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EMPIRICAL ARTICLE

CHILD DEVELOPMENT

Diversity of spatial activities and parents' spatial talk complexity predict preschoolers' gains in spatial skills

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Abstract
Children's spatial activities and parental spatial talk were measured to examine their associations with variability in preschoolers' spatial skills (N=113, M_{age}=4 years, 4 months; 51% female; 80% White, 11% Black, and 9% other). Parents who reported more diversity in daily spatial activities and used longer spatial talk utterances during a spatial activity had children with greater gains in spatial skills from ages 4 to 5 (β=.17 and β=.40, respectively). Importantly, this study is the first to move beyond frequency counts of spatial input and investigate the links among the diversity of children's daily spatial activities, as well as the complexity of parents' spatial language across different contexts, and preschoolers' gains in spatial skills, an important predictor of later STEM success.

Spatial cognition, which refers to a range of cognitive abilities related to visualizing, manipulating, and transforming objects and spaces in the environment, is a unique component of general intelligence as well as a predictor of math performance (LeFevre et al., 2010; Mix & Cheng, 2012; Uttal et al., 2013). Some spatial abilities are present in infancy and undergo 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 versus mirrored objects are better at mentally transforming shapes at age 4 (Lauer & Lourenco, 2016). Moreover, children's spatial and patterning abilities predict later math skills (Rittle-Johnson et al., 2019), which in turn are related to better health and medical decision-making (Reyna et al., 2009). In addition, greater spatial cognition in high school is linked to greater educational and occupational outcomes, especially in STEM fields (Wai et al., 2009). Thus, spatial cognition acts as a foundational skill that relates to human capital throughout the life course. Despite its importance for many aspects of human life, the development of spatial skills has not received as much attention in research as numeracy (Zippert & Rittle-Johnson, 2020).

Children encounter a variety of opportunities to acquire and improve spatial skills throughout their everyday lives. For example, when children build with Legos, they learn to follow instructions and map 2D representations in the instructions to the 3D models they build, which involves rotating the pieces and arranging them correctly. Importantly, children who are better at building Lego models according to instructions tend to have better spatial skills in general (Brosnan, 1998). In addition, children who engage in spatial activities more frequently tend to have better spatial skills (Jirout & Newcombe, 2015; Levine

Abbreviation: ASA, academic stimulation activities; ATUS, American Time Use Survey; CMTT, children's mental transformation task; GS, geometric sensitivity; MUL, mean utterance length; PPEL, Parents Promoting Early Learning; SES socioeconomic status et al., 2012). However, the association between the diversity of daily spatial activities (i.e., engaging in a variety of spatial play ranging from puzzle building to sorting objects by size or shape) and spatial outcomes in preschoolers has not been studied. In general, across learning domains, greater variability of stimuli led to deeper, more abstract understanding of content as well as more skillful generalizability to new learning (Raviv et al., 2022). Therefore, it stands to reason that repeated practice of spatial skills through frequent engagement in the same spatial activities, as well as practicing a broad range of spatial skills in different contexts, are important for improving children's spatial skills. Thus, investigating the frequency and diversity of spatial activities is one way to capture environmental differences that may contribute to individual differences in young children's spatial ability.

In addition to the frequency and diversity of activities that may foster children's spatial skills, previous studies have also highlighted the importance of providing children with spatial language input which can occur in a variety of contexts (Pruden et al., 2011). 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 available stimuli (i.e., toys; Cartmill et al., 2010; Ho et al., 2018; Pruden et al., 2011; Verdine et al., 2017). Importantly, increased exposure to spatial language is positively correlated with children's spatial word comprehension (Kısa et al., 2019) and performance on mental rotation and mapping tasks (Casasola et al., 2020; Loewenstein & Gentner, 2005).

Thus, the overarching goal of the current study is to measure children's opportunities to improve spatial skills in the home learning environment in a variety of different ways and to test their influences on preschoolers' spatial skills. Specifically, the first aim 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 gains in spatial skills from age 4 to age 5. We focus on 4-year-olds in line with previous research (Casasola et al., 2020; Ferrara et al., 2011; Verdine & Golinkoff, 2014; Verdine, Golinkoff, et al., 2014; Verdine, Irwin, et al., 2014) and a delay of 1 year to allow an appreciable amount of time to pass for gains in spatial skills to emerge (Miller, 2013). The second aim examines whether the frequency or complexity of parent spatial talk, that is, any conversations related to spatial properties or spatial relations during spatial and non-spatial play activities, predicts the gains 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 and are uniquely predictive of gains in children's spatial skills.

Theoretical perspectives on spatial cognition

There is growing consensus that the cognitive processes underpinning spatial cognition are multi-dimensional rather than unidimensional (Casey, 2013; Eliot & Czarnolewski, 2007). Chatterjee (2008) proposed a 2×2 framework to describe the multi-dimensional nature of spatial abilities, whereby objects have both intrinsic (within object) and extrinsic (between objects) as well as static and dynamic properties. These properties can be used to compare the size of objects (intrinsic–static), describe objects' positions relative to one another (intrinsic–dynamic), characterize tasks like map reading (extrinsic–static), or navigate a forest trail (extrinsic–dynamic).

