MULTIDISCIPLINARY APPROACHES TO UNDERSTANDING EARLY DEVELOPMENT OF SPATIAL SKILLS: ADVANCES IN LINGUISTIC, BEHAVIORAL, AND NEUROIMAGING STUDIES

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MULTIDISCIPLINARY APPROACHES TO UNDERSTANDING EARLY DEVELOPMENT OF SPATIAL SKILLS: ADVANCES IN LINGUISTIC, BEHAVIORAL, AND NEUROIMAGING STUDIES

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EDITORIAL
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Editorial: Multidisciplinary Approaches to Understanding Early Development of Spatial Skills: Advances in Linguistic, Behavioral, and Neuroimaging Studies

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Editorial on the Research Topic

Multidisciplinary Approaches to Understanding Early Development of Spatial Skills: Advances in Linguistic, Behavioral, and Neuroimaging Studies

Spatial cognition is a fundamental component of human cognition. Early spatial skills have longitudinal relations with later educational and occupational achievements in science, technology, engineering, and mathematics (STEM). Thus, it is critical to develop and deliver early interventions for young children to acquire spatial skills to lay a solid foundation for their future development. To achieve this goal, there is a need to understand how space is represented and presented by young minds and how young children acquire spatial language and skills using linguistic, behavioral, and neuroimaging approaches. This Special Collection represents an important endeavor to collect multidisciplinary studies on the early development of spatial skills and their implications for child development. As the guest editors, we strongly wish to advance the study on this topic by presenting this special collection.

EARLY SPATIAL SKILLS: AN UNDERSTUDIED AREA

Spatial skills are a group of core cognitive abilities including spatial visualization (the ability to imagine and mentally transform spatial information), form perception (the ability to copy and distinguish shapes from other shapes, including symbols), and visual-spatial working memory (the ability to hold the locations of different objects, landmarks, etc.) (Rittle-Johnson et al., 2019). Young children regularly engage their spatial skills as they play blocks, puzzles, and videogames (Newcombe, 2010; Levine et al., 2012; Verdine et al., 2014; Jirout and Newcombe, 2015). Infants and toddlers also hear many spatial words when talking with their parents, and the frequency of hearing spatial words is a predictor of their development of spatial skills (Pruden et al., 2011). And mounting empirical evidence has suggested that spatial skills predict success in children's long-term development in the field of STEM (Wai et al., 2009; Newcombe, 2010; Uttal et al., 2013). Uttal and Cohen (2012) even regard spatial skills as a STEM "gateway."

Despite the evidence, the importance of spatial skills is often overlooked in early childhood education. For instance, in the US, spatial skills have received minimal attention in the Pre-K and

Kindergarten standards [National Council of Teachers of Mathematics, 2006; National Association for the Education of Young Children (NAEYC), 2014]. This public neglect of spatial development creates an additional barrier to children's early STEM learning. Therefore, there is growing advocacy for more attention to spatial skills early in education (Newcombe, 2010; Verdine et al., 2014). Further, there is much evidence to suggest that it is easy to foster early spatial learning as a core component of early childhood programs. Thus, research on the early development of spatial skills is urgently needed.

This Frontiers Research Topic aims at understanding how spatial skills develop in the early years (Age 0–8) from the perspectives of linguistics, behavioral science, and neuroscience. We have successfully collected nine cutting-edge studies to reflect the latest developments and advances in this rapidly emerging field. These articles were written by emerging and leading researchers from linguistics, psychology, education, neuroscience, and related fields. They have scrutinized spatial skills development in the early years using linguistic, behavioral, and neuroimaging approaches. This editorial will briefly review these studies and present some implications for future research.

THE LINGUISTIC APPROACH TO STUDYING EARLY SPATIAL DEVELOPMENT

Spatial language lays the foundation for developing and learning spatial concepts. Studies on its acquisition using the linguistic approach can shed light on how the abstract concepts are acquired and constructed in the early years. Therefore, early spatial language acquisition and production studies are of great importance in understanding the complicated relationships between language and cognition in the early years (Majid et al., 2013). However, the existing studies on spatial terms have extensively adopted the experimental approach and only examined the acquisition of task-relevant spatial terms (Casasola et al., 2020), leaving the naturalistic production of spatial terms unexplored. This Research Topic thus deliberately collected three empirical studies on the natural language production of spatial terms.

Xu et al. article, *"The Use of a Novel Term Helps Preschoolers Learn the Concept of Angle: An Intervention Study with Chinese Preschool Children"*, opens this special issue with an early language intervention study aiming to foster preschoolers' conceptual understanding and linguistic presentation of "angle." As an important concept in geometry, angle is widely used in daily communication and learning; but it is very abstract and difficult for young children to understand. This is because they have difficulties in differentiating "angle size" from "length of angle sides" due to limited word knowledge. This study adopted a quasi-experimental research design to investigate the effectiveness of two ways of separating angle from angle size in 3- to 6-year-old Chinese preschoolers. In this study, Xu et al. found that the experimental group improved significantly more than the other two groups. But, separating the words/phrases for angle and angle size might not help young children differentiate the two concepts, which share the same Chinese character/word "jiao" (angle). Some novel terms should be used to improve young children's learning. This finding indicates that language shapes or limits cognition in the early years, providing empirical evidence to the Whorf Hypothesis. This Hypothesis suggests that the structure of a language affects its speakers' world view or cognition, and thus people's perceptions are relative to their spoken language. Although still arguable and debatable, this Hypothesis proves to be true with preschoolers in this study.

In the second article, "*A Corpus-Based Comparison of the Pragmatic Use of Qian and Hou to Examine the Applicability of Space-Time Metaphor Hypothesis in Early Child Chinese,*" Tsung and Wu have examined the Universal Space-Time Mapping Hypothesis using natural language data elicited from a corpus. The Hypothesis suggests that temporal expression is based on spatial metaphor for all human beings and languages. Thus, this study explored its applicability in the Chinese language produced by 168 Mandarin-speaking preschoolers in a toy play context. To do so, they tested the use of the unique pair of Chinese words, qian (前/before/front) and hou (后/after/back), which could express either time (before/after) or space (front/back) in daily communication. They found a significant age difference and a critical period (before 4.5 years) in the pragmatic use. The pair was produced to express time (before/after) much earlier and more than space (front/back). Therefore, they concluded that time expression might not necessarily be based on the spatial metaphor, which challenged the Hypothesis.

The third article, "*Spatial Language of Young Children during Block Play in Kindergartens in Urban China,*" reports findings from a study on preschoolers' language use during block play. It is widely believed that spatial language can predict spatial skills and can be facilitated by peer interactions and goal-oriented building behaviors. In this study, Yang and Pan investigated the frequency, type, and level of children's spatial language and their associations with the level of block play by observing 228 young children. They found that young children used more words about spatial locations, deictic terms, dimensions, and shapes. But fewer words about spatial features or properties and spatial orientations or transformations were produced. In addition, most young children used gestures in conjunction with spatial deictic terms. Although very descriptive, this study has also provided empirical evidence to indicate the potential relationship between language and early spatial skills.

THE BEHAVIORAL APPROACH TO STUDYING EARLY SPATIAL DEVELOPMENT

Many traditional ways can facilitate early spatial development, such as paper folding, block building, fine arts, and painting. For instance, paper folding and block building are common activities in Chinese and Japanese kindergartens. Still, their potential contribution to early spatial skills has not received adequate attention in the literature. This special issue also collects four articles reporting behavioral studies on early spatial development.

The fourth paper, "*Exploring the Relationship between Parental Involvement, Paper Folding Skills, and Early Spatial Ability: A Mediation Model,*" presents an innovative study on traditional paper folding activities. In this study, Wu and Sun investigated whether and how paper folding skills could predict early spatial ability. To do so, they developed and validated a measure of paper-folding skills. They found a significant age effect in paper folding performance, and parental involvement could also contribute to the performance. Besides, paper folding skills could also contribute to early spatial development. Therefore, they established a mediation model of the relationship between parental involvement and spatial ability. This finding has revealed the educational values of paper folding and provided a reliable measure of paper folding skills, which have tremendous implications for early childhood education. This line of research deserves extending and further digging.

The fifth article, "*The development of spatial representation through teaching block-building in kindergartners,*" evaluates the effects of a block-building intervention on kindergarteners' spatial representation skills, using a quasi-experimental research design. In this study, Cai et al. delivered the well-planned block-building program to the experimental group, leaving those control group children to play with blocks freely. They found that the intervention significantly promoted Chinese kindergarteners' spatial representations. This finding has revealed the educational value of well-prepared block building activities and indicates a new research direction warranting further studies.

The sixth article, "*Spatial skills associated with block building complexity in pre-schoolers,*" also explores the educational values of block building activities in Chinese kindergartens. In this study, Zhang X. et al. investigated the relationships between six measures of spatial skills and block building complexity. They found that shape recognition, shape composition, and shape-recognition-by-gender interaction significantly predicted children's block building complexity. This finding has some implications for improving block building activities and enhancing early spatial complexity.

In the seventh article, "*The Effect of Finger Gnosis on Young Chinese Children's Addition Skills*", Zhang L. et al. have explored the association between finger gnosis and arithmetic skills in Chinese children and the underlying mechanism. In the literature, finger gnosis has been found to facilitate children's spatial learning, which might help children develop a mature number line. First, they found that finger gnosis was significantly associated with addition performance. Second, they found that girls' finger gnosis was better than boys', and children with musical training outperformed those without the experience. Third, they found that the children with high finger gnosis performed better in number line estimation than those with low finger gnosis. Last, they found that the number line estimation fully mediated the relationship between finger gnosis and addition performance. These findings have jointly revealed the educational values of finger gnosis and provided practical implications for early childhood education.

The eighth article, "*Is Early Spatial Skills Training Effective? A Meta-Analysis,*" is a meta-analysis review conducted by Yang et al. They systematically analyzed 20 spatial intervention studies (2009–2020) with children aged 0–8 years and found the average effect size (Hedges's g) was 0.96 ($SE = 0.10$). In addition, they also analyzed the effects of several moderators such as the type of study design, sex, age, outcome category, research setting, and type of training. The results indicated that many training strategies or programs could significantly foster young children's spatial skills, such as hands-on exploration, visual prompts, and gestural, spatial training. This finding has provided implications for future research, policy-making, and practical improvement.

THE NEUROIMAGING APPROACH TO STUDYING EARLY SPATIAL DEVELOPMENT

The last article of this special issue, "*Neural Correlates of Mental Rotation in Preschoolers with High or Low Working Memory Capacity: An fNIRS Study,*" is an fNIRS study of the differentiated neural correlates of mental rotation (MR) in preschoolers with high and low working memory. Yang et al. tested 38 Chinese preschoolers with Working Memory Capacity (WMC), Mental Rotation, and Control tasks. They found no significant differences in MR task performance between the High- and Low-WMC groups. However, the two groups differed significantly in the activation of BA44 and BA9 during mental rotation. They concluded that BA9 and BA44 should be the neural correlates of mental rotation. This finding has provided neuroimaging evidence about the cognitive processing of mental rotation in preschoolers.

FUTURE DIRECTIONS: WHERE SHALL WE GO?

This special edition calls for attention to the early development and facilitation of spatial skills, given its fundamental importance for future learning outcomes and significant literature gaps. The gaps include a lack of research on how children's spatial language works together with their spatial skills to facilitate their early cognitive development and other learning outcomes; how the facilitation of early spatial skills can be integrated into the early childhood education curriculum and be supported in children's everyday interactions with parents; and the neural mechanisms underlying early spatial learning and relevant impairment.

The existing studies have identified scattered relationships between spatial language and the mastery of particular spatial concepts and suggested that spatial language supports spatial skills proficiency. Such evidence is not able to provide a comprehensive picture of the relationship between spatial language and skills. With a group of core cognitive abilities including spatial visualization, form perception, and visual-spatial working memory, spatial skills deserve more systematic studies to further reveal how spatial language lays the foundation for developing different aspects of spatial concepts and skills.

Another consensus from the existing correlational and experimental studies is the neglected value of daily spatial activities, such as paper folding and block building, on early spatial development. It is worth paying more attention to children's daily spatial-related activities and integrating these activities in the systematic early childhood education curriculum and parenting education, given the popularization, playfulness, and potential educational benefits in such activities.

Last but not least, we still know very little about how the brain processes different forms of spatial information in the early years and whether such processes differ when children grow up. The fNIRS, a non-invasive neuroimaging technique, might provide potential to explore this area among young children due to its tolerance of children's head motion, physical movement, and relatively comfortable experiences compared to other invasive techniques. Future well-designed neuroscientific studies should extend this research line with more diverse samples and longitudinal designs to enrich the theory building of developmental cognitive neuroscience considering children's spatial skills.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Is Early Spatial Skills Training Effective? A Meta-Analysis

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Spatial skills significantly predict educational and occupational achievements in science, technology, engineering, and mathematics (STEM). As early interventions for young children are usually more effective than interventions that come later in life, the present meta-analysis systematically included 20 spatial intervention studies (2009–2020) with children aged 0–8 years to provide an up-to-date account of the malleability of spatial skills in infancy and early childhood. Our results revealed that the average effect size (Hedges's *g*) for training relative to control was 0.96 ($SE = 0.10$) using random effects analysis. We analyzed the effects of several moderators, including the type of study design, sex, age, outcome category (i.e., type of spatial skills), research setting (e.g., lab vs. classroom), and type of training. Study design, sex, and outcome category were found to moderate the training effects. The results suggest that diverse training strategies or programs including hands-on exploration, visual prompts, and gestural spatial training significantly foster young children's spatial skills. Implications for research, policy, and practice are also discussed.

Keywords: spatial skills, infancy and early childhood, training, meta-analysis, spatially enriched curriculum, STEM

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INTRODUCTION

Spatial skills are often applied in problem-solving situations, especially when processing and manipulating visuospatial information (Rafi et al., 2005). Studies have revealed that these skills strongly predict educational and occupational achievements in STEM (science, technology, engineering, and mathematics) domains (Wai et al., 2009; Lubinski, 2010; Uttal and Cohen, 2012; Stieff and Uttal, 2015). Improving spatial skills is therefore an important agenda for both research and educational practice (Hawes et al., 2017). Although previous studies have showed that early interventions for young children are more effective than interventions that come later in life (Heckman and Masterov, 2007), to what extent spatial skills training programs can effectively improve young children's spatial development remains understudied. It is worth noting that Uttal et al. (2013) have conducted a meta-analysis of training studies on spatial skills in general populations. However, this seminal work only included research evidence produced in 1984–2009 and did not focus on the training of early spatial skills.

In the past decade, we have observed an increase in research work on early spatial training and its effects, with more types of training approaches being used. In order to achieve an up-to-date understanding of the malleability of spatial skills in infancy and early childhood, the present meta-analytic study aims to synthesize spatial intervention studies that target young children aged 0–8 years from 2009 to 2020. Using a 2×2 typology of spatial skills (intrinsic vs. extrinsic and static vs. dynamic; Newcombe and Shipley, 2015), we meta-analyzed the eligible (quasi-)experimental studies for examining the effect of training on early spatial skills and the potential moderating effects on the relationship between the training and early spatial development.

Spatial Skills in the Early Years

Spatial skills refer to the cognitive processing of spatial information, which "concerns shapes, locations, paths, relations among entities and relations between entities and frames of reference" (Newcombe and Shipley, 2015, p. 180). There are two traditions of conceptualizing spatial skills, including the psychometric approach and the classification system approach (Uttal et al., 2013). The former relies on exploratory factor analysis for identifying the key components of spatial skills, while the latter is rooted in a system comprised of two fundamental distinctions, i.e., between intrinsic and extrinsic information and between static and dynamic tasks (Uttal et al., 2013; Newcombe and Shipley, 2015). In this study, we extended the line of research on spatial skills training by following the 2 × 2 framework of spatial skills used in Uttal et al.'s (2013) seminal meta-analysis. According to Newcombe and Shipley (2015), the 2 × 2 typology of spatial skills leads to four categories of spatial skills and various assessments, as shown in **Table 1**. Based on the 2 × 2 framework of spatial skills (Newcombe and Shipley, 2015), the measurements of spatial skills can be put into categories as aligned with the four categories of spatial skills.

Spatial skills or spatial thinking skills are found to undergo considerable development during infancy and early childhood (0–8 years of age) (Newcombe and Frick, 2010). Prior research evidence indicated that infants as young as 4 months could show precursors of mental transformation (Rochat and Hespos, 1996; Hespos and Rochat, 1997). Frick and Wang (2010) also found that 13- to 16-month-old infants could perform mental rotation tasks after practice. Besides mental rotation, Bai and Bertenthal (1992) showed that 8-month-old infants had the ability of perspective taking when they moved to keep track of the location of an object. Preschoolers aged 3–5 years were also shown to be able to locate an object relative to a different viewpoint (Newcombe and Huttenlocher, 1992). However, individual differences exist in the early development of spatial skills (Hazen, 1982; Harris et al., 2013).

The significance of early spatial skills has been demonstrated by an extensive body of research, which links the early development of spatial thinking to map use (Liben et al., 2013), numerical skills (Zhang, 2016; Cornu et al., 2018; Fanari et al., 2019), arithmetic development (Zhang et al., 2014), math reasoning (Casey et al., 2015), math knowledge (Rittle-Johnson et al., 2019), early writing skills (Bourke et al., 2014), motor skills (Jansen and Heil, 2010), and executive functions (Lehmann et al., 2014; Frick and Baumeler, 2017). However, several lines of evidence suggest that there are early sex and socioeconomic status (SES) differences in spatial skills, with advantages for males and those with higher SES on spatial tests (Levine et al., 1999, 2005; Quinn and Liben, 2008). Therefore, it is of importance to know whether early spatial skills can be improved, especially in girls and socially disadvantaged children.

