D., Satyam, V., Burgoyne, A., & Levine, S. (2018). The latent structure of spatial skill: A test of the 2 × 2 typology. *Cognition*, *180*, 268–278. https://doi.org/10.1016/j.cognition.2018.07.012

Moore, D., & Johnson, S. (2011). Mental rotation of dynamic, three-dimensional stimuli by 3-month-old infants. *Infancy*, *16*(4), 435–445. https://doi.org/10.1111/j.1532-7078.2010.00058.x

Mutaf Yildiz, B., Sasanguie, D., De Smedt, B., & Reynvoet, B. (2018). Investigating the relationship between two home numeracy measures: A questionnaire and observations during Lego building and book reading. *British Journal of Developmental Psychology*, *36*(2), 354–370. https://doi.org/10.1111/bjdp.12235

National Science Foundation, National Science Board (2010). *Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital* (Report No. NSB-10-33). Retrieved from http://www.nsf.gov/nsb/stem/innovators.jsp

Newcombe, N., Bandura, M. M., & Taylor, D. G. (1983). Sex differences in spatial ability and spatial activities. *Sex Roles*, *9*(3), 377–386. https://doi.org/10.1007/BF00289672

Newcombe, N., & Huttenlocher, J. (2000). *Making space: The development of spatial representation and reasoning*. MIT Press.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education*, *4*(3), 102–111. https://doi.org/10.1111/j.1751-228X.2010.01089.x

Newman, S. D., Hansen, M. T., & Gutierrez, A. (2016). An fMRI study of the impact of block building and board games on spatial ability. *Frontiers in Psychology*, *7*. https://doi.org/10.3389/fpsyg.2016.01278

Oostermeijer, M., Boonen, A. J. H., & Jolles, J. (2014). The relation between children's constructive play activities, spatial ability, and mathematical word problem-solving performance: a mediation analysis in sixth-grade students. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.00782

Ozel, S., Larue, J., & Molinaro, C. (2004). Relation between sport and spatial imagery: Comparison of three groups of participants. *The Journal of Psychology*, *138*(1), 49–64. https://doi.org/10.3200/JRLP.138.1.49-64

Pan, B. A., Rowe, M. L., Spier, E., & Tamis-Lemonda, C. (2004). Measuring productive vocabulary of toddlers in low-income families: Concurrent and predictive validity of three sources of data. *Journal of Child Language*, *31*(3), 587–608. https://doi.org/10.1017/S0305000904006270

Peterson, E. G., Weinberger, A. B., Uttal, D. H., Kolvoord, B., & Green, A. E. (2020). Spatial activity participation in childhood and adolescence: Consistency and relations to spatial thinking in adolescence. *Cognitive Research: Principles and Implications*, *5*(1), 43–43. https://doi.org/10.1186/s41235-020-00239-0

Phipps, P. A., & Vernon, M. K. (2009). Twenty-four hours: An overview of the recall diary method and data quality in the American Time Use Survey. *Calendar and Time Diary*, 108–128. https://doi.org/10.4135/9781412990295.d11

Polinsky, N., Perez, J., Grehl, M., & McCrink, K. (2017). Encouraging spatial talk: Using children's museums to bolster spatial reasoning. *Mind, Brain and Education*, *11*(3), 144–152. https://doi.org/10.1111/mbe.12145

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

Purpura, D. J., King, Y. A., Rolan, E., Hornburg, C. B., Schmitt, S. A., Hart, S. A., & Ganley, C. M. (2020). Examining the factor structure of the home mathematics environment to delineate its role in predicting preschool numeracy, mathematical language, and spatial skills. *Frontiers in Psychology*, *11*. https://www.frontiersin.org/article/10.3389/fpsyg.2020.01925

Quinn, P., Cummins, M., Kase, J., Martin, E., & Weissman, S. (1996). Development of categorical representations for above and below spatial relations in 3- to 7-month-old infants. *Developmental Psychology*, *32*(5), 942–950. https://doi.org/10.1037/0012-1649.32.5.942

Ramani, G. B., Rowe, M. L., Eason, S. H., & Leech, K. A. (2015). Math talk during informal learning activities in Head Start families. *Cognitive Development*, *35*, 15–33. https://doi.org/10.1016/j.cogdev.2014.11.002

Reilly, D., & Neumann, D. L. (2013). Gender-role differences in spatial ability: A meta-analytic Review. *Sex Roles*, *68*(9–10), 521–535. https://doi.org/10.1007/s11199-013-0269-0

Reyna, V. F., Nelson, W. L., Han, P. K., & Dieckmann, N. F. (2009). How numeracy influences risk comprehension and medical decision making. *Psychological Bulletin, 135*(6), 943-973. doi:http://dx.doi.org.pitt.idm.oclc.org/10.1037/a0017327

Rigal, R. (1996). Right-left orientation, mental rotation, and perspective-taking: When can children imagine what people see from their own viewpoint? *Perceptual and Motor Skills*, *83*(3), 831–842. https://doi.org/10.2466/pms.1996.83.3.831

Rittle-Johnson, B., Zippert, E. L., Boice, K. L. (2019). The roles of patterning and spatial skills in early mathematics development. *Early Childhood Research Quarterly*, *46*, 166–178. https://doi.org/10.1016/j.ecresq.2018.03.006

Siegel-Hinson, R. I., & McKeever, W. F. (2002). Hemispheric specialisation, spatial activity experience, and sex differences on tests of mental rotation ability. *Laterality: Asymmetries of Body, Brain and Cognition*, *7*(1), 59–74. https://doi.org/10.1080/13576500143000078

U. S. Bureau of Labor Statistics (2016). *American time use survey user guide: Understanding ATUS 2003 to 2015.* Washington, DC: U. S. Bureau of Labor Statistics.

Uttal, D., Meadow, N., Tipton, E., Hand, L., Alden, A., Warren, C., & Newcombe, N. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402. https://doi.org/10.1037/a0028446

Verdine, B.N., Golinkoff, R.M., Hirsh-Pasek, K., Newcombe, N.S., Filipowicz, A.T., Chang, A. (2014). Deconstructing building blocks: Preschoolers' spatial assembly performance relates to early mathematical skills. *Child Development, 85*(3), 1062–1076. https://doi.org/10.1111/cdev.12165

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2017). I. Spatial Skills, their development, and their links to mathematics. *Monographs of the Society for Research in Child Development*, *82*(1), 7–109. https://doi.org/10.1111/mono.12280

Verdine, B.N, Golinkoff, R.M. (2014), Test of Spatial Assembly (TOSA) Instruction Manual [Measurement Instrument]

Wai, J., Lubinski, D., Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*, 817–835. doi:10.1037/a0016127

Weckbacher, L. M., & Okamoto, Y. (2012). Spatial experiences of high academic achievers: Insights from a developmental perspective. *Journal for the Education of the Gifted*, *35*(1), 48–65. https://doi.org/10.1177/0162353211432038

Zippert, E. L., and Rittle-Johnson, B. (2020). The home math environment: more than numeracy. *Early Childhood. Research Quarterly*. *50*, 4–15