Evidence in support of this framework has come from adults and adolescents, whereas elementary school-aged children's spatial skills seem to be better fit by a two-factor model distinguishing only intrinsic and extrinsic dimensions (Mix et al., 2018). The current study sought to add to the existing literature by investigating the development of intrinsic spatial skills (Xie et al., 2020) between the ages of 4 and 5.

The current work is also informed by the opportunity–propensity (O-P) framework (Byrnes, 2020) in that we focus on how opportunity factors may contribute to individual differences in children's spatial abilities. Here, we focus on the relation between opportunity factors commonly encountered in the home learning environment (i.e., parent–child dialogue during puzzle building and other activities as well as frequency and diversity of spatial activities) and gains in children's intrinsic spatial skills.

Development of spatial skills

Foundational spatial skills are present in infancy and develop throughout life. During the first 18 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 et al., 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 3 and 5 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 categories of similar spatial relations between different objects in the scenes, suggesting that they need linguistic support to extract commonalities in spatial relations between objects (Casasola, 2005; Choi et al., 1999).

Intrinsic spatial skills are present in infancy, but more abstract extrinsic concepts like map reading do not develop until around the age of 5 (Jirout & Newcombe, 2014). Very few studies investigate intrinsic spatial skills in preschool-aged children (e.g., 3- to 5-year-olds; Bower et al., 2020; Verdine & Golinkoff, 2014; Verdine, Golinkoff, et al., 2014; Verdine, Irwin, et al., 2014), and although a general understanding of age-related differences in children's spatial skills exist, very little is known about individual differences in spatial skills and the environmental influences that may contribute to their gains. Thus, the current study aims to fill this gap by exploring how a broad range of common and novel measures capturing a range of different opportunities to improve spatial skills in children's home environments relate to gains in children's intrinsic spatial skills before kindergarten entry.

Specifically, to measure children's intrinsic spatial skills, we use two tasks that do not rely on children's receptive or productive spatial language: the children's mental transformation task (CMTT; Levine et al., 1999) and the geometric sensitivity test (GS; Dehaene et al., 2006). While the CMTT has been widely used in previous research including work examining the association between parental input and children's spatial skills (Ehrlich et al., 2006; Levine et al., 1999; Pruden et al., 2011), the GS test has different task demands but has previously been successfully used with a broad range of populations (e.g., indigenous people in the Amazon and low-socioeconomic status (SES) preschoolers in India; Dehaene et al., 2006; Dillon et al., 2017). In addition, the CMTT requires mental visualization and manipulation of shapes, while the GS test taps into a broad range of basic properties of Euclidean geometry (e.g., parallel lines, angles, and distance). Thus, these two measures tap into complementary aspects of children's intrinsic spatial skills while simultaneously avoiding spatial language confounds.

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). Studies have shown that engaging in spatial activities (e.g., puzzles and block building) positively influences spatial thinking and reasoning (Baenninger & Newcombe, 1989, 1995; Casey et al., 2008; Cherney, 2008; Costa-Giomi, 1999; Doyle et al., 2012; Jirout & Newcombe, 2015; Levine et al., 2012; Ozel et al., 2004; Weckbacher & Okamoto, 2012). Further longitudinal work showed that participation in spatial activities in childhood predicted spatially related problem-solving strategies and spatial ability as well as participation in spatial activities in adolescence (Peterson et al., 2020). 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 (Baenninger & 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).

In sum, engagement in spatial activities is associated with better spatial skills throughout development. However, most of the previously published research relies only on parent-reported *frequencies of spatial activities*, which may be subject to biases or influenced by parents' desire to depict a more academically oriented home environment (Bachman et al., 2020; Jirout & Newcombe, 2015; Newcombe et al., 1983; Oostermeijer et al., 2014; Siegel-Hinson & McKeever, 2002) without much consideration for the diversity of spatial activities. Previous research in word learning has shown that exposing children to a broad range of learning opportunities leads to more generalized learning than equally frequent but highly similar learning opportunities (Perry et al., 2010). Thus, the present study asks whether gains in children's spatial abilities are related to the frequency *and diversity* of their spatial activities or one more so than the other.

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

Parent spatial talk frequency

Children who are exposed to a broad range of spatial words are able to transfer their understanding of spatial vocabulary to other spatial contexts like mental rotation tasks (Casasola et al., 2020). Prior work has demonstrated that the frequency with which parents employ spatial words at 14 months was predictive of children's productive spatial language and spatial problem-solving at 46 months (Pruden et al., 2011). Furthermore, Bower et al. (2020) showed that children who received feedback during spatial assembly training outperformed children in the control group who did not receive feedback. Similarly, Polinsky et al. (2017) found that when parents were prompted to discuss spatial concepts with their 4-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 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, or whether the context impacts children's spatial abilities. The present study seeks to address this gap by using direct observations of parents' spatial language during semi-structured spatial and non-spatial activities with their children to investigate whether children's spatial skills are influenced by parent spatial talk in different contexts.