Neurological evidence supports that early intervention can enhance the neural functioning for spatial thinking (Gersmehl and Gersmehl, 2007). Prior studies also showed that the effects of early spatial training could be transferred to children's math skills (Cheng and Mix, 2014; Bower et al., 2020; Ribeiro et al., 2020; Thomson et al., 2020) and science understanding (Bower, 2017). For instance, Ribeiro et al. (2020) and Thomson et al. (2020) revealed that parental support such as spatial concept support and spatial language use in block building tasks or toy play situations tended to enhance young children's math performance. However, whether spatial skills training and support could lead to a substantial magnitude of improvement in early spatial development, as well as how it can be brought in an early childhood setting and incorporated into an early childhood curriculum, deserves more research.

Malleability of Spatial Skills and Early Interventions

Previous research supports that spatial skills are malleable and can be improved through spatial training or instruction. However, most of the solid evidence for supporting the malleability of spatial skills is revealed by studies in the population of adolescents and adults (Uttal et al., 2013). In the most recent meta-analysis of spatial skills training studies conducted by Uttal et al. (2013), 217 intervention studies were included for analysis, revealing that the average effect size for

TABLE 1 | The 2 × 2 typology of spatial skills and examples of each category.

Category	Description	Example	Measurement
Intrinsic–static	Configuration of objects	To categorize objects based on their spatial features	Mazes, Odd One Out Span, etc.
Intrinsic–dynamic	Transformation of the spatial codings of objects	To imagine the future state of rotating an object	Mental rotation test, Visual–Spatial Puzzle Task, etc.
Extrinsic–static	Identifying the spatial location of objects relative to others	To represent the location of objects in a map	Rod and Frame Test, performance of spatial relations, etc.
Extrinsic–dynamic	Transformation of the inter-relations of objects in movement	To enable perspective taking in understanding astronomy	Piaget's Three Mountains Task, water tilting task, etc.

Newcombe and Shipley (2015); Uttal et al. (2013).

spatial skills training relative to control was Hedges's $g = 0.47$ (SE = 0.04). However, of the 217 studies, only 53 studies focus on children younger than 13 years, with very few focusing on infants, toddlers, and preschoolers. Therefore, it remains to be further explored how to promote spatial skills in the early years.

It is worth noting that most of the training interventions were conducted in a much more controlled setting rather than the naturalist educational setting (Uttal et al., 2013; Hawes et al., 2017). Recent studies (e.g., Newcombe and Frick, 2010) have suggested that integrating spatial content into formal and informal instruction is meaningful for improving spatial functioning and reducing digital divides as related to sex and SES. As a result, more research is needed to test whether there is a difference in training effects across diverse settings, as well as demographic factors such as sex and SES. This will be a significant step forward in searching for an early spatially enriched curriculum (or "spatial curriculum" as promoted by Uttal, 2012) demonstrating the educational relevance of spatial training in the early years.

In terms of classroom-based spatial training, some have been conducted in early childhood settings. For instance, Ehrlich et al. (2006) found that gesturing provided meaningful cues about 5-year-old children's spatial strategies, which implied that gesture-based spatial training in the early childhood setting could be effective in improving mental rotation skills. In an experimental study, Casey et al. (2008) used block building activities to promote 6-year-old kindergarteners' spatial skills. They found that storytelling would provide a practical and useful context for teaching spatial content, while block building could develop children's various spatial skills (Casey et al., 2008). Petty and Rule (2008) also demonstrated the impact of mapping activities as supported by the use of materials such as toy figures, toy buildings, and photograph maps on the spatial skills of children aged 2.5–9, through a pretest–posttest quasi-experimental study. Furthermore, Hawes et al. (2015) conducted a randomized controlled trial among 6- to 8-year-olds to test the impacts of spatial skills training in regular classroom settings. Their research used iPad devices as the platform of early spatial skills training, and the intervention lasted 6 weeks. Evidence indicated that as compared to children in the control group, children who received the computerized spatial training demonstrated enhanced spatial skills (i.e., mental rotation) (Hawes et al., 2015). To make the spatial training more situated in the classroom, Hawes et al. (2017) further designed a 32-week geometry curriculum and conducted another experimental research study with 6-year-olds in their school. Results revealed that those young children's spatial and numerical skills (i.e., spatial language, visual–spatial reasoning, mental rotation, and symbolic number comparison) had been effectively improved using the spatially enriched approach to early geometry instruction (Hawes et al., 2017).

In the past decade, there have been an increasing number of studies on the effects of early spatial skills training. In general, these studies seem to support that young children would significantly benefit from participating in intentional spatial tasks or activities. However, the effects of early spatial skills training have not been systematically investigated. To address this knowledge gap, we conducted this meta-analytic study to examine the effects of interventions on spatial skills among children aged 0–8 years. This study intended to determine to what extent early spatial skills training would work and what the potential moderating factors are (e.g., study design, sex, age, category of spatial skills assessment, research setting, and type of training).

The Present Meta-Analytic Review

As mentioned above, spatial skills are shown to be malleable; therefore, early spatial skills training activities comprised of interactive components such as hands-on exploration and environmental feedback (e.g., visual cues) are expected to show positive effects. This theoretical assumption can be further supported by understanding the early development of spatial skills (i.e., early spatial development).

The underlying mechanism of early spatial development is complex and dynamic, as comprised of multiple elements, including natural maturation, cultural scaffolding, environmental feedback, and active exploration (Newcombe and Learmonth, 1999). It involves both quantitative and qualitative aspects of cognitive change and continuity (Newcombe and Learmonth, 1999), which could be explained by Piaget's theory of cognitive development and Vygotsky's social development theory. The spatial development framework (Piaget, 1953; Piaget and Inhelder, 1956) describes children's progressive understanding of spatial relationships, from appreciating limited objects in the topological stage to considering distances and angles in the Euclidean stage. Although Piaget's cognitive constructivist approach has minimal emphasis on the role of cultural scaffolding, the functioning of schema through assimilation and accommodation provides implications that children's cognitive development can benefit from their interaction with the (physical) world in which they are living. Apart from Piaget, Vygotsky's (1978) sociocultural approach suggests that social interaction plays a fundamental role in cognitive development, which also applies to the specific development of spatial cognition.

Accordingly, the theoretical mechanism of early spatial development has assumed that environmental feedback and guidance in spatial training will improve an individual's ability to handle and manipulate specific spatial tasks. This meta-analysis assessed the extent to which spatial skills training programs could effectively improve young children's spatial development. Some meta-analytic or systematic reviews have examined the effectiveness of spatial skills training or related experiences (e.g., Baenninger and Newcombe, 1989; Spence and Feng, 2010; Uttal and Cohen, 2012; Uttal et al., 2013). However, to our knowledge, to date, there has been no systematic and dedicated research to examine the effect of spatial training on improving the spatial skills of children aged 0–8 years. To address this knowledge gap, we explored the effects of spatial skills training in the crucial life periods of infancy and early childhood, lasting from birth to 8 years. The following research questions thus guided this meta-analytic study:

1. What is the effect of early training on the spatial skills of children aged 0–8?
2. What variables moderate the effect of early spatial skills training?

METHODS

Literature Search

The first author and the third author conducted an extensive automated search of electronic articles through the databases of PsycINFO, ERIC, EBSCO, ProQuest, and Scopus from February 1, 2009, through February 1, 2020. The literature search aimed to thoroughly identify randomized controlled trials or (quasi-)experiments studying the effects of early childhood interventions on the spatial skills development of children aged 0–8 years. Three different sets of terms with two Boolean operators (AND and OR) and the truncation character (*) were utilized to search for and download relevant literature from the databases: predictors (specific terms included "curriculum," "intervention," "approach," "training," and "program"), outcomes (specific terms included "spatial*," "space," "map," "form perception," "visual*," and "visuospatial"), and sample (specific terms included "preschool," "pre-K," "prekindergarten," "pre-kindergarten," "kindergarten," "primary school," "elementary school," "younger children," "infant," "toddler," and "young children"). We created the search terms through extensive piloting. We used the operators "AND," to connect search terms between the categories, and "OR," to connect search terms within each category.

Inclusion and Exclusion Criteria

Two researchers (the first two authors) independently selected and reviewed a subset (25%) of the articles following the inclusion criteria:

1. Included studies were (quasi-)randomized controlled trials or (quasi-)experimental designs.
2. Participants were 0–8 years of age (i.e., mean age of the participants).
3. Spatial skills were measured as outcomes of the intervention.
4. The reported information was sufficient enough for effect sizes to be calculated.
5. English was the written language used.

We excluded correlational studies (e.g., Levine et al., 2012) and reviews (e.g., Zimmermann et al., 2019). Non-full-text documents were also excluded because they may lack sufficient and credible information for meta-analysis.

Study Selection

Based on the above inclusion and exclusion criteria, the two researchers divided 25% of the selected articles into three categories: eligible, possibly eligible, and ineligible. The inter-rater reliability was good (Cohen's kappa coefficient $\kappa = 0.70$) (Cohen, 1960). In view of the differences, the two researchers discussed the adequacy of the articles marked as "possibly eligible" and made the final inclusion decision based on full common consensus. The first author finished the selection of the remaining articles (75%).

As shown in **Figure 1**, which follows the PRISMA statement (Moher et al., 2009), of the 505 records initially identified, 445 were excluded by title and abstract based on the predefined inclusion and exclusion criteria. Of the 60 records remaining and screened, nine were duplicates. We then performed manual searches of the reference list of eligible research reports and repeated this process until no other studies were found, thus adding eight full-text articles. Twenty studies were eventually included, resulting in 50 independent effect sizes.

Data Extraction

To identify interesting variables for research synthesis, Lipsey (2009) proposed three groups of study descriptors: extrinsic variables, method variables, and substantive variables.

1. Extrinsic variables are represented by fixed characteristics of the study, such as the date of publication, publication type, and funding source. We coded the date of publication in this meta-analysis.
2. Method variables are related to the control of the implementation fidelity and the psychometric properties of the measures. We included the type of study design and the category of spatial skills measures as the two method variables for the moderator analysis.
3. Substantive variables are related to subjects (e.g., sex and age), treatments, and settings. In the current meta-analysis, sex, age, type of training, and research settings represent examples of substantive variables.

To ensure coding reliability, two researchers (the first two authors) independently reviewed a subset (25%) of the articles and used a predefined coding scheme to extract the respective data. The coding scheme addressed the following characteristics of each study: the authors, publication year, sample size, participants' age and sex, types of spatial skills training, categories and measures of children's spatial skills, training settings, study design, and performance of children's spatial skills (effect sizes). After verifying the data coding results, the two researchers showed a high degree of agreement (86%) on all coding items in the subset. The inter-coder reliability (Cohen's kappa) is 0.72, which is considered substantial. Any inconsistencies were resolved through discussion and consensus. The first author finished coding the rest of the articles (75%).

Data Analyses

We used the Comprehensive Meta-Analysis Version 3 (CMA v3; Borenstein et al., 2013) statistical software package to compute and analyze all the meta-analytic data, as follows:

Computing Effect Sizes

We calculated the effect sizes using Hedges's g, as the sample sizes in the included studies were mostly small (below 50) (Cohen, 2013; Hedges and Olkin, 2014). This metric is appropriate, as it corrects biases due to sample size (Cohen, 2013). The coefficient of Hedges's g represents the difference in means between the two groups relative to

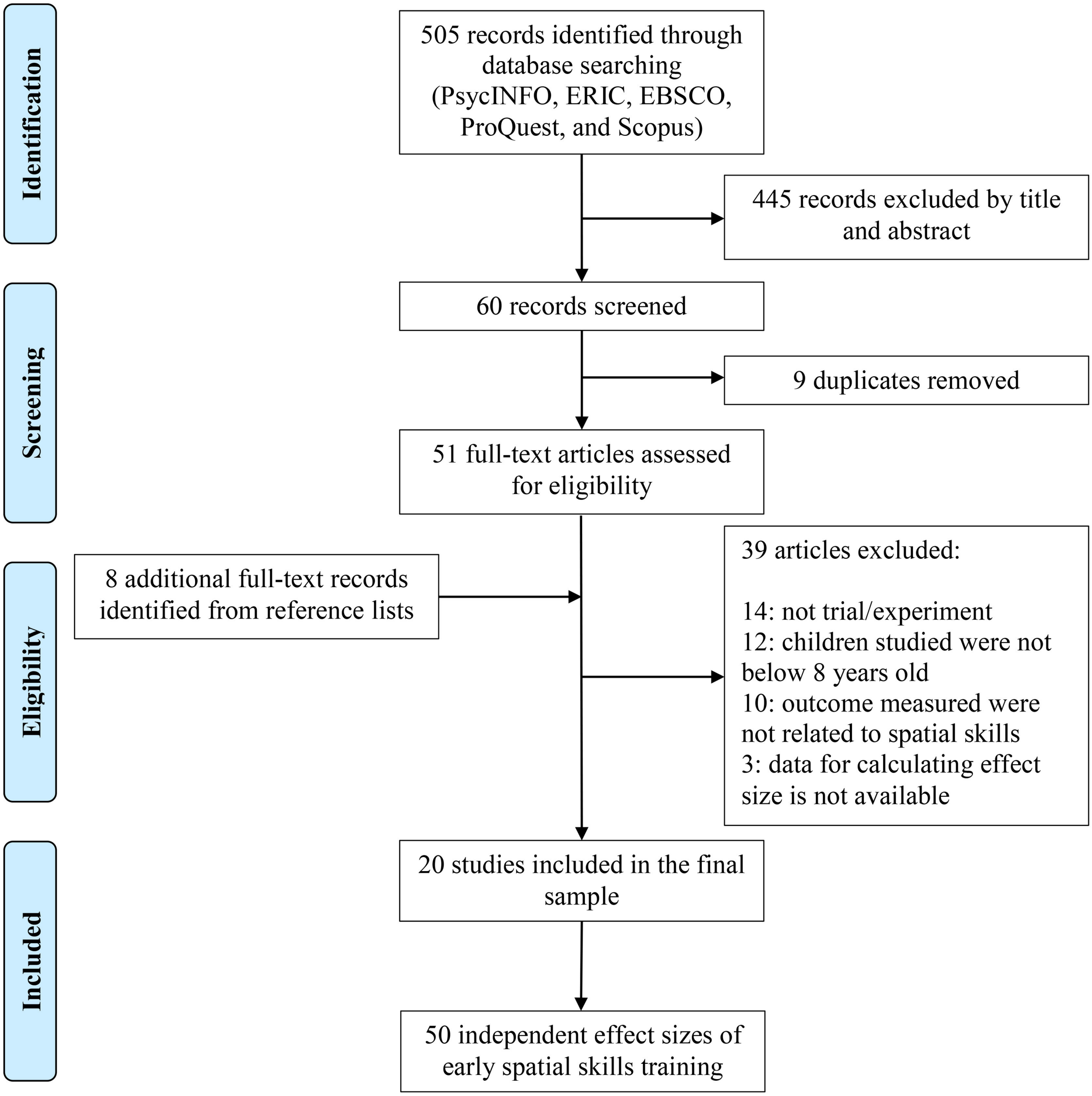

FIGURE 1 | PRISMA diagram of included studies in the meta-analysis.

the pooled and weighted standard deviation (Cohen, 2013). One effect size was calculated for each outcome category in each study.

Since the data for this meta-analysis were obtained from a series of published studies conducted by different people, it is unlikely that all studies are functionally identical (Borenstein et al., 2007, 2011). In this case, it is suggested that the random effects model is a more reasonable option for the meta-analysis (Borenstein et al., 2007, 2010, 2011). However, when the number of studies is small ($N < 10$), the variance estimate between the studies is usually low, so it is better to calculate the average difference according to the fixed effect model (Borenstein et al., 2010). Therefore, this meta-analysis used a random effects model to calculate the overall effect size and chose either the random effects approach ($N \geq 10$) or the fixed effect approach ($N < 10$) to calculate and compare the effect sizes across studies involving different categories of outcomes in the moderator analyses.

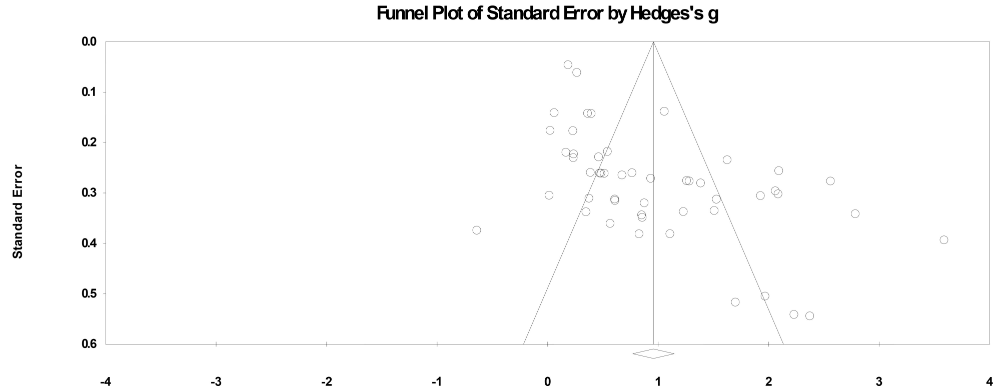

FIGURE 2 | Funnel plot of 50 effect sizes (Hedges' g) generated from included studies to measure for publication bias.

Publication Bias

We verified the possibility of publication bias using the trim-and-fill method and a funnel plot of standard error by Hedges's *g* (Duval and Tweedie, 2000). The trim-and-fill analysis only slightly reduced the estimated average effect sizes. The estimated mean values of the trim-and-fill analyses were all significantly different from zero. The results of the additional analysis did not find any variable that could be used as an alternative interpretation of the current results. In addition, a funnel plot was generated against the results to examine the effect size distribution relative to the sample sizes (see **Figure 2**). Since most of the studies were symmetrically distributed around the average effect size, there was little publication bias observed (Borenstein et al., 2009). Therefore, we report the combined results of the 20 studies and 50 effect sizes in this meta-analysis.

Analyzing Variance in Effect Sizes

We studied the variability of the effect sizes across studies through the heterogeneity test (Hedges and Olkin, 2014; Schmidt and Hunter, 2014; Cooper, 2016). We thus identified moderators that may not have been studied in a single experiment and that may affect the magnitude of the training effects (Cooper, 2016).

A heterogeneity test compares the variance shown by a set of effects with the assumed variance due to sampling error (Higgins et al., 2003; Cooper, 2016). If the heterogeneity test results indicate that the difference in a set of effects can be attributed only to the sampling error, then the data can be assumed to represent the population of participants (Hunter et al., 1982). We used the inter-group statistic, Q, to assess whether the group average effect is homogeneous (Yang et al., 2019). A statistically significant Q indicates that the grouping factor contributes to the variance in effect size; in other words, the grouping factor has a significant effect on the measurement of outcomes (Higgins et al., 2003).

RESULTS

Effects of Early Spatial Interventions

We meta-analyzed 20 intervention studies on spatial skills for children aged 0–8 years. There were 900 children in the training group and 635 children in the control group. **Table 2** presents the effect sizes and key characteristics of the included studies.

As shown in **Table 2**, previous studies used different types of training to promote young children's spatial skills, including video games, play, hands-on operation, classroom-based courses, and specific spatial tasks. Among the 20 intervention studies, 35% ($N = 7$) used video games, play, or hands-on operation for training; 35% ($N = 7$) used classroom-based courses; and 30% ($N = 6$) used specific spatial tasks. In terms of the setting where the training took place, 35% ($N = 7$) of training programs were conducted in a lab, with 35% ($N = 7$) conducted in the children's original classroom and 30% ($N = 6$) in other places such as another room in their preschool settings. All studies sampled children aged 0–8, with 15% ($N = 3$) of them being infants and toddlers (0–3 years) and 85% ($N = 17$) in early childhood (3–8 years). Study design and measurement of children's spatial skills also varied across studies, with details presented in **Table 2**.

Although publication biases always exist in any meta-analysis (Lipsey and Wilson, 1993) (see the funnel plot in **Figure 2**), the random effects analysis results revealed that the average effect size (Hedges's g) for training relative to control was 0.96 ($SE = 0.10$).

Moderator Analyses

We further analyzed the moderating effects of several study descriptors, including the type of study design, sex, age, outcome category (i.e., type of spatial skills), research setting (e.g., lab vs. classroom), and type of training. We used the Q statistic to assess the significance of the heterogeneity test in the effect size. **Table 3** presents the results of the moderator analysis of the effects of these six study descriptors on the spatial skills of the participating children.

As shown in **Table 3**, the type of study design [within subjects ($g = 0.328$) < between subjects ($g = 0.529$) < mixed ($g = 0.759$)], sex [girls ($g = 0.909$) > boys ($g = 0.686$) > mixed ($g = 0.499$)], and outcome category [generic ($g = 0.326$) < intrinsic, static ($g = 0.456$) < extrinsic, static ($g = 0.770$) < intrinsic, dynamic ($g = 0.952$)] were found to moderate the training effects. However, there was no significant difference in age, type of training, and research setting as related to children's spatial skills outcomes.

TABLE 2 | Effect sizes and key characteristics of studies included in the meta-analysis.

Study (year)	Training description	Training category[a]	Training setting[b]	*N* of children (T/C)	Effect size (Hedges's *g*)	Study design[c]	Outcome measure	Outcome category[d]	Age[e]	Sex[f]
Frick et al. (2009): overall		1	3 (school but not the original classroom)	32	0.311	1	Water tilting task	5	2	1, 2
Frick et al. (2009): treatment 1	Visibly executed movement in the water tilting task (manual tilting task)									
Frick et al. (2009): treatment 2	Seeing but not executing movement in the water tilting task (visible but regulated by means of remote control tilting task)									
Frick et al. (2009): treatment 3	Executing but not seeing movement in the water tilting task (blind tilting task)									
Frick et al. (2009): control	Not perceiving any movement in the water tilting task (static judgment task)									
Tzuriel and Egozi (2010): overall	Visuospatial representation and transformation program based on Quick Draws activities	2	2	60/56	0.582	3	PMA—Spatial Relations (SR) subtest; WT	2	2	1, 2
Ping et al. (2011): overall		1	1		2.066	3	CMTT; MROT	2	2	1, 2
Ping et al. (2011): treatment 1	Using gesture to rotate objects on a computer screen			22						
Ping et al. (2011): treatment 2	Turning a joystick to rotate objects on a computer screen			20						
Ping et al. (2011): control	No training			21						
Goldin-Meadow et al. (2012): overall	Performing a Move gesture as compared to observing a Move gesture	3	1	78/80	0.211	3	Mental transformation task (piece cards and choice card)	2	2	1, 2
Keren et al. (2012): overall	Playing with Kindergarten Assistive Robotics (KAR) through a musical game	1	2	9	1.539	1	Acquisition of spatial–motor knowledge measured using a metaphor of movement velocity	5	2	1, 2

(Continued)

TABLE 2 | Continued

Study (year)	Training description	Training category[a]	Training setting[b]	*N* of children (T/C)	Effect size (Hedges's *g*)	Study design[c]	Outcome measure	Outcome category[d]	Age[e]	Sex[f]
Nachtigäller et al. (2013): overall	Comprehending the preposition UNDER with six object sets, with the word UNDER embedded in a narrative context	3	1	20/20	0.386	3	Performance of the spatial relations UNDER and ON	3	1	1, 2
Chen et al. (2013): overall		2	3 (medical center)		0.655	3	TVPS-3	3	2	1, 2
Chen et al. (2013): treatment 1	Multimedia visual perceptual group training program			15						
Chen et al. (2013): treatment 2	Multimedia visual perceptual individual training program			15						
Chen et al. (2013): treatment 3	Paper visual perceptual group training			19						
Chen et al. (2013): control	No visual perceptual training			15						
Möhring and Frick (2013): overall	Manual exploration of the object	1	1	20/20	0.909	2	Mental rotation test (looking time)	2	1	1, 2
Henry et al. (2014): overall		2	3 (school but not the original classroom)		0.862	3	Odd One Out Span	1	2	3
Henry et al. (2014): treatment	10 min working memory intervention tasks, three times a week, for a total of 6 weeks			18						
Henry et al. (2014): control	Equal one-to-one attention but simpler versions of the tasks, with no requirement for memory storage			17						
Chabani and Hommel (2014): overall	Tangram problem solving with visual prompts	3	1	99/94	0.282	3	Tangram puzzles	5	2	1, 2
Frick and Wang (2014): overall	Acting upon the turntable themselves (self-turning condition)	1	1	14/14	0.091	2	Sensitivity to spatial object relations (mean looking times)	2	1	1, 2
Hawes et al. (2015): overall	Computerized mental rotation games (playing three games that were all housed within an application in iPad)	1	2	32/29	1.297	3	CMTT; Visual–Spatial Puzzle Task; tests of 2D and 3D mental rotation	2	2	1, 2
Metin and Aral (2016): overall	Project-based education for supporting visual perception	2	2	22/22	1.519	3	MVPT-3	3	2	1, 2

(Continued)

TABLE 2 | Continued

Study (year)	Training description	Training category[a]	Training setting[b]	*N* of children (T/C)	Effect size (Hedges's *g*)	Study design[c]	Outcome measure	Outcome category[d]	Age[e]	Sex[f]
Xu and LeFevre (2016): overall	Non-numerical spatial training (i.e., decomposition of shapes)	3	3	42/42	0.553	3	2D mental transformation task	2	2	1, 2
Hawes et al. (2017): overall	A 32-week teacher-led spatial reasoning intervention (i.e., geometry lessons and quick challenge spatial activities)	2	2	39/28	2.702	3	Spatial language test; visual–spatial geometry test; CMTT	2	2	1, 2
Borriello and Liben (2018): overall	Conversational instructions for guiding parents to engage their children in spatial play	1	1	19/22	0.496	2	Spatial language coded	5	2	1, 2
Levine et al. (2018): overall		3	3 (school but not the original classroom)		0.359	3	Mental transformation task (piece cards and choice card)	2	2	1, 2
Levine et al. (2018): treatment 1	Making a motor movement that is relevant to the mental transformation through action (concrete training)			41						
Levine et al. (2018): treatment 2	Making a motor movement that is relevant to the mental transformation through gestural movements (abstract training)			38						
Levine et al. (2018): control	Point-gesture training			35						
Yeterge et al. (2019): overall	Creative drama as an approach to sensory integration education	2	2	17/17	0.867	3	FVPT	1	2	3
Cornu et al. (2019): overall	A tablet-based visuospatial intervention, with many different tasks targeting different aspects of visuospatial skills	2	2	68/57	0.136	3	Spatial orientation measure adapted from FVPT; CMTT	1, 2	2	1, 2
Bower et al. (2020): overall	Constructing puzzles to match a model composed of various geometric shapes	3	3 (school but not the original classroom)		2.053	3	2D TOSA; 3D TOSA	2	2	1, 2
Bower et al. (2020): treatment 1	Giving modeling and feedback			46						
Bower et al. (2020): treatment 2	Giving gesture feedback			48						

(Continued)

TABLE 2 | Continued

Study (year)	Training description	Training category[a]	Training setting[b]	*N* of children (T/C)	Effect size (Hedges's *g*)	Study design[c]	Outcome measure	Outcome category[d]	Age[e]	Sex[f]
Bower et al. (2020): treatment 3	Giving spatial language feedback			47						
Bower et al. (2020): control	No feedback			46						

T, training group; C, control group; CMTT, Children's Mental Transformation Task; MROT, Mental Rotation Task; TVPS-3, Test of Visual Perception Skills, 3rd Edition; PMA, Primary Mental Abilities; WT, Windows Test; CMTT, Children's Mental Transformation Task; MVPT, Motor-Free Visual Perception Test, 3rd Edition; FVPT, Frostig Visual Perception Test; TOSA, Test of Spatial Assembly.
[a]1 = video game/play/hands-on operation; 2 = classroom-based course; 3 = spatial task training.
[b]1 = lab; 2 = classroom; 3 = others.
[c]1 = within subjects; 2 = between subjects; 3 = mixed.
[d]1 = intrinsic, static; 2 = intrinsic, dynamic; 3 = extrinsic, static; 4 = extrinsic, dynamic; 5 = measure that spans cells.
[e]1 = 0–3 years; 2 = 4–8 years.
[f]1 = female; 2 = male; 3 = not specified.

TABLE 3 | Heterogeneity tests of effect sizes (Hedges's g) for potential moderators.

Potential moderators	*Q*	*N*	*g*	*SE*
Study design[a]	61.830*			
Within subjects		5	0.328*	0.037
Between subjects		7	0.529*	0.126
Mixed		38	0.759*	0.041
Sex[a]	9.405*			
Girls		5	0.909*	0.143
Boys		5	0.686*	0.141
Not specified		40	0.499*	0.028
Age[a]	0.000			
0–3 years		5	0.518*	0.153
4–8 years		45	0.520*	0.027
Spatial skills outcomes[a]	111.263*			
Intrinsic–static		3	0.456*	0.145
Intrinsic–dynamic		31	0.952*	0.050
Extrinsic–static		5	0.770*	0.154
Measure that spans cells		11	0.326*	0.033
Research setting[b]	4.229			
Lab		17	0.690*	0.169
Classroom		19	1.158*	0.155
Others		14	0.989*	0.177
Type of training[b]	1.673			
Video game/play/hands-on operation		21	1.069*	0.156
Classroom-based course		17	0.993*	0.171
Spatial task training		12	0.752*	0.194

*N, number of effect sizes; SE, standard error; *p < 0.01.*
[a]Fixed effect approach is used for the moderator analysis of this variable.
[b]Random effects approach is used for the moderator analysis of this variable.

DISCUSSION

Although existing meta-analyses have demonstrated that spatial skills are malleable and can be improved by training (Baenninger and Newcombe, 1989; Uttal et al., 2013), none of them exclusively focuses on the effect of training on young children's spatial skills. To the best of our knowledge, this meta-analysis is the first attempt of its kind to systematically review and investigate the effects of spatial skills training in children aged 0–8 years.

Early Intervention Matters in the Development of Spatial Skills

This meta-analysis revealed that diverse training strategies or programs including hands-on exploration, visual prompts, and gestural spatial training could significantly foster young children's spatial skills. This finding demonstrated that young children's spatial skills could be significantly improved if they are given specific training, with an average effect size (Hedges's g) of 0.96 for training relative to control. The effect size obtained in the current meta-analysis is greater than the average effect (g = 0.47) indicated in Uttal et al.'s (2013) results. Therefore, our finding seems to support the argument that spatial skills, a kind of cognitive trait, are more malleable in the early years of life than the later stages such as adolescence and adulthood. However, this argument warrants further investigation, as only published papers are included in this meta-analysis, and publication bias may exist (Thornton and Lee, 2000).

The positive effect of early spatial skills training revealed in this study aligned with the theoretical links between action and cognition for understanding the underlying mechanism of effective early spatial training strategies or programs. According to Newcombe and Frick (2010), mental rotation and spatial perspective taking are the most crucial precursory forms of spatial skills in the early years, which are commonly related to motor development. Motor activities can thus facilitate children's performance in mental rotation and spatial perspective-taking tasks by engaging them in active movement (Newcombe and Frick, 2010). As found in the present meta-analysis, most of the effective spatial training used video games, play, hands-on exploration, spatial tasks, or classroom-based courses as the intervention or stimuli. What they have in common is that hands-on exploration, visual prompts, and gestures are used to support the process of actively practicing spatial skills in various activities (e.g., Frick et al., 2009; Borriello and Liben, 2018; Bower et al., 2020). It is possible that the engagement in manipulating visuospatial information would require the involvement of different neural processes. This could further shape the neural functioning related to spatial skills. However, the neural mechanism has not yet been thoroughly unveiled in spatial training studies and requires more future research to make sense of the positive effects of early intervention on children's spatial skills.

Differences in the Response to Training: Study Design, Sex, and the Category of Spatial Skills

Our results revealed that the type of study design, sex, and outcome category moderated the effects of early spatial skills training. However, the moderator analyses revealed that age, research setting, and type of training did not have a significant, moderating effect on the training outcomes. The combined effect sizes indicated that different groups of age, training settings, and training approaches did not generate significantly different effect in promoting young children's spatial functioning. These findings suggest that various approaches such as hands-on exploration, visual prompts, and gestural spatial training could all lead to improvements in spatial skills across different age groups in the early years. This aligns with theoretical arguments given by Ehrlich et al. (2006) that environmental input plays a crucial role in the development of spatial skills, even though biology also contributes to spatial skills.

As revealed in this meta-analysis, research setting did not play a moderating role; however, as argued by Klahr and Li (2005), there is an urgent need for studies on integrating cognitive research in laboratories with teaching in classrooms. A recent experimental study conducted by Hawes et al. (2017) provided empirical evidence that a classroom-based spatially enriched geometry course with a relatively long duration of 32 weeks could lead to young children's considerable progress in spatial skills. This research agenda requires more attention and endeavors, as our evidence indicated that classroom-based spatial skills training might be more effective ($g = 1.16 > 0.69$ in the laboratory setting). Below we further discuss the confirmed moderating factors.

Study Design

This meta-analysis revealed that the study design quality moderated the training effects. Although we only included studies using a (quasi-)experimental design, there are three different levels of quality regarding the rigor of design. The results showed that those experiments with both a within- and between-subjects design ($N = 38$) had the largest effect sizes regarding the training effect (average $g = 0.759$). However, it is unclear why within-subject comparison does not lead to a higher extent of positive training effect on average. There are two possible explanations. First, this may be caused by the effect of publication bias, as academic journals tend to be in favor of between-subject experimental research with more positive results (Song et al., 2010). Second, the existence of a control group seems to increase the effect sizes of training; therefore, we suggest that there could be negative effects brought by the lack of targeted spatial skills training for specific assessments. As this may be contradictory to the potential learning of test-taking strategies by children in the control group (Müller et al., 2012), more research is needed to directly investigate these claims regarding the effect in the control group such as practice effects in spatial skills assessments among young children.

Sex

Existing meta-analyses demonstrated that men outperform women on measures of mental rotation and spatial perception (Linn and Petersen, 1985; Voyer et al., 1995; Maeda and Yoon, 2013). The male performance advantage in spatial skills seems to start as early as infancy and early childhood (Levine et al., 1999; Moore and Johnson, 2008; Quinn and Liben, 2008). Our meta-analysis revealed that early spatial skills training would lead to greater effect for girls ($g = 0.909$) than boys ($g = 0.686$). Our finding supports the suggestion given by Newcombe and Frick (2010) that the integration of spatial learning opportunities into early childhood education could not only promote spatial skills in general but also reduce early sex differences that may impede female citizens' full participation in the current digital world. Such an encouraging consequence of introducing spatial skills training in early childhood settings further demonstrates that experiences with spatially enriched stimuli and activities would benefit children in their spatial cognition and reduce the sex differences in this cognitive trait (Baenninger and Newcombe, 1989; Moore and Johnson, 2008).

Category of Spatial Skills Assessment

This meta-analysis revealed that the category of spatial skills measures moderated the training effects. Results indicated that different categories of spatial tasks respond differently to training, with the mean weighted effect sizes for intrinsic–static, extrinsic–static, and intrinsic–dynamic kinds of assessment at 0.456, 0.770, and 0.952, respectively. The moderating role of the kinds of spatial skills assessment is consistent with the result revealed in Uttal et al.'s (2013) meta-analysis. However, in the early years, children tended to perform better in mental rotation as featured in the intrinsic–dynamic category of assessment instead of the extrinsic–static category. Although our finding seems to align with an extensive body of literature that records infants' and young children's performance in mental rotation tasks (e.g., Moore and Johnson, 2008; Frick and Wang, 2014; Lehmann et al., 2014), more direct research is needed to ascertain what the exact differences of effects are when measuring children's spatial skills using different assessments.