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. Although *spatial* utterance length has not been linked to children's spatial skills, 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. In a longitudinal study investigating the impact of maternal language input on 2-year-olds' vocabulary, the only attribute of mothers' speech that significantly predicted children's vocabulary 10 weeks later was MUL (Hoff, 2003). Furthermore, maternal speech complexity, as indexed by MUL, when children were 36 months old mediated the relation between developmental risks associated with SES and children's executive functioning at 48 months (Daneri et al., 2019). These findings suggest that parents engaging children in more complex conversations provide children with enriched opportunities to expand their vocabulary. In addition, parents' MUL is only moderately associated with the total number of words or the number of different words they used during free play with their children (Pancsofar & Vernon-Feagans, 2006). Thus, it is important to examine whether the mean length of parents' spatial utterances is predictive of preschoolers' spatial skills (above and beyond the frequency of spatial talk) and whether effects are context specific, that is, whether spatial talk occurred during spatial versus non-spatial activities.

In sum, previous studies of the relation between children's engagement in spatial activities and exposure to spatial language during play have neglected to investigate aspects of spatial activity engagement and parent spatial language use beyond frequency. Furthermore, no prior investigation has simultaneously considered the roles of engagement in spatial activities and parent spatial language on children's spatial skills. The current study seeks to address these gaps by exploring the connection between gains in preschoolers' spatial ability and the frequency and diversity of their spatial learning opportunities, as well as the frequency and complexity of parent spatial language used in spatial and non-spatial play contexts.

Research aims

The first aim of the present study is to use parent reports of monthly spatial activities as well as diversity in daily spatial activities to examine how they relate to gains in preschoolers' spatial skills. We hypothesize that both frequency and diversity of children's spatial activities at age 4 will significantly predict gains in children's spatial ability 1 year later.

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 relation between parent spatial talk frequency and spatial utterance length during spatial and non-spatial play activities and preschoolers' gains in spatial skills. Given results of previous investigations, we hypothesize that parents' spatial talk frequency during semi-structured play opportunities will predict children's later spatial skills. 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.

Finally, the present study investigates the unique contributions of measures of children's spatial activities and parent spatial talk to gains in children's spatial ability. A previous study investigated the relation between kindergartners' math skills and two measures of the home numeracy environment: a questionnaire and numeracy talk observed during dyadic interactions (Mutaf Yildiz et al., 2018). Interestingly, parent questionnaire responses and numeracy talk were not related to each other, but rather the questionnaire responses were positively related to children's math abilities and numeracy talk was negatively related to children's math abilities. Thus, we hypothesize that parent reports of preschoolers' 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 and child outcomes as seen in the study by Mutaf Yildiz et al. (2018) given our focus on preschoolers' spatial skills rather than kindergarteners' numeracy.

It should be noted that associations between children's age as well as SES and children's math skills at kindergarten entry have been well documented, such that older children and those from higher SES households enter school with higher math skills than their younger peers or those from lower SES families (DeFlorio & Beliakoff, 2015; Litkowski et al., 2020). Thus, the present study controls for child age and SES (a composite of household income and parental education) in all analyses that address the research questions above.

Finally, if Aims 1 or 2 yield significant results, sensitivity analyses will be conducted to test the domain specificity of the results. To date, no one has tested whether children's opportunities to learn spatial concepts in the home environment relate only to children's spatial skills or may be more broadly associated with other cognitive abilities. Thus, we will test the specificity of the associations between spatial activities or parental spatial talk and a non-spatial cognitive skill. Specifically, children's performance on a non-symbolic number comparison task will be substituted for the spatial skills variables. We chose children's gains in non-symbolic number comparison skills because, similar to our intrinsic spatial skills measures, the task does not rely on language skills and previous studies show rapid development of these skills during the preschool years (e.g., Halberda & Feigenson, 2008). We expect that neither children's spatial activities nor parent spatial talk relates to gains in children's non-verbal number comparison skills.

METHODS

Participants

Data were drawn from a larger longitudinal study, the Parents Promoting Early Learning (PPEL) study, of 127 parent–child dyads living in the greater metropolitan area of a mid-Atlantic city. These data were collected between 2019 and 2022. Families were recruited via an institutional 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 speak English. Parents provided written informed consent prior to data collection in accordance with a protocol approved by the local Institutional Review Board.

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, and 5 years, 5 months (SD = 0.3, range = 5.1–5.9) at the second time point. There was an average of 12 months and 22 days (SD = 23 days) between data collection at age 4 and age 5. At age 5, 113 children participated (11% attrition). At the first time point, parental age ranged from 24 to 56 years (M = 36) with reported annual household incomes ranging from $1000 to $425,000 with a median of $93,000 (SD = $70,924). Twenty-six percent of families were classified as low income (i.e., earnings below 200% of the federal poverty line), 33% as middle income (i.e., earning from 200% to 399% of the federal poverty line), and 41% as high income (i.e., earnings 400% and above of the poverty line). Levels of parental education varied, ranging from parents who did not finish high school (2%), attained a high school diploma (6%), associate degree (6%), post-high-school vocational or technical training (2%), some college (9%), a bachelor's degree (33%), or graduate degree (43%). Figure S1 shows the distribution of SES, a composite of standardized household income and years of parents' education. Most participating parents (94% female) reported being White (80%), with the remainder being Black or African American (11%), and Asian, Latino, multiracial, or other (9%). The majority of participating parents reported being employed (40% full-time and 27% part-time) and married (73%).

Procedures

Age 4 procedures

Child assessments and semi-structured tasks for parent–child dyads were administered during two home visits. Three semi-structured observations were administered at the first visit in the same order (book, puzzle, and grocery task, see below) 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 them to play like they normally would for about 5–8 min. Researchers left the room to reduce distraction. If siblings were present, they were cared for by research assistants in a different room.