Limitations of This Meta-Analysis

One of the limitations of our meta-analysis is that as the number of studies involved is relatively small, the effect sizes across studies are considerably heterogeneous. The variance in effect size may explain why heterogeneity between groups is not significant for the results of moderator analyses of certain research descriptors (e.g., type of training and research setting). Although the publication biases were shown to be acceptable using the trim-and-fill method, the generalization of our findings to other contexts and populations should be conducted with caution due to the small number of eligible studies included. Moreover, only published English papers were included in this meta-analysis due to the inaccessibility of other types of articles. This may have led to biases in our meta-analysis because studies reporting a significant impact are more likely to be published than studies not reporting statistical significance (Rosenthal, 1979).

Also, our moderator analyses did not cover the factors of SES, initial level of performance on spatial tasks, and intervention duration. The included studies reported that their participants were from families of diverse socioeconomic backgrounds; therefore, we were not able to analyze the moderating effect of SES in the current meta-analysis. Although this meta-analysis attempted to control study design, it was still unable to adequately capture or control certain variables, such as trainers' qualifications and the duration of training, because these variables were not clearly reported in the included studies.

Last but not least, this meta-analysis did not include non-experimental research as well as those studies on transfer effects of spatial skills training to untrained tasks. The current meta-analysis only included studies examining the relationship between training programs and the development of spatial skills. However, meta-regression can also be used to examine the relationship between spatial training and children's spatial skills and other related outcomes (e.g., math skills, scientific task performance, and executive function), so that correlational studies can be meta-analyzed. Correlational studies may be valuable for exploring the complex behavioral and neural mechanisms behind the training effect. Subsequent qualitative systematic reviews or meta-regression analyses of the processes and mechanisms through which early spatial skills can be enhanced would be of great importance.

Implications for Research, Policy, and Practice

Our research contributes to the literature in the field of spatial thinking by showing whether and how early intervention approaches and programs can promote young children's spatial functioning through meta-analytic evidence. Our meta-analysis thus expands this line of research on the malleability of spatial skills in the early years and provides the following implications for future research, policy-making, and practice in early childhood education.

First, early spatial intervention matters. Our evidence indicated that the malleability of spatial skills is stronger in younger children, as compared to the average effect size ($g = 0.47$) found in the general population (Uttal et al., 2013).

Second, a spatially enriched curriculum should play a more vital role in early childhood education via the integration of effective practices such as spatial play (block building) and purposeful use of visual and verbal cues. This is also supported by our evidence that classroom-based spatial skills training is more effective ($g = 1.16$) than laboratory-based training ($g = 0.69$). To implement effective spatially oriented curricula in early childhood settings, more specific research is needed to design, implement, and evaluate classroom-based spatial training programs for young children.

Third, as linked to the previous implication, both early childhood policymakers and practitioners should consider scaling up effective classroom-based spatial training. Publicity and promotion require not only more research endeavors but also initiatives in policy and practice so as to bridge the gap between the laboratory environment and authentic learning settings and foster early spatial skills among children from diverse backgrounds, especially those placed in socially disadvantaged environments such as poverty and adverse parenting practices.

Fourth, to support children with difficulties in spatial functioning, spatially relevant game tasks can be used. For instance, visuospatial representation and transformation activities based on Quick Draws (Tzuriel and Egozi, 2010), playing with robotics (Keren et al., 2012), rotating objects on mobile devices or computers (Ping et al., 2011; Hawes et al., 2015; Cornu et al., 2019), and tangram-related activities (Chabani and Hommel, 2014) are shown to significantly foster young children's spatial skills. Moreover, adult educators such as teachers and parents can provide children with more opportunities of manual exploration of the object, such as building blocks (Möhring and Frick, 2013), and intentionally give various types of feedback (e.g., modeling, gesture feedback, and spatial language feedback) during spatially relevant activities (Bower et al., 2020). Some early interventions such as a multimedia visual perceptual individual training program (Chen et al., 2013) and spatial reasoning intervention including geometry lessons and quick challenge spatial activities (Hawes et al., 2017) can also be provided. However, more studies are needed to explore how to tailor spatial training programs to the specific abilities and disabilities of individual children.

Fifth, as early spatial skills training is demonstrated to more effectively enhance girls' spatial functioning and minimize the male advantage in this aspect, girls should be given the priority to engage in spatially enriched experiences.

Last but not least, more future research is warranted to explore the behavioral and neural mechanisms underlying the effects of spatial training in the early years. Two aspects should be focused on: study design and assessment. On the one hand, future research should draw upon a more rigorous design using randomized controlled trials and even a longitudinal design to investigate the training effects in the long run. One the other hand, there is an urgent need to conduct specific research on measuring children's spatial skills using different assessments. Moreover, how the improvement of early spatial skills may be linked to fostering other core skills such as numeracy, math reasoning, early writing skills, and executive functions can be explored in the future.

CONCLUSION

This meta-analysis supports the notion that effective spatial learning components could be infused into early childhood settings, so as to spatialize the curriculum and encourage children learn to think spatially (Newcombe and Frick, 2010; Bruce et al., 2015). To implement effective spatially oriented curricula in early childhood settings (Newcombe and Frick, 2010; Uttal and Cohen, 2012), early childhood researchers, policymakers, and practitioners should work together to intentionally support children's hands-on, proactive manipulation and processing of spatial information. The US National Research Council (2006) has released a national report to call for a curriculum and support system for spatial thinking in the K-12 educational context. Taking off from this research and policy achievement, high-quality, evidence-based, contextually appropriate spatial curricula should also be developed and provided for children to promote their spatial intelligence and help them become better prepared for the high-tech world.

AUTHOR CONTRIBUTIONS

WY designed the research and drafted the manuscript. WY, HL, NC, and PX collected and extracted data for analysis. XL provided important ideas and substantial feedback for the study and edited the manuscript. All of the authors read and approved the final manuscript.

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Effect of Finger Gnosis on Young Chinese Children's Addition Skills

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Evidence has revealed an association between finger gnosis and arithmetic skills in young Western children, however, it is unknown whether such an association can be generalized to Chinese children and what mechanism may underlie this relationship. This study examines whether finger gnosis is associated with addition skills in young Chinese children and, if so, what numerical skills could explain this correlation. A total of 102 Chinese children aged 5–6 years were asked to complete finger gnosis and addition tasks in Study 1. Results showed that finger gnosis was significantly associated with addition performance. However, no significant correlation was found between finger gnosis and the use of finger counting in solving addition problems. Moreover, girls' finger gnosis was better than boys', and children with musical training demonstrated better finger gnosis than those without. In Study 2, 16 children with high finger gnosis and 20 children with low finger gnosis were selected from the children in Study 1 and asked to perform enumeration, order judgment, number sense, and number line estimation. Children with high finger gnosis performed better in number line estimation than their counterparts with low finger gnosis. Moreover, the number line estimation fully mediated the relationship between finger gnosis and addition performance. Together, these studies provide evidence of a correlation between finger gnosis and addition skills. They also highlight the importance of number line estimation in bridging this association.

Keywords: finger gnosis, addition skills, number line estimation, young children, the addition strategy

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INTRODUCTION

Finger use for math calculations is natural and intuitive (Jordan et al., 2008). A large body of research has found that fingers (e.g., finger gnosis, finger tapping, and finger counting) play an important role in arithmetic processing (e.g., Noël, 2005; Gracia-Bafalluy and Noël, 2008; Costa et al., 2011; Lafay et al., 2013; Crollen and Noël, 2015b; Soylu and Newman, 2016). Finger gnosis, also termed "finger sense" or "finger schema" (Penner-Wilger and Anderson, 2008), is defined as the ability to identify fingers without visual involvement. Emerging evidence has suggested an association between finger gnosis and arithmetic skills in young Western children, however, it is not clear whether such an association can be generalized to Chinese children and what mechanisms may underlie this relationship. In this study, we examine the correlation between finger gnosis and addition skills in young Chinese children and the mechanism underlying this relationship.

Findings supporting the relationship between finger gnosis and arithmetic skills have originated from cross-sectional, longitudinal, training, and neuropsychological studies in young Western children (e.g., Rusconi et al., 2005; Costa et al., 2011; Reeve and Humberstone, 2011;

Crollen and Noël, 2015b). For instance, Fayol et al. (1998) found that scores on a neuropsychological battery of somatosensory integrity of the sensory cortex, which included a finger gnosis test, represented a longitudinal predictor of arithmetic performance in 5–6-years-old children in France. Based on a longitudinal sample of first graders in Belgium, Noël (2005) reported that finger gnosis predicted numerical performance (including later addition, subitizing, number writing and digit comparison, collection comparison, and finger counting) 1 year later. Penner-Wilger et al. (2007) discovered that finger gnosis directly predicted number system knowledge and indirectly predicted calculation skills in Canadian first graders; they speculated that children with high finger gnosis solve mathematics problems by using their fingers as representational tools. Reeve and Humberstone (2011) explored the relationship between non-motoric finger gnosis, which does not involve motor movement (e.g., pointing), and single-digit addition operations in 5–7-years-old Australasian children. Their findings provided direct evidence for the importance of measuring non-motoric finger gnosis when predicting arithmetic ability. An electrostimulation study of Gerstmann syndrome (Roux et al., 2003) found that electrostimulation in the angular gyrus, supramarginal gyrus, or close to the intraparietal sulcus produced disturbances in finger recognition and calculation abilities. This finding suggests that finger gnosis and arithmetic calculation may share common neural mechanisms. Similarly, a functional magnetic resonance imaging study by Andres et al. (2012) revealed that finger discrimination and mental arithmetic induced a similar pattern of parietal activity in adults.

Recently, several researchers (Poltz et al., 2015; Long et al., 2016; Wasner et al., 2016) have reported that the magnitude of the correlation between finger gnosis and arithmetic skills might be smaller than previously assumed. For example, Poltz et al. (2015) found that the correlation of finger gnosis with numerical abilities (numerals knowledge, counting skills, and calculation) was weaker than its correlation with non-verbal intellectual ability in German preschool children. Similarly, Wasner et al. (2016) recruited a sample of German first graders (mean age: 6.47 years) and found that finger gnosis predicted a unique and relevant but only a small proportion (1–2%) of the variance in arithmetic performance beyond a pool of general cognitive abilities and numerical precursor competencies.

Moreover, in a study with Australasian first and second graders, Long et al. (2016) found no meaningful association between finger gnosis and either counting or arithmetic skills after controlling for the effects of age, however, participants were from primary schools. For younger children who have not entered primary school, finger gnosis may play a more critical role because it helps them to construct the counting system and acquire number concepts. By contrast, the importance of finger gnosis could decline after children enter primary school because finger use is often regarded as an inefficient strategy at this level. For instance, a longitudinal study by Jordan et al. (2008) examined changes in the frequency of finger use in learning number combinations from the beginning of kindergarten (mean age = 5.7 years) to the end of second grade. Finger use was found to be most adaptive when children were first learning number combinations in kindergarten, but this benefit lessened over time. Indeed, in the study by Long et al. (2016), finger gnosis correlated moderately with the arithmetic ability (r = 0.43). However, once age was controlled, the relationship between finger gnosis and calculation ability became negligible, accounting for just 1.4% of the variance, suggesting the importance of age in the correlation between finger gnosis and arithmetic ability. Hence, we can speculate that the disassociation between finger gnosis and addition skills in Long et al. (2016) may be due to children's less frequent use of a finger strategy in solving arithmetic problems after entering primary school.

Contrary to our speculation, Newman (2016) studied a sample of US children and found that the association between finger sense and addition skills did not exist in the younger group (5–8-years-old children) but in the older group (9–12-years-old children). However, Newman's study had a number of critical limitations, such as small sample size (N = 34) and a timed addition test that was extraordinarily difficult for 5–8-years-old children (i.e., the accuracy rate was approximately 50% on average for this age group). Hence, Newman's finding remains to be verified with a larger sample and by adopting more appropriate tasks.

Overall, most studies have suggested a relationship between finger gnosis and arithmetic skills in young Western children, although a few studies have indicated that this correlation may not be strong. Scholars have also expressed interest in the mechanisms underlying the association between finger gnosis and arithmetic skills. Three explanations have dominated the field to this point.

First, *the functionalist explanation* asserts that the correlation between finger representation and mathematical ability is due to children's experience and development. The link between finger gnosis and math ability formed experientially throughout normal development to represent quantities and perform counting and arithmetic procedures (Butterworth, 1999). Gracia-Bafalluy and Noël (2008) argue that their study can provide support for the functional link between finger gnosis and number skills in a training study. After the finger training, which consisted of 2 weekly sessions of 30 min each for 8 weeks, children with poor finger gnosis performed significantly better than those in the control group on finger gnosis, representation of numerosities with fingers, and quantification tasks. These results indicate that improving finger gnosis can provide useful support for learning mathematics.

Second, *the localizationist explanation* posits that the association between finger gnosis and mathematical ability is caused by adjacent brain areas in the parietal lobe that are responsible for the two skills (Dehaene et al., 2003). Simon et al. (2002) found that regions in the human parietal cortex activated for calculation are adjacent to those for grasping and pointing.

Third, *the redeployment explanation* suggests that finger gnosis is associated with mathematical ability because of an overlap between the functional representations of fingers and mathematics (Penner-Wilger and Anderson, 2008). Specifically, one of the functional circuits originally evolved for finger representation is redeployed to support number representation and finally serves both functions. By comparing functional neuroimaging data across cognitive domains, Penner-Wilger and Anderson (2011) identified a region within the left precentral gyrus contributing to finger gnosis and number representation. With a variety of number and finger tasks, functional imaging studies have consistently shown overlapping activation in parietal regions (Andres et al., 2007, 2012). In a series of experiments, Rusconi et al. (2005) found that rTMS over the left angular gyrus disrupted magnitude comparison and finger gnosis in adults, implying that a common neural substrate exists between number and fingers. Using direct cortical stimulation, Roux et al. (2003) identified a site in the left angular gyrus that produced acalculia and finger gnosis.

A careful inspection of the three explanations suggests that they are not mutually exclusive. Specifically, *the redeployment explanation* is actually an integration of functionalism and localism. Close or overlapping neural foundations of finger gnosis and arithmetic skills are the common emphases of the redeployment and localizationist views. Dynamic cognitive use shaped by experience and development is the common emphasis of the redeployment and functionalist views. In this sense, Penner-Wilger and Anderson (2013) suggest that it is difficult to distinguish between redeployment and functionalism. For example, two dual-task studies have revealed that finger movements interfere with addition (Michaux et al., 2013; Soylu and Newman, 2016), which can provide support for both the redeployment and functionalism views.

The purpose of the present study is twofold. First, we seek to examine whether an association between finger gnosis and addition skills exists in young Chinese children. So far, it is unknown whether the correlation identified between finger gnosis and addition skills in Western children can be generalized to Chinese children. Chinese children tend to use a culturally unique one-hand-finger-counting strategy. They often count 1–5 on the right hand in a way that is familiar to their peers in North America and most European countries. However, they usually count 6–10 using symbolic sign gestures continued on the same hand (Domahs et al., 2010; Morrissey et al., 2016). Finger counting is inherently time-consuming, so using symbolic sign gestures to represent 6–10 may be beneficial for children to acquire a flexible representation of fingers. As Reeve and Humberstone (2011) proposed, finger gnosis may develop through two stages: (1) acquisition of a flexible representation of fingers and (2) a flexible ability to use fingers as a cognitive tool in number cognition. Young Chinese children's flexible representation of fingers may exert a positive role in their addition skills before they enter primary school. Therefore, we hypothesized that there was a significant association between finger gnosis and addition skills. Studying such an association may provide further evidence for the importance of finger gnosis in children's arithmetic development in a culture different from the West.

To accomplish the first objective, the present research offers one improvement over prior work. We explore the correlation between children's finger gnosis and their use of a finger-counting strategy in solving addition problems. Finger counting plays an important role in early mathematical calculation skill development (Moeller et al., 2012). It differs from other strategies such as memory retrieval, verbal counting, and decomposition (e.g., Siegler, 1999) in that it provides preliminary and grounding sensorimotor experiences for children's perceptions of quantities. Moreover, finger counting is conducive to representing and executing quantities, which accelerates the transition between early non-verbal representations and traditional symbolic representations. Studies have shown that finger counting could bridge an accurate correlation between number combination and its solution (e.g., Siegler and Shipley, 1995; Jordan et al., 2008). Scholars have also found that the use frequency of a finger-counting strategy in preschool and first-grade children is positively correlated with addition performance (e.g., Jordan et al., 1994, 2008; Roesch and Moeller, 2015). Based on previous studies (e.g., Penner-Wilger et al., 2007), we hypothesize that finger gnosis is correlated with finger counting.

The second purpose is to explore whether basic number processing mediates the relationship between finger gnosis and addition skills. Most studies have examined the direct link between finger gnosis and arithmetic skills; to the best of our knowledge, only one study (Penner-Wilger et al., 2007) has explored the indirect link between finger gnosis and arithmetic skills. The study revealed that finger gnosis had an indirect effect on arithmetic skills via the mediating role of children's number system knowledge, which included counting, ordering, recognizing numerals, sequencing, and place value (Penner-Wilger et al., 2007). However, it is unclear whether other number processing abilities could mediate the link between finger gnosis and arithmetic skills. Previous studies have shown that children's mathematical achievements are closely associated with their number processing abilities, including enumeration (e.g., Hannula-Sormunen et al., 2015), numerical ordering (e.g., Lyons and Beilock, 2011), number sense (e.g., Halberda et al., 2008; Mazzocco et al., 2011; Starr et al., 2017), and number line estimation (e.g., Siegler and Booth, 2004; Muldoon et al., 2013; Bos et al., 2015). In the present research, we explore whether the association between finger gnosis and addition skills is mediated by number processing abilities, including enumeration, number ordering, number sense, and number line estimation. Compared with Penner-Wilger et al. (2007), we expanded the number system knowledge by including number sense and number line estimation. Although it is theoretically important to examine the differential roles of finger gnosis in multiple domains of arithmetic operations (addition, subtraction, multiplication, and division) that involve very different strategies (Zhou et al., 2011), the present research focused solely on addition skills.

To address the discussed objectives, we examined whether finger gnosis was associated with young Chinese children's addition skills and the use of a finger-counting strategy in solving addition problems in Study 1. We tested whether the relation between finger gnosis and addition skills could persist after controlling for the child's sex and experience of playing musical instruments. Previous research has shown that men performed more quickly and regularly than women in finger tapping (e.g., Nicholson and Kimura, 1996; Schmidt et al., 2000; Prigatano et al., 2008). There is also evidence showing that children who played musical instruments (e.g., piano or guitar) performed better on finger gnosis tests and numerical tasks than children who did not (Gracia-Bafalluy and Noël, 2008). We, therefore, included the child's sex and musical training experience as control variables in the present research. In Study 2, we further examined whether children's numerical abilities mediated the relationship between finger gnosis and addition skills.

STUDY 1

Materials and Methods

Participants

Participants were 111 children recruited from the affiliated kindergarten of a university in Southwest China. Nine children were excluded because they did not complete all tests; thus, 102 children (51 boys and 51 girls) were included in the analysis. Their ages ranged from 60 to 83 months ($M = 67.68$, $SD = 4.59$ months). Among these children, 45 children reported that they were playing musical instruments such as piano, guitar, and flute. Children received stickers after each round of testing. Parents were asked to give their written consent to their child's participation in advance. The study procedure was approved by the Institutional Review Board of Southwest University and complied with the ethical guidelines of the American Psychological Association.

Procedures and Measures

Children completed the finger gnosis task first and then the addition task on an individual basis in a sound-attenuated room.

Finger gnosis

The finger gnosis task was adapted from Gracia-Bafalluy and Noël (2008) and Reeve and Humberstone (2011). Each child sat facing the experimenter and placed his/her hand palm-down in a special box on a table with fingers spread. The box was open on the experimenter's side with a 10 × 4 cm hole on the child's side. The hole was large enough for the child to put his/her hand through but small enough for the child not to be able to see his/her hand. In each trial, the experimenter gently touched the child's fingernail(s) with a fingertip and then removed the box and asked the child to identify which finger or fingers had been touched. The test consisted of two parts. The first part was administered on each child's dominant hand (i.e., the hand the child used to write), and the second part was on the non-dominant hand. Each part consists of three blocks. In the first block, the experimenter touched only one finger, and each finger was touched twice (i.e., 5 × 2 = 10 trials). In the second block, the experimenter touched two fingers simultaneously, and each finger was touched twice (i.e., five trials). In the third block, the experimenter touched two fingers successively, and each finger was touched twice (i.e., five trials). Therefore, 40 trials were presented in total (i.e., 20 trials each for the dominant and non-dominant hand). Finally, the number of correct trials was computed as the performance in the finger gnosis task.

Addition task

The addition task contained 30 addition problems in which the addends varied from 2 to 7. Twenty-two problems had sums up to 10 (e.g., 3 + 7), and the remaining eight problems had sums ranging from 11 to 13. No problems had identical addends (e.g., 2 + 7 and 7 + 2). Each addition problem was presented visually in a card. Each child accepted a given order of the problems and was presented with one problem at a time. Children were allowed to use his/her fingers or count aloud to solve each problem. No time limit was instituted on the problems.

Children's addition performance was indexed by accuracy (i.e., the percentage of problems solved correctly). To measure strategy use, the experimenter observed the children closely and recorded any overt signs of strategy use (e.g., counting aloud, silently moving lips, or using fingers) in solving each of the 30 problems. In the absence of overt behaviors, the experimenter asked the child how he or she had "figured [the problem] out." Overt behavior and verbal explanations were each used to determine the strategy a child used to solve each problem. Based on previous studies (e.g., Rittle-johnson and Siegler, 1999; Laski et al., 2013), five strategies were coded: finger counting, oral counting, retrieval, decomposition, and other. A strategy was categorized as retrieval if the child reported that he or she "just knew" the answer, and the response speed was relatively fast compared with other strategies. A strategy was categorized as "other" when the child said "I don't know" or reported having guessed the answer. The retrieval strategy involves recalling the solution to an arithmetic problem from memory. Decomposition involves decomposing a problem into simpler problems; for example, to solve 5 + 7, a child might first add 5 + 5 to get 10 and then add two to arrive at 12. Four experimenters, who did not know our research hypotheses, coded children's strategies. Before coding, they were trained about how to assign one of five possible codes to addition problems. As long as they were not sure about how to code one problem, the researchers and four coders discussed carefully together and then gave a final code.

Statistical Analysis

We first conducted a series of 2 (sex: boy vs. girl) × 2 (musical training: yes vs. no) analysis of variance (ANOVA) tests to examine sex and musical training differences in finger gnosis and addition skills. In these ANOVAs, sex and musical training were the between-subjects variables with age as a covariant; finger gnosis, addition accuracy, and frequency of each strategy were the dependent variables. We then carried out zero-order correlations and multiple regressions to evaluate whether finger gnosis was associated with children's addition performance and strategy use. All data analyses were conducted in SPSS 21.0.

Results

Results of the 2 × 2 ANOVAs with age as a covariant showed that the main effect of sex on finger gnosis was significant, $F(1, 102) = 9.23$, $p = 0.003$, $\eta^2 = 0.087$, Cohen's $d = 0.53$, with lower finger gnosis in boys than in girls. The main effect of musical training was also significant, $F(1, 102) = 4.72$, $p = 0.032$, $\eta^2 = 0.046$, Cohen's $d = 0.47$. Children who had musical training performed better on finger gnosis than those with no musical training. No significant interaction effect was observed between sex and musical training ($p = 0.447$).

In addition, a significant sex main effect was observed in the use of retrieval strategies, $F(1, 102) = 6.07$, $p = 0.016$, $\eta^2 = 0.059$, Cohen's $d = 0.54$. Boys tended to use retrieval strategies more frequently than girls. No significant main effect of musical training or interaction effect was observed between sex and musical training ($ps > 0.928$). Analyses of addition accuracy

TABLE 1 | Descriptive statistics in Study 1.

	Sex				Experience of playing musical instruments				Total	
	Boy		Girl		Yes		No			
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Finger gnosis	75.01	11.55	80.86	10.94	80.89	12.03	75.61	10.65	77.94	11.53
Addition accuracy	76.88	26.30	76.29	22.69	80.00	24.80	73.89	24.03	76.59	24.44
Finger counting	36.86	36.08	49.61	37.86	44.03	36.06	42.22	39.31	43.23	37.35
Oral counting	16.41	24.67	25.56	34.35	22.92	30.98	18.52	29.13	20.98	30.11
Retrieval	25.82	30.39	11.96	20.34	17.60	23.70	20.52	30.18	18.89	26.66
Decomposition	4.18	9.63	1.83	4.28	2.16	4.52	4.07	10.07	3.01	7.51

Legend for finger gnosis and addition accuracy is the percentage of correct trials (%); legend for each strategy is the percentage of using the strategy (%).

TABLE 2 | Correlations among the variables in Study 1.

	1	2	3	4	5	6	7
1. Finger gnosis	–						
2. Addition accuracy	**0.346****	–					
3. Finger counting	0.063	−0.042	–				
4. Oral counting	0.167	0.161	**−0.513*****	–			
5. Retrieval	−0.010	**0.395****	**−0.533*****	−0.066	–		
6. Decomposition	0.030	0.254 ∗∗	−0.286 ∗∗	−0.062	**0.327****	–	
7. Child age	0.277**	**0.341*****	−0.032	−0.076	0.217*	**0.300****	–

*Correlations that are significant after Bonferroni–Holm correction for multiple testing (alpha = 0.05/21 is 0.0024) are indicated in boldface. *p < 0.05. **p < 0.01. ***p < 0.001.*

and the other three strategies showed no significant main effects of sex or musical training or interaction effects between sex and musical training ($ps > 0.111$). Descriptive statistics are listed in **Table 1**.

We also analyzed correlations between finger gnosis and addition skills and strategies. We only considered correlations that remained significant after applying Bonferroni–Holm corrections for multiple tests (resulting in a reduced alpha = 0.05/21 or 0.0024). Correlations are presented in **Table 2**. Addition accuracy was significantly correlated with finger gnosis as well as the child's age and use of retrieval and decomposition strategies. However, the use of a finger-counting strategy did not correlate with finger gnosis but correlated negatively with the use of oral counting and retrieval strategies.

Finally, we conducted multiple regressions to examine whether finger gnosis was associated with addition accuracy after controlling for the child's age and the use of a retrieval strategy. Results are shown in **Table 3**. Finger gnosis significantly predicted addition accuracy even after controlling for covariates. The proportion of variance in addition accuracy explained by finger gnosis was 7.7%.

TABLE 3 | Regression model predicting addition accuracy.

	Addition accuracy				
	B	*SE*	β	*t*	*P*
Use frequency of retrieval strategy	0.329	0.079	0.359	4.15	0.000
Finger gnosis	0.635	0.186	0.300	3.41	0.001
Age	0.952	0.475	0.180	2.00	0.048

Discussion

Consistent with our hypothesis, a positive correlation was found between finger gnosis and addition skills in 5–6-years-old Chinese children. Furthermore, finger gnosis explained a unique and substantial proportion of variance in addition performance after controlling each child's age, sex, experience of musical training, and strategy use. These findings provide evidence for the close association between finger gnosis and young Chinese children's addition performance. Unexpectedly, children's use of a finger-counting strategy in solving addition problems was not associated with finger gnosis and children's addition performance. We went on to examine the possible mechanism underlying the close association between finger gnosis and addition performance in Study 2, such as number processing abilities.

This study also observed sex differences in finger gnosis; girls demonstrated better finger gnosis than boys. Experience playing musical instruments was also found to be related to finger gnosis, with children who had more musical training demonstrating better finger gnosis. The use of retrieval strategies also revealed a sex difference, indicating that boys were more likely to use retrieval strategies than girls. We discuss these findings further in section "General Discussion."

STUDY 2

Study 2 aimed to examine the roles that basic number processing abilities play in explaining the correlation between finger gnosis and children's addition skills. To this end, we conducted four basic number processing tests, namely the enumeration task, the number sense task, the order judgment task, and the number line estimation task.

Materials and Methods

Participants

Based on children's finger gnosis scores in Study 1, two groups of children were selected for participation in Study 2. One group had high finger gnosis and included 7 boys and 13 girls (top 20%; accuracy ranging from 0.87 to 0.97). Their ages ranged from 61 to 78 months (M = 70.30, SD = 4.37 months). The other group had low finger gnosis and included 10 boys and 6 girls (bottom 20%; accuracy ranging from 0.42 to 0.67). Their ages ranged from 61 to 75 months (M = 66.63, SD = 4.80 months). For the low finger gnosis group, 20 children were selected initially, but 4 did not complete all tasks; thus, 16 children were analyzed. The ratio of boys to girls in the two groups did not differ significantly, $\chi^2(1) = 2.697$, $p = 0.101$. An independent sample t-test revealed a significant difference in finger gnosis between the two groups, with higher accuracy for the high finger gnosis group (M = 0.91, SD = 0.03) than for the low finger gnosis group (M = 0.62, SD = 0.07), $t(35) = -15.808$, $p < 0.001$.

Procedure and Materials

Four computerized tasks were administered to the children in Study 2. Three tasks (enumeration, number sense, and number line estimation) were administered online[1]. The children completed all tasks individually in a sound-attenuated room while facing a computer screen from a distance of approximately 60 cm. The experiment included two sessions: in the first, children finished the enumeration and order judgment tasks in random order; in the second, they completed the number sense and number line estimation tasks in random order. The entire experiment was compiled using E-prime.

Enumeration task

The stimuli were displayed on a computer screen with black dots (1 cm in diameter) distributed randomly in the central screen box (10 × 10 cm). The number of black dots in the box varied from 1 to 6. The dots were repeated five times, resulting in 30 trials. Each trial was presented randomly. In each trial, the black dots were displayed for 300 ms after a fixation point "+" was presented for 500 ms. Children were instructed to orally state the number of black dots quickly and accurately, and the experimenter helped each child press the corresponding number response. Each child completed six practice trials before the formal experiment. The proportion of problems solved correctly indexed children's performance.

Order judgment task

This task was adapted from Turconi et al. (2006). The display shown in each trial consisted of a pair of single-digit Arabic numbers ranging from 1 to 9, one on the left and one on the right of the screen. Eight quantity combinations were presented, including those with far distance (2–5, 3–6, 4–7, and 5–8) and those with close distance (2–3, 3–4, 6–7, and 7–8). All pairs were presented in ascending (e.g., 2 3) and descending order (e.g., 3 2), resulting in 16 pairs. Each pair was repeated four times, resulting in a total of 64 trials, and divided into two blocks. In each trial, the fixation "+" was first presented for 500 ms followed by two numbers. The numbers remained on the screen until a button was pressed. The intertrial interval was 500 ms. Children were asked to read the two numbers from left to right and judge whether the number pair was in the "correct" (i.e., ascending from left to right) or "incorrect" counting order. In one block, children were asked to press "F" with their left index finger if the numbers were in the correct order and "J" with their right index finger if the numbers were not. In the other block, the assignment of response keys was reversed with the "J" key representing a correct order and the "F" key representing an incorrect order. Before the formal experiment, there were eight practice trials. The proportion of problems solved correctly indexed children's performance.

Number sense task

The non-symbolic magnitude comparison adapted from Ginsburg and Baroody (1990) was used to assess children's number sense. Children were asked to estimate (without counting) which of the two sets of dots, presented simultaneously on the screen, contained more dots (36 trials, 5 s per trial). The number of dots varied from 5 to 12, and the ratios were 2:3, 5:7, and 3:4. Dots differed in size, but the total combined area of all dots in each set was controlled to be the same. Children were required to press the "Q" key with their left index finger when there were more dots on the left or press the "P" key with their right index finger when there were more dots on the right. The proportion of problems solved correctly indexed children's performance.

Number line estimation task

This task was adapted from Booth and Siegler (2006). Children were instructed to locate 26 numbers in the number axis (range: 0–100). Each number was presented only once. In each trial, a horizontal line appeared on the screen with the left endpoint labeled "0" and the right endpoint labeled "100." Each child was required to either mark the presented number position on the 0–100 axis with the mouse or point to the location with his/her finger (some children could not use the mouse). This task had no time limit. Each number appeared on the left side above the line. The 26 numbers presented were 3, 4, 6, 8, 12, 14, 17, 18, 21, 24, 25, 29, 33, 39, 42, 48, 52, 57, 61, 64, 72, 79, 81, 84, 90, and 96. Their order was randomized for each child. The computer accurately recorded the children's responses. The score on this test was calculated in terms of accuracy using the following formula (Cui et al., 2017): Accuracy = 100 − (response − standard answer)/(standard answer + [response − standard answer]) × 100. The formula returns values from 0 to

[1] www.dweipsy.com/lattice

100. *Response* refers to the child's answer, and *standard answer* refers to the correct answer. Deviation of a child's answer from the standard answer is divided by the sum of the standard answer and the deviation, which gives the degree of deviation from the standard value. The formula was adapted from the formula for the percentage absolute error (PAE) (Siegler and Mu, 2008): PAE = (estimate – estimated quantity)/scale of estimates. Given that the children could provide any number as the solution in some cases, there was no limit on their responses. To address this issue, the denominator in Siegler and Mu's formula was revised. The final score for each child was the average accuracy of all trials.

Statistical Analysis

To examine whether children with high finger gnosis differed from their peers with low finger gnosis in basic number processing abilities, a series of ANOVAs were conducted, taking the group as a between-subjects factor and four basic number processing abilities as dependent variables. In addition, the age was a covariant in all ANOVAs. Finally, path analysis was carried out to test the potential mediation effect of basic number processing abilities in the relationship between finger gnosis and addition skills. Data analysis was executed in SPSS 21.0.

Results

The ANOVA results revealed a significant difference between children with high finger gnosis and their peers with low finger gnosis in the number line estimation task even after Bonferroni–Holm correction, $F(1, 33) = 4.003$, $p = 0.054$, Cohen's $d = 0.980$. Children with high finger gnosis performed better on the number line task than their peers with low finger gnosis. Conversely, no significant difference was found between the two groups in enumeration, $F(1, 32) = 0.16$, $p = 0.693$; order judgment, $F(1, 33) = 0.23$, $p = 0.632$; and number sense, $F(1, 33) = 0.12$, $p = 0.731$. Descriptive statistics appear in **Table 4**.

Based on the discussed results, a path model was estimated to test whether the correlation between finger gnosis (X) and addition accuracy (Y) was mediated by number line estimation (M). Mediation was assessed using the process outlined in Preacher and Hayes (2008). Partial correlation results with age as a covariant are presented in **Table 5**.