After the semi-structured observations, the participating parent completed a battery of assessments and paperwork with one researcher while the second administered a series of tests to measure children's spatial skills, math abilities, and executive functioning, the latter two of which are not considered here. Task orders were counterbalanced between children, but the GS task was consistently administered prior to the CMTT (see below for details). The non-verbal number task was always the first task administered on the second visit. In addition, parents completed an online survey and two time diaries by phone on separate days.

Age 5 procedures

At age 5, children completed an assessment battery online using video conferencing software. Assessments were divided into three calls to keep testing sessions between 15 and 30 min each. Within each session, task order was consistent (i.e., the non-verbal number task always occurred before the two spatial tasks, the GS task always occurred second during one session, and the CMTT occurred last in another), but the order of testing sessions was counterbalanced between children with three possible orders (ABC, BCA, and CAB). A one-way

ANOVA comparing the effect of order on children's outcomes revealed no significant differences as a function of testing session order (CMTT: $F(2,107)=.58$, $p=.56$; GS: $F(2, 108)=.02$, $p=.98$; non-verbal number task: $F(2, 101)=.62$, $p=.54$).

All materials were presented to participants on PowerPoint slides using 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 questions independently. Tasks were designed so that children could complete the sessions without parental assistance once the call began. To keep children engaged, they were shown a brief animation after each task and were allowed to add items to a virtual "sticker book". Additionally, at the end of the three sessions, children selected a small prize to be mailed to their homes.

Measures

Children's spatial and number skills

Children's mental transformation task

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 1a). 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 16 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. Five of the test trials required children to use horizontal translation, three of the test trials required children to use horizontal rotation, five of the test trials required children to use diagonal translation, and three of the test trials required children to use diagonal rotation. Children received 1 point for every correct answer (range=0–16), and the proportion correct was the outcome measure on the task. Spearman–Brown-adjusted split-half reliability in our sample at age 4 was $r=.70$. Children who completed fewer than 13 trials were recoded as missing. At age 4, 5% of the observations were coded as missing.

Fifteen of the original sixteen test items were used again at age 5 and similar administrative methods were employed, although some changes were required to administer the task through videoconferencing. The last test item was accidentally replaced by an item similar to one of the practice trials at age 5 but required the same horizontal translation as the original test item used at age 4. 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 at age 5 was identical to the task used at age 4, with a Spearman–Brown-adjusted split-half reliability of $r=.87$. At age 5, 18 of the CMTT observations were coded as missing. Across both time points two participants were missing values for both administrations.

Geometric sensitivity

The GS test (Dehaene et al., 2006; Dillon et al., 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

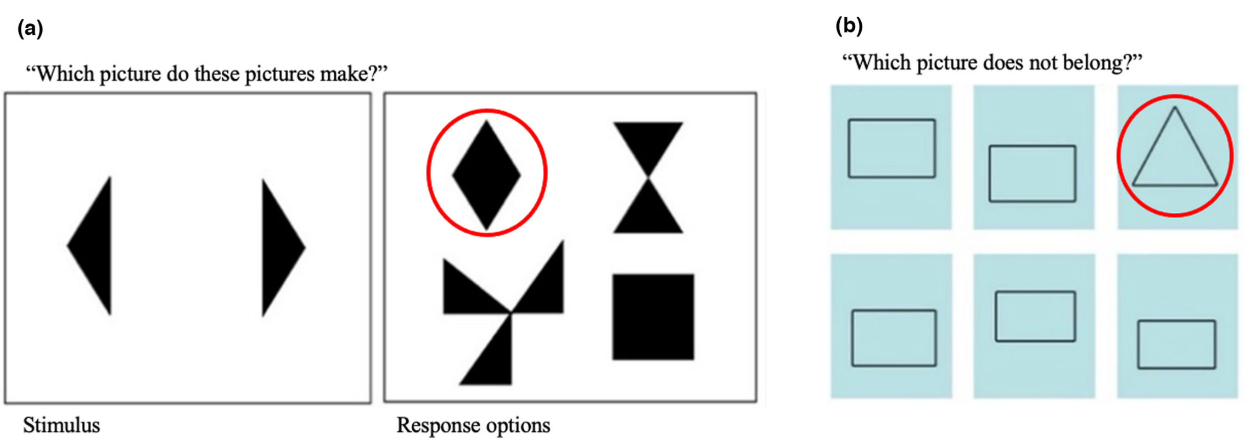

FIGURE 1 Sample items from the (a) children's mental transformation test and (b) geometric sensitivity test. Correct answers are circled in red.

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 1b). Children are asked to point to the picture that does not belong. Displays include trials relating to Euclidean geometry (5 items), asymmetry (3 items), metric properties (2 items), geometric transformations (1 item), and geometric figures (1 item). Four practice trials with feedback were included, followed by 12 test trials without feedback. Children received 1 point for every correct response (range = 0–12) which was then converted to proportion correct. Spearman–Brown-adjusted split-half reliability in our sample at age 4 was $r = .58$. Scores were recoded to missing if the child completed fewer than 10 trials. At age 4, 3% of the observations were coded as missing.