The first step estimated the effect of finger gnosis on addition accuracy (i.e., c-path or X→Y relationship). The second step estimated the effect of finger gnosis on number line estimation accuracy (i.e., a-path or X→M relationship). The third step estimated the effect of number line estimation on addition accuracy (i.e., b-path or M→ Y relationship), controlling for the independent variable (X). The effect of X on Y in the third step constituted the c'-path (i.e., change in the outcome not explained by the mediator). Finally, the indirect effect was calculated as the product of a and b estimates, denoted as ab. When ab is significant, then the mediation path proposed in the research hypothesis exists (Preacher and Hayes, 2008). A bias-corrected bootstrap-confidence interval (CI) for the product of these paths that does not include zero suggests a significant indirect effect (Preacher and Hayes, 2008). As seen in **Figure 1**, using the INDIRECT procedure with 5,000 bootstrap samples taking age as a covariate revealed a significant positive indirect effect of finger gnosis on addition accuracy through number line estimation (effect = 0.258, 95% CI = 0.0018–0.5835). Moreover, when controlling for the mediating variable, the direct effect of finger gnosis on addition accuracy was not significant ($B = 0.113$, $p = 0.680$, 95% CI = −0.4383 to 0.6635). This finding suggests that number line estimation played a fully mediating role in the relationship between finger gnosis and addition accuracy.

Discussion

Study 2 indicated that children with high finger gnosis performed better in number line estimation than their counterparts with

TABLE 4 | Descriptive statistics in Study 2.

	Children with low finger gnosis		Children with high finger gnosis	
	M	*SD*	*M*	*SD*
Enumeration task	81.67	11.12	85.05	12.78
Order judgment task	86.67	8.99	89.20	7.05
Number sense task	80.90	11.38	84.31	12.66
Number line estimation task	71.38	9.97	79.80	7.90
Finger gnosis	62.25	7.39	91.05	3.49
Addition accuracy	69.13	28.00	81.65	18.10

Legend for all tasks is the percentage of correct trials (%); percentage for number line estimation task is based on the following formula (Cui et al., 2017): Accuracy = 100 – (response – standard answer) / (standard answer + [response – standard answer]) × 100.

TABLE 5 | Correlations among finger gnosis, addition skills, and number line estimation after controlling for age.

	M	*SD*	Addition accuracy	Finger gnosis	Number line estimation
Addition accuracy	76.08	23.53	–		
Finger gnosis	78.25	15.51	0.238	–	
Number line estimation	76.06	9.72	0.435**	0.408*	–

**p < 0.05. **p < 0.01.*

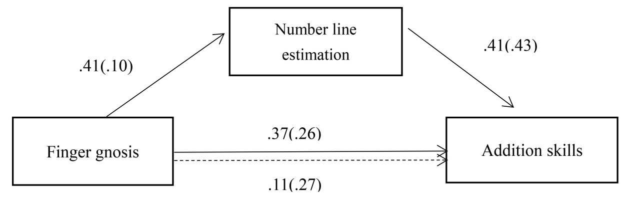

FIGURE 1 | Solid line indicates a significant direct path from finger gnosis to number line estimation, from finger gnosis to addition skills, and from number line estimation to addition skills. Dotted line denotes a non-significant path from finger gnosis to addition skills when controlling for number line estimation. Standardized OLS regression coefficients and standard errors (in brackets) were on the path.

low finger gnosis. More importantly, number line estimation fully mediated the correlation between finger gnosis and addition skills. These findings imply that number line estimation may underlie the relationship between finger gnosis and addition skills. In other words, children with higher finger gnosis may develop a more mature mental number line, which helps them perform better on addition tasks. Study 2 also showed that children with high finger gnosis did not differ from their peers with low finger gnosis in enumeration, order judgment, or number sense. This result suggests that these number processing abilities cannot explain why finger gnosis is relevant to addition problem-solving.

GENERAL DISCUSSION

This study examined for the first time whether finger gnosis was associated with addition skills in young Chinese children. Results revealed two noteworthy findings. First, finger gnosis was associated with addition performance in 5–6-years-old Chinese children, and this correlation persisted after controlling for children's age. Second, the relationship between finger gnosis and addition performance was fully mediated by number line estimation. Moreover, we found that girls performed better in finger gnosis than boys, and children who had musical training performed better than their peers who had no musical training. We discuss the underlying reasons for these findings and their important implications later.

In line with most previous research (e.g., Fayol et al., 1998; Noël, 2005; Gracia-Bafalluy and Noël, 2008; Penner-Wilger and Anderson, 2008; Reeve and Humberstone, 2011), our results suggest that finger gnosis explains a unique and substantial proportion of variance in young children's addition skills.

One important finding from the present research is that the association between finger gnosis and addition skills seems to be fully mediated by number line estimation. Number line estimation is closely associated with mathematical competence (see a meta-analysis by Schneider et al., 2018). Typically, number line estimation is regarded as an indicator of numerical representations (e.g., Siegler and Booth, 2004; Opfer and Siegler, 2007; Booth and Siegler, 2008; Siegler and Ramani, 2008). Recently, performance on the number line task is highly correlated with visuospatial skills (Gunderson et al., 2012; Lefevre et al., 2013; Thompson et al., 2013; Crollen and Noël, 2015a). Furthermore, the relationship between number line estimation and mathematical achievement can be fully explained by visuomotor integration and visuospatial skills (Simms et al., 2016). Numerical representations or visuospatial skills that underlie number line estimation likely drive the correlation between finger gnosis and addition skills. Fingers are highly important for several related tasks, including understanding the cardinal meaning of number words (Butterworth, 1999), establishing the one-to-one correspondence principle (Gallistel and Gelman, 1992), and mapping the symbolic system onto the preexisting non-symbolic, spatial magnitude system (Fayol and Seron, 2005). Therefore, strong finger gnosis may help children to acquire number knowledge and to establish number and spatial representations (Noël, 2005; Penner-Wilger and Anderson, 2013), which are essential to the development of arithmetic skills.

Finger gnosis may also facilitate children's development of spatial skills. Recently, Soylu et al. (2018) contended that the finger gnosis task measures one's ability to activate an internal body representation and then map that spatial representation onto external objects. In other words, the spatial representation underlying finger gnosis can influence arithmetic skills. Indeed, Newman (2016) identified a strong correlation between finger sense and matrix reasoning, which involves a series of figures representing a pattern with one figure left blank. Potentially, children with higher finger gnosis tend to develop stronger spatial skills, which facilitates a more mature mental number line and better arithmetic skills.

Our findings can be reconciled with weak associations between finger gnosis and arithmetic skills from studies by Poltz et al. (2015) and Wasner et al. (2016). In Wasner et al. (2016), general cognitive ability was measured using continuing rows and matrices subtests from the Culture Fair Intelligence Test—Revised (Weiß and Osterland, 2013). The two subtests measure children's visual–spatial reasoning abilities. Therefore, in Wasner et al. (2016), the correlation between finger gnosis and arithmetic was likely overridden by general cognitive ability. Similarly, in Poltz et al. (2015), the relationship between finger gnosis and calculation was likely overridden by non-verbal intelligence, which, in fact, measures children's visual–spatial abilities. As for the study by Long et al. (2016), the association between finger gnosis and arithmetic skills may have been overridden by non-symbolic magnitude judgment skills, which may also involve visuospatial abilities as suggested in recent studies (Burr and Ross, 2008; He et al., 2015).

Our finding that the association between finger gnosis and addition skills was fully mediated by number line estimation may provide some support for the redeployment hypothesis. Finger gnosis circuit may share some circuits with number line estimation, which is redeployed to support complex arithmetic skills. In other words, the functional overlaps between finger gnosis and number line estimation provide strong support for addition skills. Specifically, fingers have an ordinal meaning that is determined by a finger's specific position within the counting sequence (Sixtus et al., 2020). Finger gnosis is typically shaped by counting a number on 10 fingers, which involves the successor and predecessor knowledge in the number sequence (Sella and Lucangeli, 2020). In this sense, finger gnosis can scaffold number line estimation, which involves placing a number on the number sequence. Both finger counting and number line are powerful conceptual structures to unfold the understanding of the magnitude relation between symbols and constitute the basis for building the first arithmetical operations (Sella et al., 2020). However, children seem to rely more on a spatial organization than on counting to achieve a full understanding of the magnitude relations between digits (Sella et al., 2017). Number line estimation has been suggested to involve the ability to accurately divide space and/or numbers (e.g., Berteletti et al., 2010; Barth and Paladino, 2011; Ashcraft and Moore, 2012; Rouder and Geary, 2014) as well as one's ability to judge the scale of a line and to parse the space into segments (Simms et al., 2016). These abilities are similar to arithmetic addition and subtraction, which involve adding parts to make a whole or dividing a whole into parts. Therefore, the circuits for number line estimation could potentially be redeployed for addition skills.

In the present research, finger gnosis was not correlated with children's use of a finger-counting strategy when solving addition problems. Finger gnosis may represent a domain-general ability that develops in finger-use activities, including counting as well as handcrafting. By contrast, finger counting is a domain-specific strategy used only in arithmetic problem-solving. Therefore, when facing an addition task, children with good finger gnosis do not necessarily use a finger-counting strategy. According to the two developmental stages proposed by Reeve and Humberstone (2011), many children in our study may have been in the second stage in which they could flexibly and adaptively use their fingers; that is because they could use other more economic strategies such as memory retrieval; they did not resort to finger counting. Chinese families also tend to emphasize children's rote memorization of arithmetic facts. When facing addition and subtraction problems, children are encouraged to provide answers as quickly as possible, which may lead children to shift from relying on finger counting to memory retrieval. In addition, many kindergartens in China teach primary-school-level lessons, including addition and subtraction. It is thus unsurprising that 25.8% of children in this study used retrieval strategies, which can predict their addition performance. During children's addition skill development, retrieval gradually becomes a dominant strategy compared with finger counting. In turn, as revealed by some previous studies, the use of finger-counting strategies may be negatively associated with later mathematics achievement (Fennema et al., 1998; Geary et al., 2004; Carr and Alexeev, 2011).

In the present research, children's sex and experience playing musical instruments explained some individual differences in finger gnosis: girls were better in finger gnosis than boys. This sex difference might be due to the distinct games boys and girls play in early childhood. Girls generally prefer games that involve their fingers (e.g., handicrafts and dressing up dolls). By contrast, boys prefer games that require little fine finger participation (e.g., basketball and toy guns). In this sense, finger training among girls might be greater than among boys. It is, therefore, not surprising that girls had better finger gnosis than boys. In addition, our research indicated that children who had played finger instruments, including piano, guitar, and flute, had better finger gnosis than those who had not. This finding suggests that playing musical instruments may be somewhat helpful for improving finger gnosis. In other words, playing musical instruments may indirectly and positively influence children's addition skills. Previous studies have found that musical training can promote mathematical abilities such as number conception, addition, and subtraction to a certain extent (e.g., Cheek and Smith, 1999; Cabanac et al., 2013). Finally, our study revealed that boys were more likely to use retrieval in solving addition tasks than girls. This finding is consistent with prior work (e.g., Carr and Jessup, 1997; Fennema et al., 1998; Carr and Davis, 2001). One explanation is that boys are more influenced by perceived adult beliefs or actions than girls (Carr et al., 1999). Because boys believe that adult-like strategies are reflective of ability, they may be more heavily influenced by teacher instructions regarding retrieval strategies. Conversely, girls' strategy use may be less affected by adults.

It should be noted that the finding that girls with high levels of finger gnosis did not have better addition performance than boys can be reconciled with the conclusion of a positive relationship between finger gnosis and addition performance. Indeed, girls had a higher level of finger gnosis than boys. However, boys used retrieval strategies more frequently than girls. Both the frequency of retrieval strategy and finger gnosis predicted arithmetic performance (see **Table 3**). Therefore, high levels of finger gnosis might have counterbalanced infrequent use of retrieval strategy for girls. As a result, they did not show better addition performance than boys. Similarly, frequent use of retrieval strategy might have counterbalanced low levels of finger gnosis for boys, which may explain why boys did not show better addition performance than girls.

Certain limitations of this study should be noted. First, in Study 2, we selected only children with high and low finger gnosis due to practical limits and ignored those with moderate finger gnosis. This selection may have reduced the statistical power of Study 2. Future studies should use a representative sample to replicate our research findings. Second, the present research is cross-sectional; longitudinal and training studies are necessary to establish prospective and causal relations between finger gnosis and children's arithmetic skills.

CONCLUSION

In conclusion, the findings of this study enhance our understanding of the correlation between finger gnosis and arithmetic skills. One practical suggestion is that encouraging young children's finger use may be beneficial, particularly as finger use could be helpful for finger gnosis and thus for children's numerical and arithmetic development. Therefore, we encourage educators (including teachers and parents) to offer appropriate finger training for their children in their educational practices.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/**Supplementary Material**.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Administration Committee of Psychological Research in Southwest University and in compliance with the ethical guidelines of the American Psychological Association. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

LZ conceived and designed the experiments. WW performed the experiments and analyzed the data. LZ and XZ wrote the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2020.544543/full#supplementary-material

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The Development of Spatial Representation Through Teaching Block-Building in Kindergartners

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This study investigated the effects of the teaching block-building intervention on overall spatial representation and its three sub-forms, namely linguistic, graphic and model representations, in kindergartners. Eighty-four children (39 girls and 45 boys), aged 5–6 years old, were randomly selected and equally divided into two groups, i.e., experimental group and control group. The experimental group received the intervention of teaching block-building for 14 weeks (45 min each time, once a week), while children in the control group freely played with blocks for the equivalent time. Children's spatial representation performances were measured in both pre- and post-tests by the *Experimental Tasks of Spatial Representation for Children*. The results showed that: (1) teaching block-building could promote not only the overall spatial representation but also all three sub-forms of spatial representations; (2) there was no gender differences regarding the effect of teaching block-building on neither the overall nor three sub-forms of spatial representations; (3) after the intervention, the diversity of children's choices regarding the use of sub-forms spatial representations was also promoted in the experimental group. In summary, these results contributed to a comprehensive and systematic understanding of the effects of teaching block-building on spatial representation among children in kindergartens.

Keywords: children, block-building, spatial representation, linguistic representation, graphic representation, model representation

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INTRODUCTION

Spatial representation, or cognitive representation of spatial relations, refers to how the knowledge of space is represented in the brain (Olson and Bialystok, 1983; Bisiach et al., 1985; Eilan et al., 1993; Grieves and Jeffery, 2017). It belongs to a broad concept known as spatial ability or spatial skills. Generally, spatial ability refers to the capacity for individuals to generate, retain, retrieve, and transform well-structured information, such as visual, diagrammatic, or symbolic form (Lohman et al., 1987; Lohman, 1996). It may involve not only the understanding of the outside world but also the processing of outside information and reasoning with it through representation in mind (Kosslyn, 1995), i.e., spatial representation.

Spatial ability is vital for achievement in subjects and careers related to Science, Technology, Engineering, and Mathematics (i.e., STEM) (Caldera et al., 1999; Assel et al., 2003; Chen, 2009; Wai et al., 2009; Uttal and Cohen, 2012; Stieff and Uttal, 2015; Ha and Fang, 2016). The claim that spatial ability contributes to STEM academic performance has been verified in many subjects, such as chemistry, physics, and anatomy, etc. (e.g., Pallrand and Seeber, 1984; Delialioğlu and Aşkar, 1999; Harle and Towns, 2011; Lufler et al., 2012; Sweeney et al., 2014). In recent years, STEM has been emphasized in all periods of school education, as well as early childhood education; hence, it is also of great importance to pay attention to the development of children's spatial ability.

Previous Studies of Teaching Block-Building on Spatial Ability

Following this direction, it has been suggested that children engage in building and playing with blocks could significantly promote their spatial ability (e.g., Brosnan, 1998; Caldera et al., 1999; Martin-Dorta et al., 2014; Verdine et al., 2014a,b; Jirout and Newcombe, 2015). For example, Casey et al. (2008) reported that block-building supported the development of spatial visualization in kindergartners. Traditionally, there are two main aspects of spatial ability found to be closely related to block-building activities–spatial visualization and mental rotation (Linn and Petersen, 1985; Casey et al., 2008; Newman et al., 2016). On the one hand, spatial visualization, which involves the ability to generate images of different shapes and then mentally combine them to produce a new design, is necessary for all block building activities (Newman et al., 2016). It is suggested that when a child is playing with blocks, he or she is mentally visualizing how blocks will fit and interact with one another (Newman et al., 2016); therefore, building blocks may facilitate the development of spatial visualization. On the other hand, mental rotation, which consists of the ability to look at an object or a picture of an object and visualizes what it might look like if rotated in either two- or three-dimensional space, has also been commonly found during block building activities (Casey et al., 2008). That is, children will inevitably utilize strategies to rotate blocks to different orientations and build the whole structure. For example, when building blocks, children do spatial flips to fit them into a particular slot in the structure, and spatial turns to make corners with blocks. In this case, children's block-building activities may generate many benefits to their spatial ability development. Moreover, this benefit on spatial ability, which comes from block-building and similar activities, is even higher than children could gain from other usually played activities, such as drawing, playing with sound-producing toys (e.g., guitars) and other toys (e.g., trucks), riding bikes, etc. (Jirout and Newcombe, 2015).

Although researchers have dedicated to investigating how block-building could contribute to children's spatial ability, few of their efforts have been invested to directly test whether and how block-building can benefit children's spatial representation specifically. In particular, there are different sub-forms of spatial representations. For example, researchers have identified that there are linguistic and non-linguistic categorizations of spatial relations (Hayward and Tarr, 1995; Crawford et al., 2000). In terms of the non-linguistic aspect, it has been suggested that spatial representation also contains the cognitive representation of spatial relations on a map (Kulhavy et al., 1983), which is also called map representation (Blaut and Stea, 1971; Landau, 1986), including both two- and three-dimensional forms (i.e., graphic and model, respectively). Researchers have highlighted the importance of these sub-forms of spatial representations, i.e., linguistic, graphic, and model, during early childhood development (Pang et al., 2008). For this study, we briefly propose the executive definitions of these sub-forms according to the previous literature (e.g., Blaut and Stea, 1971; Bluestein and Acredolo, 1979; Landau, 1986; DeLoache, 1989, 2000; Landau and Jackendoff, 1993; Netelenbos and Savelsbergh, 2003; Szechter and Liben, 2004; Pang et al., 2008; Lahav et al., 2018). First, linguistic representation is the ability to express spatial experience and relations through language. Second, graphic representation, also called map-reading skills, means children's ability to infer the position of an object in a three-dimensional environment from information contained on a two-dimensional map. Third, model representation refers to the self-orientation, object-orientation, and place-orientation of the three-dimensional object in the real environment according to the model; and the model is used as a symbol for obtaining information about the position of the object in the real world. Similar to the overall spatial representation, there is also a lack of research on whether and how block-building can improve these sub-forms of spatial representations among children during early childhood. In this case, it is needed to design intervention studies that are focusing on exploring whether block-building can benefit the development of spatial representation, including its sub-forms. Therefore, in the following sections, we first depict how block-building could relate to the development of spatial representation. Then, the potential influence factors to intervention effects, in particular gender, are also discussed.

Why and How Can Block-Building Contribute to Spatial Representation?

It is regarded as a significant improvement of research efforts to shift to explore how children use spatial representation to understand the real world. It is evidenced that block-building can help children improve their perception of spatial relations in the real world, i.e., overall spatial representation. For example, through the analysis of practical teaching cases, researchers have found that block-building may help children understand the concept of orientation and improve their cognition of spatial relations (Blades and Cooke, 1994).

Moreover, there are also pieces of evidence that block-building could benefit the sub-forms of spatial representations among children. First, block-building can improve children's language use regarding space, i.e., linguistic representation. For example, some scholars have tested to provide children with a complete three-dimensional bonding model and a set of randomly arranged blocks and ask them whether the blocks fit the model. Results have indicated that block-building promoted the communication using spatial language between children and adults (Verdine et al., 2014a,b). Another experimental study also found that teachers' use of spatial language during teaching block-building would further encourage children to use more spatial vocabulary as well (Cohen and Emmons, 2017); therefore, it could further improve children's linguistic representation. Second, block-building that also brings challenges to children's graphic cognition may also be conducive to their spatial ability (Szechter and Liben, 2004), especially the graphic representation. For example, a qualitative study has found that block-building activity is beneficial to children's understanding of geometric shapes (Park et al., 2008); thus it might facilitate children's representation ability in two-dimensional aspect. Therefore, it would contribute to the development of graphic representation, as well. Finally, block-building involves enriched interactions with three-dimensional objects; in this case, it will also possibly improve children's model representation of space. Based on the above literature review, we accordingly propose that block-building is a promising activity for improving children's spatial representation, which might include not only the overall spatial representation but also its sub-forms.

Will Gender Be an Influential Factor in the Intervention Effect?

Recently, various studies have also been conducted to identify the factors that might affect children's spatial representation. It has been suggested that individual experiences, e.g., family social-economic status (SES), construction materials, etc., are all potential factors that may influence the development of spatial ability among children (e.g., Caldera et al., 1999; Verdine et al., 2014a). Among these factors, gender is one of the most frequently mentioned variables (e.g., Casey et al., 2008; Jirout and Newcombe, 2015). Some scholars have reported that boys usually outperform girls on some spatial tasks (e.g., Casey et al., 1995), and are better at mastering building skills and understanding the structure balance with blocks (Tian et al., 2018). However, there are also inconsistent findings regarding this gender difference. For example, a longitudinal study has shown that there is no significant gender difference in spatial ability after 3 years of equal time playing with blocks (Hanline et al., 2001). Therefore, it remains unclear whether there are gender differences regarding the development of children's spatial representation with the intervention of block-building.

Research Gaps

To sum up, researchers have invested considerable efforts to explore the effects of block-building on the development of spatial ability, as well as spatial representation, and have obtained significant research findings. However, there are still research gaps that need to be filled. First, spatial representation consists of at least three sub-forms: linguistic, graphic, and model. Most previous studies have studied these sub-forms of spatial representations separately (e.g., Szechter and Liben, 2004; Ferrara et al., 2011); however, few of them have investigated them comprehensively and explored how these sub-forms of spatial representations can be promoted by the block-building within the same intervention or training program. The *Experimental Tasks of Spatial Representation for Children* developed by Pang et al. (2008) is among the very few tasks that can test spatial representations regarding its sub-forms among Chinese children. Therefore, this study aims to use this task to examine how children's spatial representation and its sub-forms can be promoted by the intervention of block-building more comprehensively and systematically. Second, previous training or intervention programs are relatively independent of the conventional teaching processes of kindergarten (e.g., Newman et al., 2016). There are also very few studies that have investigated to what extent a systematic instruction of block-building by teachers or assistants could benefit children's spatial representation. The intervention of teaching block-building, which will be used in this study, refers to an instructional process that teachers plan and organize the symbolic and constructive gaming activities according to the teaching objectives and contents. In addition, within this kind of systematic instruction, whether gender differences in children's spatial representation could exist needs to be further explored. Last but not least, most of the previous studies have focused on the development of spatial abilities; thus, it is still unclear that when children exposure to a new task, how would they choose to finish it with different forms of spatial representations. Therefore, children's choices regarding these three sub-forms of spatial representations should also be investigated.

The Present Study

To fill the research gaps mentioned above, we use the experimental design, including both experimental and control groups, to explore whether the intervention of teaching block-building could benefit spatial representation and its sub-forms in a kindergarten. The research questions (RQs) are specified as followings:

RQ1: Will the intervention of teaching block-building improve children's overall spatial representation while considering gender?

RQ2: Will the intervention of teaching block-building benefit children's sub-forms of spatial representations, i.e., linguistic, graphic, and model, respectively, while considering gender?

RQ3: How will children use their different spatial representations? That is, will children receiving the intervention use more sub-forms of spatial representations in a given context?

MATERIALS AND METHODS

Participants

A total of 84 children, aged 5–6 years old, were randomly selected from a kindergarten in a city of southern China and were equally divided into two groups, i.e., experimental group (42 children, with 20 girls and 22 boys) and control group (42 children, with 19 girls and 23 boys). We did not take an additional screening process on the development conditions of children for two reasons. On the one hand, Chinese kindergartens have not to implement inclusive education at the moment. On the other hand, according to the teacher, no extra care should be paid to children in both groups. Therefore, children should be regarded as typically developed from the selected kindergarten.

The Chi-square test revealed that there were no differences in gender between two groups (χ^2 = 0.048, p = 0.827). The principal of the kindergarten and all teachers agreed to participate before the recruitment of participants. Parental approval and children's consent were also obtained before the study. This study was approved by the ethics review committee at the first author's institute.

Measures

Children's spatial representation was tested by the *Experimental Tasks of Spatial Representation for Children* (Pang et al., 2008). This test was developed by a team of expert Chinese scholars in early childhood development and was supported with face validity in early studies (Pang et al., 2008). Four games (or sub-tasks) were included in the test: *taking the bear home, hide and seek (I)*, *hide and seek (II)*, and *hiding treasures*. First, the game *taking the bear home*, in which participants should place items as required, focused on the development of children's linguistic representation. Second, the game *hide and seek (I)*, in which the participants were asked to find the target location according to the model and then describe the location in their own words, with a focus on investigating their abilities of linguistic and model representations. Third, the game *hide and seek (II)*, in which children should find the targets by referring to picture cards and then orally describe the target locations, which was designed to test children's performance of linguistic and graphic representations. Last, the game *hiding treasures*, where children were encouraged to use appropriate forms of spatial representation to tell others the spatial information of an object in a free context, was intended to examine the development of children's linguistic, graphic and spatial representations, as well as the comprehensive use of these sub-forms of spatial representations. For an easy understanding, here one sample task, i.e., hide and seek (I), was shown. As shown in **Figure 1**, the researcher used materials to construct a room represent the model of the room and there was a red circle represents there was something hide there. Children were asked to indicate the target location in the real room accordingly and then describe the location in their own words. Therefore, this task tested both linguistic and model representations.

FIGURE 1 | A sample task from the Experimental Tasks of Spatial Representation for Children.

According to the tasks above, the total score for the whole test consisted of the scores from the sub-scores of spatial representations: linguistic, graphic, and model representations. The total score of the test was 64 points, of which linguistic representation accounted for 16 points (8 scoring points), and graphic and model representations both accounting for 24 points (12 scoring points), respectively. On each scoring point, children were rated on a three-point scale (i.e., 0–2) and then the results were summarized into a total score for each sub-form of spatial representation. For example, when testing the graphic representation, a child would get zero points if he or she failed to identify the target location, get one point if he or she referred to the nearby location, and get two points if he or she identified the target location precisely. As for the comprehensive use of spatial representation, it referred to how many types of spatial representations children could use to finish the last task. The score was ranged from 1 (i.e., using one sub-form only) to 3 (i.e., using all three sub-forms). This score also reflected children's ability in the diversity of choices regarding the use of sub-forms spatial representations.

Experimental Design and Procedure

The pre- and post-test experimental design was adopted to investigate the effects of teaching block-building on children's spatial representation. The experimental group received the teaching block-building intervention (45 min each time, once a week) for 14 weeks, while no intervention was applied to the control group's block-building activities during this period. Both groups also had the same other activities in the kindergarten and were required not to play blocks after school during the whole period.

Two themes of block-building activities, i.e., "*I Love You, My Motherland*" and "*I Am Here for Emergency Help*," were used as teaching materials for the experimental group. Within each theme, both object and context constructions were included. Each of the theme took about 7 weeks and contained about five or six object construction sessions, such as helicopter, ambulance, fire truck etc., and one to two content construction sessions. Educational activities were generally made up of four steps: first, children should observe both physical and block modeling pictures to understand the structure of the object (object observation); second, children explored ways to represent characteristics of the object with different blocks (exploration and analysis); third, children used various blocks to build the object (free construction); and last, children shared their constructed works and ideas with others (sharing and expression). For example, children were asked to build an ambulance in one object construction session. In the first step, children were shown pictures of the ambulance, which displaying its front, rear, left, right, internal, and outward appearances, and they observe them carefully. Then, children explored which blocks they could use to build the ambulance. Later on, they freely construct the different parts of the ambulance and combine them. And finally, they shared with others about their thoughts and processes. The teaching activities were performed by a teacher from the participating kindergarten. The main role of the teacher was to observe during children's block-building and identify difficulties that children might face to help them proceed. They did not directly teach or model block-building to children. And also, spatial language was not intentionally taught to children, however, it could happen naturally in some circumstances, such as general introduction or problem solving.

The assessment was conducted by well-trained postgraduates, who majored in early childhood education. The students who performed the assessment were blinded of children's group conditions during the testing process. The pre- and post-tests were implemented individually. Before each test, experimenters were asked to begin with a pilot test to adjust their guidance. Then experimenters were required to take participants to warm up and helped them get familiar with the experimental environment and materials. The formal test was conducted strictly following the unified instruction, and experimenters were randomly assigned to record children's answers. The first three tasks and the fourth task were separated by an interval of 2–3 days to avoid potential interferences. When the tests were completed, children's performances were coded according to the recording sheet and were input to SPSS for analysis.

RESULTS

A series of statistical analyses, including descriptive analysis, mixed ANOVAs, and Chi-square test, were performed on the collected data. **Table 1** shows both the mean (SD) from descriptive analysis and adjusted mean (SE) from mixed ANOVAs of overall and sub-forms of spatial representations for both groups.

Effects on Children's Overall Spatial Representation

To explore whether the teaching block-building can generate different effects on overall spatial representation and whether there are differences between girls and boys, we carried out a 2 (Gender: boys and girls) × 2 (Group: experimental group and control group) × 2 (Time: pre- and post-tests) mixed ANOVA. The results showed that the interactions between group, gender and time were not significant [$F(1,80) = 0.267$, $p = 0.607 > 0.05$, $\eta_p^2 = 0.003$], nor was the interaction between gender and time [$F(1,80) = 0.073$, $p = 0.787 > 0.05$, $\eta_p^2 = 0.003$]. Besides, there were no main effects of gender as well [$F(1,80) = 0.532$, $p = 0.468 > 0.05$, $\eta_p^2 = 0.007$]. These results suggested that after the intervention of teaching block-building, there was no gender difference between the experimental group and the control group.

However, the interaction between group and time was significant [$F(1,80) = 142.012$, $p = 0.000$, $\eta_p^2 = 0.640$] and the main effect of time [$F(1,80) = 147.929$, $p = 0.000$, $\eta_p^2 = 0.649$] and group [$F(1,80) = 13.212$, $p = 0.000$, $\eta_p^2 = 0.142$] were both significant. As a result, it suggested that the intervention had a significant promoting effect on children's overall spatial representation. The *post hoc* analysis revealed that, regarding the overall spatial representation, while children in the control group maintained their performance [Adjusted Mean_{pre} (SE) = 46.08 (0.74), Adjusted Mean_{post} (SE) = 46.15 (0.65); $p = 0.863$], children's performance in experimental group was significantly improved [Adjusted Mean_{pre} (SE) = 46.35 (0.74), Adjusted Mean_{post} (SE) = 52.74 (0.64); $p = 0.000$]. The results are shown in **Figure 2**.

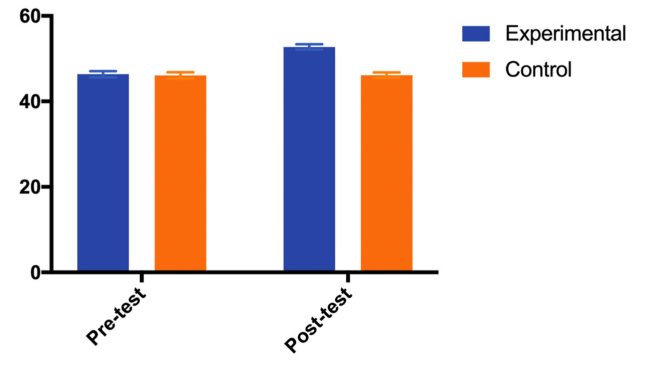

FIGURE 2 | Mean for overall spatial representation by test and group.

Effects on Different Sub-Forms of Spatial Representation

To investigate the effects of teaching block-building on sub-forms of spatial representations, i.e., linguistic, graphic, and model,

TABLE 1 | Mean (SD) and adjusted mean (SE) of overall and sub-forms of spatial representation by group and time.

Measures	Group	Pre-test		Post-test	
		Mean (SD)	Adjusted mean (SE)	Mean (SD)	Adjusted mean (SE)
Overall spatial representation	Experimental	46.36 (4.62)	46.35 (0.74)	52.74 (3.39)	52.74 (0.64)
	Control	46.14 (4.87)	46.08 (0.74)	46.21 (4.79)	46.15 (0.65)
Linguistic representation	Experimental	10.86 (1.88)	10.88 (0.28)	12.98 (1.42)	13.00 (0.24)
	Control	10.29 (1.76)	10.26 (0.28)	10.38 (1.68)	10.36 (0.24)
Graphic representation	Experimental	16.62 (2.27)	16.60 (0.36)	19.00 (1.99)	18.99 (0.33)
	Control	17.40 (2.32)	17.38 (0.36)	17.67 (2.28)	17.61 (0.33)
Model representation	Experimental	18.88 (2.76)	18.88 (0.40)	20.76 (2.06)	20.76 (0.34)
	Control	18.45 (2.34)	18.44 (0.40)	18.74 (2.30)	18.73 (0.34)

respectively, and whether there are gender differences between girls and boys. We also performed three 2 (Gender: boys and girls) × 2 (Group: experimental group and control group) × 2 (Time: pre- and post-tests) mixed ANOVAs in this section. The results are shown in the following sections.

The Effect on Linguistic Representation

Regarding the linguistic representation, the results showed that the interactions between group, gender and time were not significant [$F(1,80) = 0.015$, $p = 0.904 > 0.05$, $\eta_p^2 = 0.000$], nor was the interaction between gender and time [$F(1,80) = 0.143$, $p = 0.706 > 0.05$, $\eta_p^2 = 0.002$]. Besides, there were no main effects of gender as well [$F(1,80) = 0.347$, $p = 0.558 > 0.05$, $\eta_p^2 = 0.004$]. These results suggested that after the intervention of teaching block-building, there was no gender difference between the experimental group and the control group on linguistic representation.

Besides, the results also showed that the interaction between group and time was significant [$F(1,80) = 77.57$, $p = 0.000$, $\eta_p^2 = 0.492$] with the main effect of time [$F(1,80) = 93.81$, $p = 0.000$, $\eta_p^2 = 0.540$] and group [$F(1,80) = 21.761$, $p = 0.000$, $\eta_p^2 = 0.214$] were both significant. As a result, it suggested that the intervention had a significant promoting effect on children's linguistic representation. The *post hoc* analysis revealed that, regarding the linguistic representation, while children in the control group maintained their performance [Adjusted $Mean_{pre}$ (SE) = 10.26 (0.28), Adjusted $Mean_{post}$ (SE) = 10.36 (0.24); $p = 0.553$], children's performance in experimental group was significantly improved [Adjusted $Mean_{pre}$ (SE) = 10.88 (0.28), Adjusted $Mean_{post}$ (SE) = 13.00 (0.24); $p = 0.000$]. The results are shown in **Figure 3A**.

The Effect on the Graphic Representation

Similarly, the results on graphic representation showed that the that the interactions between group, gender and time were not significant [$F(1,80) = 1.477$, $p = 0.228 > 0.05$, $\eta_p^2 = 0.018$], nor was the interaction between gender and time [$F(1,80) = 0.116$, $p = 0.734 > 0.05$, $\eta_p^2 = 0.001$]. Besides, there were no main effects of gender as well [$F(1,80) = 2.711$, $p = 0.104 > 0.05$, $\eta_p^2 = 0.033$]. These results suggested that after the intervention of teaching block-building, there was no gender difference between the experimental group and the control group on graphic representation.