At age 5, the same items of the GS task were administered in a similar manner with 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. Spearman–Brown-adjusted split-half reliability in our sample at age 5 was $r = .79$. At age 5, 17 (15%) of the observations were coded as missing.

Non-verbal number skills

Children completed a non-symbolic number comparison task designed to assess their non-verbal number skills (Halberda et al., 2008). At age 4, participants were presented with arrays of yellow and blue dots (generated through Panamath; www.panamath.org) on a tablet and were asked to indicate which of the two sets contained the larger number of dots. Trials included three different conditions to control for non-numerical visual confounds of the displays. In correlated trials, cumulative surface area positively correlated with the number of dots and thus, the array with more dots had a larger surface area, as average dot size was the same across arrays. In neutral trials, the cumulative surface areas of each pair of arrays were equated and thus, the arrays with more dots necessarily had smaller-sized dots. In anti-correlated trials, cumulative surface area was negatively correlated with dot numerosity, and therefore, the set with more dots had a smaller surface area and smaller-sized dots. Children first completed six practice trials in which the larger set contained around three times as many dots as the smaller (e.g., a 3:1 ratio) and received feedback from the experimenter. If children responded correctly on at least four of these six trials, they were prompted to continue with the test trials; otherwise, they repeated practice up to two times. Children then completed 48 test trials in which the ratio of the larger-to-smaller quantities of dots in each trial were either 3, 2, 1.5, or 1.3. Ratios were presented in a random order, but trials were divided into three blocks. No assessments were conducted between blocks, but children were given a sticker as a reward for completing each block. The proportion of correctly answered trials was used as a measure of children's non-verbal number skills. Spearman–Brown-adjusted split-half reliability of our sample at age 4 was $r = .86$.

At age 5, procedures were identical to age 4 procedures with the exception that the task was administered via videoconferencing and screensharing. Instead of tapping which side of the tablet screen had more dots, participants were asked to indicate which of the two sets contained the larger number of dots by verbally responding with "yellow" or "blue." In addition, the three blocks were distributed across the three videoconferencing sessions, with one block per session always as the first task in each session. Spearman–Brown-adjusted split-half reliability of our sample at age 5 was $r = .94$.

Spatial activity frequency and diversity

When children were 4 years old, parents completed a questionnaire regarding the frequency with which their child engaged in a variety of activities over the span of 1 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 ranging from 1 (*never*), 2 (*once or twice per month*), 3 (*weekly*), 4 (*several times per week*), to 5 (*every day*). A spatial activity frequency score was created by averaging all responses.

Time use diaries were completed by participating parents twice when children were 4 years old: 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 in accordance with the American Time Use Survey (ATUS; U.S. Bureau of Labor Statistics, 2016). Specific prompts and clarifying questions were employed 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. Responses indicate the variety of children's spatial play rather than the frequency or extent of time spent playing because we only probed for occurrence not frequency or duration of each activity. See Appendix A in Supporting Information for the complete list of ASA items and activity codes. 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.

Spatial talk frequency and complexity

Dyads were observed during three semi-structured tasks designed to elicit a variety of math talk, such as number and spatial talk (Elliott et al., 2017; Lee et al., 2019; Ramani et al., 2015). Dyads were provided with age-appropriate toys and instructed to play as they normally would. To record these interactions, researchers set up a 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 of the book was designed to elicit talk about number and spatial concepts by introducing a new set of animals arriving at the fox's birthday party, a bird moving its location, the sun and sky changing, and emerging patterns. After sharing the book, participants were instructed to complete a puzzle that was specifically chosen to elicit high frequencies of spatial talk. Dyads were given a magnetic whiteboard, colorful, magnetic shapes, and a picture of an animal consisting of 18 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 foils. Dyads were told they had 5 min 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, and 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 2 s, 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 in Supporting Information 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 or 3D space (e.g., time and weight). Coders then read through the utterances identified as potentially including a spatial term and coded the content based on guidelines adapted from Cannon et al. (2007; see Appendix B in Supporting Information). Twenty percent of spatial talk transcriptions for each task were double-coded and reliability among coders was strong (Cohen's kappa range = 0.87–0.94, $M = 0.91$).

Spatial talk frequencies for parents were calculated by adding the number of parents' spatial utterances during each task. The parent spatial talk utterance length was determined by finding the mean length of all spatial utterances for each parent. The spatial talk frequencies for the book (M = 21.5, SD = 13.0, $t(121) = 16.14$, $p < .001$) and grocery tasks ($M = 21.0$, SD = 11.1, $t(118) = 16.10$, $p < .001$) were both significantly lower than for the puzzle task ($M = 64.8$, SD = 31.1), so spatial talk frequencies and utterance lengths from the book and grocery 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 all tasks.

Covariates

Age was measured by calculating the number of days from the participant's date of birth to the date of the first age 5 visit, then dividing by 30 to determine children's age in months.

A composite measure of SES was created by using standardized household income and standardized years of parent education as obtained via parent reports.

Data analysis plan

To address the aims of the present study, all analyses were conducted in STATA version 16.1. To address our first aim, a multiple regression analysis was conducted to determine whether the frequency or diversity of spatial activities predicts gains in preschoolers' spatial skills. In model 1, children's spatial skills at age 5 were regressed onto the spatial activity frequency composite from the questionnaire, spatial activity diversity composite drawn from ASA questions, child spatial skills at age 4, and covariates (child age, SES).

To address our second aim of whether the frequency or length of parent spatial utterances predict gains of preschoolers' spatial skills, a multiple regression analysis (Model 2) was conducted regressing child spatial skills at age 5 onto the total number of parent spatial utterances during the spatial activity (i.e., the puzzle task), mean parental spatial utterance length during the spatial activity, total number of parent spatial utterances during the non-spatial activities (i.e., book and grocery tasks), mean parental spatial utterance length during the non-spatial activities, child spatial skills at age 4, and covariates (total parent utterances during the spatial activity, total parent utterances during the non-spatial activities, child age, and SES).

To address our third aim, determining whether spatial activities and spatial talk were unique predictors of children's gains in spatial skills, we included only the predictor variables of spatial activities and talk that were significant in models 1 and 2 in the final regression model while controlling for child spatial skills at age 4 and covariates (child age, SES).

As a sensitivity analysis to determine domain specificity, models 1 and 2 were rerun to predict children's non-verbal number skills rather than the spatial skills composite if any of the spatial input measures (i.e., spatial activities or spatial talk, respectively) were statistically significant.

Of the 127 participants, 95 (84%) had complete data for every variable. Cases with complete and missing data were compared to detect significant differences in age, SES, spatial skills at age 4 and age 5, sex, child race, and ethnicity. No significant differences between children with complete and missing data were found regarding age, spatial skills at either time point, sex, or child race and ethnicity; however, there was a significant difference observed between children with complete and missing data regarding SES. A two-sample t-test showed that children with missing data had lower SES scores ($M=-0.32$, SD = 0.17) than children with complete data ($M=0.18$, SD = 0.08), $t(123)=-3.12$, $p<.01$.

Missing data on all analytic variables were imputed via multiple imputation by chained equations using the mi impute chained command in Stata. Cases with no data at age 5 (i.e., those children who did not complete any follow-up visits, $n=14$) were excluded from the dataset prior to imputation. Imputation was conducted at the composite level (e.g., rather than imputing individual items and recreating composites). Regression models were then estimated across the 20 imputed datasets using Stata's mi estimate commands, which pool estimates and standard errors across imputations. Additionally, to aid in the interpretation of coefficients, the mi beta package was used to calculate the average standardized coefficients across imputations.

RESULTS

Descriptive statistics

Children scored an average of 0.49 on the CMTT at age 4 (SD = 0.16, range = 0.13–0.94) and 0.70 at age 5 (SD = 0.16, range = 0–1). They scored an average 0.36 on the GS task at age 4 (SD = 0.19, range = 0–0.92) and 0.53 at age 5 (SD = 0.21; range = 0–1). CMTT and GS scores were significantly correlated at each age (age 4: $r=.40$, $p<.001$; age 5: $r=.41$, $p<.001$). Thus, we combined CMTT and GS scores at each age into composite spatial skills score by averaging CMTT and GS scores at each time point. Children scored an average of .70 on the non-verbal number task at age 4 (SD = 0.15, range = 0.42–0.96) and 0.84 at age 5 (SD = 0.12, range = 0.31–1).

Table S1 shows parents' reports of the frequency with which children engaged in spatial activities over the span of 1 month based on parents' reports on a questionnaire. 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 S2 shows how many parents responded "yes" when asked if they observed their child participating in one of the listed spatial activities during the time diary interview. Overall, about 78% of parents reported that their child had participated in at least one of the four activities during the previous day with building activities reported most frequently.

Table S3 shows the descriptive statistics of parent spatial utterance frequencies and lengths for the spatial and non-spatial tasks. Parents' mean spatial utterance lengths in spatial and non-spatial activities were longer than non-spatial utterance lengths by an average of about two words. Additionally, spatial utterance lengths in the spatial activity were slightly shorter than during the non-spatial activities, while non-spatial utterance length was nearly the same in both contexts.

Table S4 shows Pearson's correlations between all measures of spatial activities and spatial talk. Parent reports of children's spatial activity frequency was positively correlated with the diversity of spatial activities ($r=.30$). Spatial talk frequencies during spatial and non-spatial tasks were positively related, as were MULs during spatial and non-spatial tasks. Unexpectedly, the frequency of spatial activities was negatively correlated with parent spatial utterance length during spatial and non-spatial tasks.

Spatial activity frequency predicting spatial skill gains (RQ1)

The first aim of the present study was to determine if children's spatial activity frequency and diversity are predictive of their gains in spatial skills from ages 4 to 5. As can be seen in Table 1, frequency of spatial activities was not predictive of children's spatial skills but rather diversity of spatial activities at age 4 was predictive of children's spatial ability 1 year later even when controlling for age, SES, and spatial ability at age 4. A 1 SD increase in diversity of daily spatial activities at age 4 was

TABLE 1 Regression model predicting children's spatial skills at age 5 from children's spatial activities.

Predictor	*B* (SE)
Diversity of spatial activities	.09 (.05)*
Frequency of spatial activities	−.01 (.03)
Child spatial skill at age 4	.42 (.09)***
Child age: 5 years	.25 (.09)**
Socioeconomic status	.08 (.04)*
Constant	−.51 (.49)
$F(5, 99.8)$	12.46***
R^2	.40

*$p<.05$; **$p<.01$; ***$p<.001$.

associated with a .17 SD increase in children's spatial skills. A sensitivity analysis revealed the domain-specific relation between children's spatial activities and their spatial skills. Neither frequency nor diversity of spatial activities were significant predictors of children's non-verbal number skills (see Table S5).

Frequency or length of spatial utterances predicting spatial skill gains (RQ2)

The second aim examines whether the frequency and mean spatial utterance length of parents' spatial talk during semi-structured tasks predict preschoolers' spatial skills at age 5 controlling for spatial skills at age 4. As can be seen in Table 2, the *frequency* of parent spatial talk did not significantly predict children's spatial skills at age 5. In contrast, parent spatial utterance length during a spatial activity (i.e., the puzzle task) was a significant predictor of children's spatial skills at age 5 even when controlling for spatial skills at age 4, all other talk variables, child age, and SES. A 1 SD increase in parent spatial utterance length during puzzle play at age 4 corresponded with a 0.40 SD increase in children's spatial skills. Importantly, the length of parent spatial utterances across the two non-spatial activities was not related to gains in children's spatial skills. Unexpectedly, the mean length of parents' non-spatial utterances during non-spatial tasks was a significant negative predictor of children's spatial skills at age 5. A 1 SD increase in the non-spatial utterance length during the two non-spatial activities was associated with a 0.12 SD decrease in children's spatial skills.

A sensitivity analysis revealed the domain-specific relation between parents' spatial talk and children's spatial skills. Both frequency of spatial utterances and MUL during spatial and non-spatial activities were not significantly related to gains in children's non-verbal number skills (see Table S6).

TABLE 2 Regression model predicting children's spatial skills at age 5 from parent spatial utterance frequency and lengths.

Predictor	*B* (SE)
Spatial utterance length: puzzle	.08 (.04)*
Non-spatial utterance length: puzzle	−0.07 (.07)
Spatial utterance frequency: puzzle	−.0003 (.002)
Non-spatial utterance frequency: puzzle	.006 (.001)
Spatial utterance length: other	.03 (.02)
Non-spatial utterance length: other	−.13 (.07)**
Spatial utterance frequency: other	−.0002 (.002)
Non-spatial utterance frequency: other	.00007 (.0005)
Child spatial skill at age 4	.40 (.09)***
Child age: 5 years	.21 (.08)*
Socioeconomic status	.21 (.03)*
Constant	−.21 (.48)
F (11, 93.4)	6.53***
R^2	.51

**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 independently predicted gains in preschoolers' spatial skills in models 1 and 2 continued to predict gains in children's spatial skills when controlling for each other as well as child age and SES (Table 3).

Regression results revealed that parent spatial utterance lengths during the spatial task, non-spatial utterance lengths during the non-spatial tasks, and diversity of children's spatial activities remained significant predictors of children's spatial skills at age 5, and the magnitude and directionality of the associations remained unchanged when they were included in the same model.

DISCUSSION

The first aim of the present study was to use parent reports of the frequency and diversity of preschoolers' spatial activities and examine how it relates to gains in spatial skills. Our results show that children's spatial activity *diversity*, but not frequency, at age 4 is predictive of their gains in spatial skills between ages 4 and 5 years. Second, the present study expanded on previous research that investigated only the relation between parent spatial talk frequencies regardless of context and children's

TABLE 3 Regression model predicting children's spatial skills at age 5 from spatial utterance length during the spatial task, non-spatial utterance length on the non-spatial tasks, and diversity of spatial activities.

Predictor	*B* (SE)
Spatial utterance length: puzzle	.06 (.02)**
Non-spatial utterance length: other	−.12 (.03)**
Diversity of spatial activities	.09 (.04)*
Child spatial skills at age 4	.36 (.09)***
Child age: 5 years	.26 (.09)**
Socioeconomic status	.08 (.03)*
Constant	−.81 (.50)
F(6, 102.6)	12.22***
R^2	.44

**p* < .05; ***p* < .01; ****p* < .001.

spatial abilities by investigating how both *parent spatial talk frequencies and utterance lengths within spatial and non-spatial play contexts* influenced preschoolers' spatial skill gains over the span of 1 year. Our results did not support our initial hypothesis that more frequent spatial utterances employed by parents would be predictive of children's gains in spatial skills. Instead, we found that parent spatial utterance length within spatial play contexts was predictive of children's gains in spatial ability from age 4 to age 5. Importantly, neither spatial activity measures nor parental spatial talk measures were predictive of children's gains in non-verbal number skills underscoring the specificity of the association between spatial input and children's spatial skills. Finally, parent spatial utterance length during the spatial activity and diversity of children's daily spatial activities remained significantly unique predictors of gains in children's spatial skills when included in the same model.

Diversity of spatial activities but not frequency predicts spatial skill gains

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) 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 (obtained from time diaries) were significantly predictive of children's spatial skill gains from ages 4 to 5.

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 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 were asked a series of questions to determine whether their child engaged in specific academically related activities (ASA) on the previous day (Bachman et al., 2020). Adding ASA to the time diary protocol can cue memories 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). The present study captured 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 2 separate days and demonstrated that engaging in a diversity of activities is related to spatial skills. While 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, it may be more susceptible to the idiosyncrasies of the 2 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).

Length of spatial utterances but not frequency predicts spatial skill gains

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 (Casasola et al., 2020; Kısa et al., 2019; Loewenstein & Gentner, 2005). However, 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 4 years, and children's subsequent gains in intrinsic spatial ability 1 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 (Ferrara et al., 2011; Kısa et al., 2019). In addition to investigating children's spatial language production, Cartmill et al. (2010) 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 production, comprehension, or gesture as a dimension of parental spatial language input 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 (Loewenstein & 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, or task demands, 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 et al. (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. Levine and colleagues used a shortened 10-item version of the CMTT, whereas we used a 16-item version of the task. 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. Finally, our measure of children's spatial skills included the CMTT and a task tapping into GS. 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; Kısa 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, it is the first to demonstrate that parents' spatial utterance length within the context of a spatial activity is a significant predictor of children's gains in spatial skills from age 4 to 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 study 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. Thus, it required a lot of conversation about location, orientation, and direction. Further work is needed to determine if these results are maintained in other spatial play scenarios like sorting shapes or block constructions where dialogue may focus more on spatial relations and features.

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 spatial abilities (Purpura et al., 2020; Zippert & Rittle-Johnson, 2020). The present study adds to the field by investigating two specific factors, diversity of daily spatial activity and parent spatial utterance length, and demonstrated that each is a unique contributor to children's spatial abilities. One possible explanation of why spatial activity diversity and spatial utterance length may be unique predictors of children's spatial skill gains is that each reflects a different aspect of the home learning environment that supports children's spatial skills development. Diversifying spatial activities increases children's familiarity with different 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.

Although the diversity of spatial activity and spatial utterance length during the puzzle task were not correlated with a meaningful degree, we observed an unexpected negative correlation between spatial activity frequency and parent spatial utterance length during spatial and non-spatial tasks. When we examined this relation further using partial correlations and controlling for children's age, we found that the correlations between children's activity frequency and parent spatial utterance lengths were 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).

Finally, and unexpectedly, parents' non-spatial utterance length during non-spatial activities was negatively associated with children's spatial skills 1 year later. Interpreting these results is outside the scope of the present study, as we do not know what topics are being discussed and what types of utterances make up the non-spatial talk during non-spatial play. Parents could be emphasizing learning opportunities within other domains (e.g., general language or abstract reasoning), and non-spatial utterance lengths could be positively associated with gains in other types of cognitive skills at the cost of gains in spatial skills. Future work should investigate additional context-specific spatial and non-spatial talk, the language embedded within the utterances, and their contributions to children's skills development more broadly.

Limitations and future directions

Although 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 et al., 2012; Ho et al., 2018; Lee et al., 2019; Ozel et al., 2004; Verdine & Golinkoff, 2014; Verdine, Golinkoff, et al., 2014; Verdine, Irwin, 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 with 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, mental rotation of 3D objects, and 2D and 3D match-to-sample assembly tasks).

Another area of opportunity for future investigations is to expand the aspects of parent–child interactions being considered. The current study only focused on MUL of parents' spatial talk. However, parents could be promoting specific activities or adjusting their language based on what they know about their child's skills. 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. In addition, children's spatial talk was not considered even though previous work has shown that children's spatial language mediates the association between parents' spatial talk and children's spatial skills (Pruden et al., 2011). Furthermore, spatial talk data were coded at the utterance level and not the word or token level, which limited the present study from investigating associations between the number of spatial words parents used during each task and children's spatial skills.

Finally, there are limitations in the external validity of the present study. Although 26% of the sample was low income, the majority of participating parents were highly educated, which may limit the generalizability of these results to more diverse populations. In addition, the majority of participating parents were mothers, which does not allow us to draw any conclusions regarding potential gender differences. Given well-documented gender differences in spatial skills (Reilly & Neumann, 2013), further work is needed to investigate how mothers and fathers might differ in the ways that they engage in spatial activities and use spatial talk while playing with their children and how their spatial talk might differ in spatial and non-spatial contexts. Furthermore, previous studies have shown that executive function skills (i.e., working memory, inhibitory control, and shifting from one task to another) are important in the development of math and spatial skills. Therefore, future work should consider how executive functioning may be associated with children's spatial skills and how children learn from spatial activities and spatial talk (Bachman et al., 2022; Cragg & Gilmore, 2014; Verdine & Golinkoff, 2014; Verdine, Golinkoff, et al., 2014; Verdine, Irwin, et al., 2014).

CONCLUSIONS

The current study aimed to advance existing knowledge regarding how engagement in spatial activities and exposure to parent spatial language influence children's spatial skill gains from ages 4 to 5. We found that diversity of engagement in spatial activities, not frequency, at age 4 was predictive of spatial ability at age 5 even when controlling for spatial ability at age 4. Furthermore, we found that only length of spatial utterances during a spatial task, not their frequency, was predictive of children's gains in spatial abilities. Finally, we demonstrated that diversity of children's spatial activities and parents' spatial utterance lengths during a spatial task were significant and unique predictors of children's spatial skill gains. 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.

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DATA AVAILABILITY STATEMENT

The analyses presented here were not preregistered. The data, analytic code, and materials necessary to reproduce the analyses presented here are not publicly accessible.

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