Furthermore, the interaction between group and time was significant [$F(1,80) = 34.070$, $p = 0.000$, $\eta_p^2 = 0.299$] with the main effect of time also significant [$F(1,80) = 50.526$, $p = 0.000$, $\eta_p^2 = 0.387$]. As a result, it suggested that the intervention had a significant promoting effect on children's graphic representation. The *post hoc* analysis revealed that, regarding the graphic representation, while children in the control group maintained their performance [Adjusted $Mean_{pre}$ (SE) = 17.38 (0.36), Adjusted $Mean_{post}$ (SE) = 17.61 (0.33); $p = 0.316$], children's performance in experimental group was significantly improved [Adjusted $Mean_{pre}$ (SE) = 16.62 (0.35),

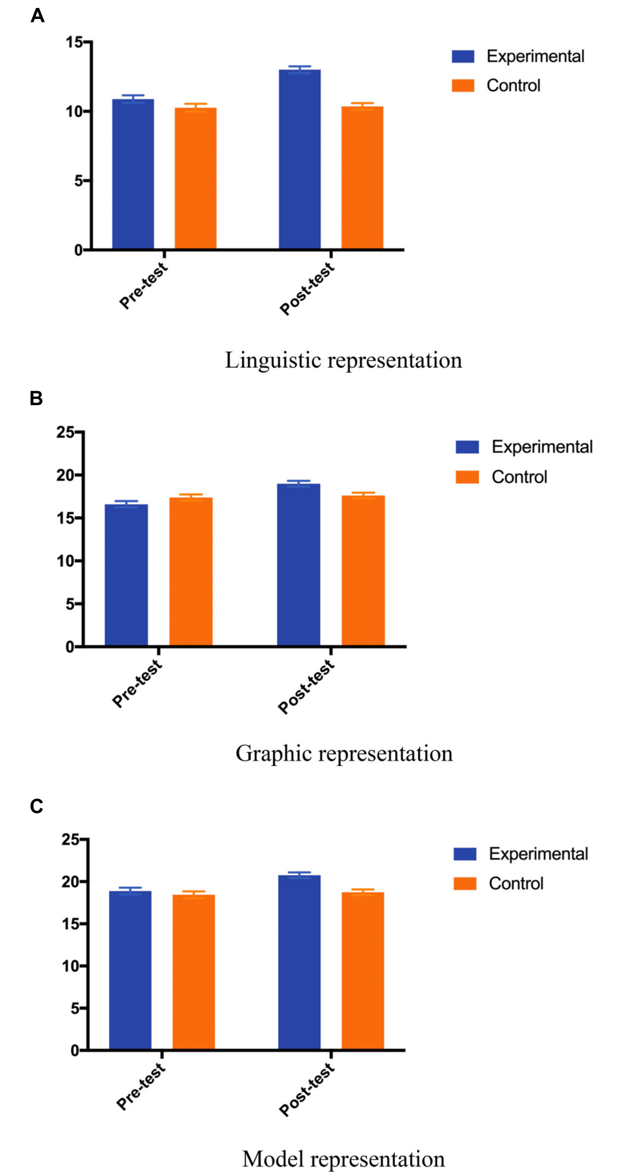

FIGURE 3 | Mean for sub-forms of spatial representations by test and group. **(A)** Linguistic representation. **(B)** Graphic representation. **(C)** Model representation. The *y*-axis is not the same across there sub-figures.

Adjusted $Mean_{post}$ (SE) = 19.00 (0.33); $p = 0.000$]. The results are shown in **Figure 3B**.

The Effect on Model Representation

Finally, the results on model representation showed that the interactions between group, gender and time were not significant [$F(1,80) = 001$, $p = 0.977 > 0.05$, $\eta_p^2 = 0.000$], nor was the interaction between gender and time [$F(1,80) = 0.019$, $p = 0.889 > 0.05$, $\eta_p^2 = 0.000$]. Besides, there were no main effects of gender as well [$F(1,80) = 0.206$, $p = 0.651 > 0.05$, $\eta_p^2 = 0.003$]. These results suggested that after the intervention of teaching block-building, there was no gender difference between the experimental group and the control group on model representation.

In addition, the interaction between group and time was significant [$F(1,80) = 23.705$, $p = 0.000$, $\eta_p^2 = 0.229$] with the main effect of time [$F(1,80) = 43.967$, $p = 0.000$, $\eta_p^2 = 0.355$] and group [$F(1,80) = 6.066$, $p = 0.016$, $\eta_p^2 = 0.070$] were both significant. As a result, it suggested that the intervention had a significant promoting effect on children's model representation. The *post hoc* analysis revealed that, regarding the model representation, while children in the control group maintained their performance [Adjusted Mean_{pre} (SE) = 18.45 (0.40), Adjusted Mean_{post} (SE) = 18.74 (0.34); $p = 0.214$], children's performance in experimental group was significantly improved [Adjusted Mean_{pre} (SE) = 18.88 (0.40), Adjusted Mean_{post} (SE) = 20.76 (0.34); $p = 0.000$]. The results are shown in **Figure 3C**.

The Effect on Children's Diversity of Choices Regarding Spatial Representations

We also conducted an additional statistical analysis regarding the children's choices of sub-forms spatial representations in a free context where they could construct an object with blocks. In the pre-test, the proportion of children in the experimental group who chose to use one representation form and two or more representation forms were 83 and 17%, respectively. In contrast, the proportions for children in the control group were 86 and 14%, respectively. After the intervention, in the experimental group, those who chose to use one spatial representation form and those who chose to use two or more representation forms came up to an equal proportion, both accounting for 50%. However, in the control group, 76% of children still decided to use one spatial representation form, while only 24% of children chose more than two or more spatial representation forms.

It was identified in **Figure 4** that the number of children in the experimental group who chose to use two or more spatial representation forms increased significantly after the intervention ($\chi^2 = 10.500$, $p = 0.001 < 0.01$). By contrast, in the control group, more children still chose only to use one spatial representation form than those who used two or more spatial representation forms in both pre- and post-tests ($\chi^2 = 1.235$, $p = 0.266 > 0.05$). The results revealed that after the intervention, children tended to diversify their choices in using more sub-forms of spatial representations.

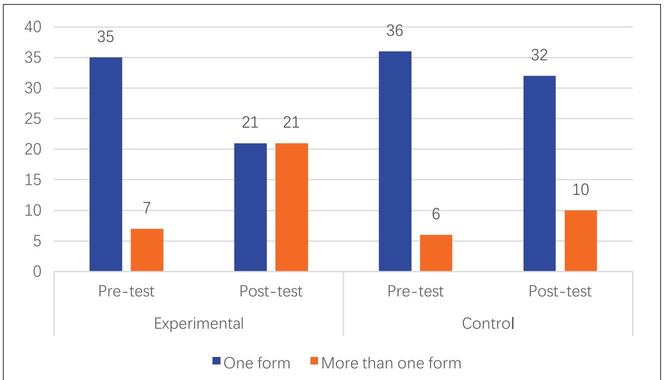

FIGURE 4 | Children's diversity of choices regarding sub-forms of spatial representations.

DISCUSSION

Main Effects of Teaching Block-Building on Children's Spatial Representations

This study investigated the effects of teaching block-building on children's spatial representation, which was measured by the *Experimental Tasks of Spatial Representation for Children* by Pang et al. (2008), employing the experimental design. By comparing data collected from both control and experimental groups, the effects of teaching block-building on the overall spatial representation were supported. We further confirmed that it was due to the improvements on all three sub-forms of spatial representations, i.e., linguistic, graphic, and model representations, respectively.

Firstly, this study found that teaching block-building promoted the development of children's linguistic representation. There are mainly three possible reasons for this result. First of all, compared with non-spatial games, block-building, as a common spatial activity, involves more spatial language (Verdine et al., 2014a,b). Children take spatial features, such as object characteristics (e.g., large, small, tall, short, etc.), shapes (e.g., circle, square, triangle, etc.) and spatial attributes of objects (e.g., bending, edge, etc.), as the communication contents in the game (e.g., Hanline et al., 2001). In this case, the spatial language has been involved in nearly all the block-building activities; therefore, it could enhance children's linguistic representation regarding space. Besides, in the process of analyzing the structure of constructions and exploring the construction method, teachers provided children with numbers, sizes, locations, space distances, and model scale and structure. For example, children were required to listen carefully to and understand the vocabulary, and to grasp spatial information to complete the construction of target objects. Accordingly, the representation system provided by spatial language could explain equivalent spatial concepts. For example, Sun (2005) found that children could understand the relationship between spatial language and space in the real world. When teachers guided them to observe the characteristics of construction objects using words, they provided spatial information to children, such as "put on the top of the cabin," "set on the tail behind the wings," and so on. Therefore, these verbal instructions would have provided children with a rich experience of linguistic representation; thus, it could improve it accordingly.

Moreover, the sharing and communicating section were also included as an essential part of teaching block-building. It encouraged children to express their ideas freely. Therefore, children might have opportunities to use spatial language to express the construction process and introduce their works. In this case, the frequency of using spatial language among children, as well as between children and teachers, could distinctly increase during the teaching of block-building, which might further contribute to the development of children's linguistic representation. This explanation was also supported by the experiment result that block-building could stimulate children to use more spatial language, and therefore, to promote their development of linguistic representation (Ferrara et al., 2011).

Secondly, teaching block-building also promoted the ability of children's graphic representation. Two points might contribute to this effect. On the one hand, the use of images during the block-play games would contribute to children's graphic representation. It was suggested that spatial relationships within graphic symbols represented the real relationships between the actual objects (Bluestein and Acredolo, 1979). In our study, teachers might ask children to observe the images of the objects for construction and the pictures of various block models from which children could extract information of object features into their minds. Then children used the blocks to construct the object freely. For example, when required to build an ambulance in the second game, children were shown by the teacher pictures of the ambulance, which displaying its front, rear, left, right, internal, and outward appearances. Then children participated in observation, meditation, and discussion for which blocks should be chosen to construct these different parts of the ambulance. Therefore, graphic representation would be cultivated through the use of images. On the other hand, some activities in the teaching process might also benefit graphic representation. For instance, children also tried to implement their thoughts by skills, such as tiling, bridging, dislocating, and enclosing after seeing pictures of real objects and complete works. This process was designed to enable children to think, reason, and operate on spatial information (Pang et al., 2008), and could promote the development of children's graphic representation as well.

Thirdly, teaching block-building promoted the development of children's model representation. Pang et al. (2008) suggested that model representation also belonged to the map spatial representation. Therefore, to fully understand the spatial representation of maps, children must understand the spatial and geometric correspondence between representing objects and referent objects in terms of distance, perspective, and orientation. In this case, the relationship between models and real-world objects was also in correspondence with a spatial relationship in blocks. In this study, the spatial factors included in the teaching block-building activities could provide children with a variety of spatial concepts and spatial relations. Moreover, children in the experimental group also had more opportunities to understand the position of each part of the block-building and the relationship among each section, and to relate it to objects in the real world. Thus, it supported the finding that teaching block-building could improve the representation ability of model space with the help of children's understanding of spatial concepts and spatial relationships, i.e., model representation.

Fourth, this study revealed that there were around six points of improvement on children's overall spatial representation; and each of the sub-forms contributed around two points after the intervention. This result might suggest that our intervention would be equally effective for all three sub-forms of spatial representations. Therefore, this intervention would be an important reference to future research which interested in improving all these three sub-forms of spatial representations together.

Finally, the gender effect, which might affect children's spatial representation, was also discussed. It turned out that there was no significant gender difference in neither the overall nor the three sub-forms of children's spatial representations, which were consistent with the previous result in spatial ability, such as Hanline et al. (2001). However, as noted earlier, studies had reported that boys had advantages over girls in spatial ability (e.g., Tian et al., 2018), which might be regarded as contradictory to the finding of this study. We suspected that this was possible because boys and girls had equal opportunities to play with blocks and were very interested in block-building due to this gamified intervention. And in our study, children in the experimental group spent equal time playing with blocks in the kindergarten. They were also controlled by not allowing them to play with blocks at home during the experiment. In this case, combining with the previous literature, our results also suggested that, if girls were offered a lot of opportunities to play with blocks and their interest in learning was aroused (e.g., with gamified activities), their spatial representation could be developed as well as that of boys.

The Use of Spatial Representations Will Be Diversified

The results of this study showed that children's use of spatial representation was more diversified in the experimental group than the control group after the intervention. According to the literature, the development of children's spatial cognition is a process that activates an individual's spatial sense from real life to form spatial concepts in their minds (Grieves and Jeffery, 2017). Therefore, when teachers had no requirements on the use of representation forms, the linguistic representation, which is closely related to children's daily lives, was highly preferred. However, after the intervention, children's abilities of graphic and model representations were both significantly improved, and the frequency of children's usage of these two forms of spatial representations could also increase. Moreover, with the accumulation of experience and the gradual development of spatial cognitive ability, children would gradually be able to use a variety of spatial representation forms comprehensively. For example, a child in the pre-test expressed the information of locations of the object only with "here," but she used more than one form of spatial representation for description in the post-test. She picked up a toy model in front of the experimenter according to the location of physical simulation, then took up picture cards to pose the position, and finally used the sentence "under the table in red, the one on the top of the green table" to deliver the spatial information.

CONCLUSION AND LIMITATIONS

This study is among the very few studies that used teaching block-building as an intervention to comprehensively and systematically investigate the development of children's spatial representation with experimental design and has gained valuable research findings. First, this study finds that teaching block-building can improve both the overall development of the spatial representation and the three sub-forms of spatial representations: linguistic, graphic, and model. Second, no gender difference has been found, which indicates boys and girls perform equally well with the support of the intervention. Third, the intervention of teaching block-building can also improve the diversity of children's choices regarding the use of spatial representation forms.

Nevertheless, this study also has some limitations. First, it only randomly selects participants aged 5–6 years old within one selected kindergarten in a city of China, which may limit the generalization ability of the results. Future research should consider recruiting more diverse samples to explore the effects of this teaching block-building intervention on diverse aspects of spatial representations among children. Second, this study only focuses on the spatial representation itself. Future research should consider involving achievement measures of STEM to explore whether the effect could be transferred. Third, only pre- and post-tests are collected in this study; therefore, the longitudinal design may contribute to the understanding of sustaining effects of the intervention in the future. Fourth, what has been used to evaluate the effect on spatial representation is the traditional task only; therefore, methodological innovations, such as integrating neuroimaging methods–electroencephalogram (EEG), functional magnetic resonance imaging (fMRI) and other brain imaging techniques–may contribute a better understanding of children's spatial representation development and provide a more scientific basis for the effects of this intervention among children.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Review Committee of the School of Education, South China Normal University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

LC designed and supervised the research, and wrote and revised the manuscript. JL analyzed the data, and wrote and revised the manuscript. HZ and JY conducted the research, collected the data, and participated in writing the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Spatial Skills Associated With Block-Building Complexity in Preschoolers

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Block building is a popular play activity among young children and is also used by psychologists to assess their intelligence. However, little research has attempted to systematically explore the cognitive bases of block-building ability. The current study (N = 66 Chinese preschoolers, 32 boys and 34 girls; mean age = 4.7 years, SD = 0.29, range = 3.4 to 5.2 years) investigated the relationships between six measures of spatial skills (shape naming, shape recognition, shape composition, solid figure naming, cube transformation, and mental rotation, with the former four representing form perception and the latter two representing visualization) and block-building complexity. Correlation results showed that three of the four measures of form perception (shape naming, shape recognition, and shape composition) were significantly and positively correlated with block-building complexity, whereas the two measures of visualization were not. Results from regression models indicated that shape recognition and shape composition, as well as shape-recognition-by-gender interaction, were unique predictors of children's block-building complexity. These findings provide preliminary evidence for the basic spatial skills underlying children's block-building complexity and have implications for classroom instructions aimed at improving preschoolers' block-building complexity.

Keywords: block building complexity, form perception, spatial visualization, spatial skill, preschooler

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INTRODUCTION

Block play is a popular activity amongst preschoolers (Varol and Farran, 2006; Schmitt et al., 2018) and has been deemed by researchers as a versatile activity to help children develop technological thinking, critical thinking, problem solving, creativity, and abstract thinking (Reifel, 1984; Robbins et al., 2011; Otsuka and Jay, 2017; Schmitt et al., 2018). Not surprisingly, psychologists have also used block building to measure children's intellectual development (Caldera et al., 1999; Hayashi and Takeshita, 2009; Ness and Farenga, 2016). Empirical studies have further found that preschool children who showed a high level of block construction would attain better math and reading achievement during their school years (elementary through high school), even after controlling for other general cognitive abilities (Wolfgang et al., 2001, 2003; Hanline et al., 2010; Nath and Szücs, 2014; Richardson et al., 2014; Verdine et al., 2014b).

The aim of the current study was to search for specific spatial abilities that serve as basic cognitive foundations for block building in preschool children. We first describe the types of block-building activities and related measures of performance, then review the literature on factors that contribute to block-building ability with a specific emphasis on spatial abilities, and finally introduce the current study.

Types of Block-Building Activities and Measures of Performance

There are three types of block-building activities: structured, unstructured (free block play), and semi-structured block building. In the structured block play, children were asked to duplicate the given models using blocks of various sizes and shapes (Caldera et al., 1999; Cohen and Emmons, 2017; Schmitt et al., 2018). Examples of structured block play include "Stacking blocks", "Three-Dimensional Constructional Praxis" (Benton and Fogel, 1962; Hayashi and Takeshita, 2009), Legos, or Mega Blocks (TOSA). Children were asked to complete the task within a limited amount of time (Verdine et al., 2014a,b). Children's performance is evaluated using two types of criteria: Match scoring and Dimensional scoring. Match scoring counts the number of blocks correctly placed (Benton and Fogel, 1962). Some researchers adopted the stringent criterion of scoring a point only if the child correctly stacked 100% of the blocks (Hayashi and Takeshita, 2009). Dimensional scoring takes into consideration the processes and mistakes in block building. Specifically, children's performance was assessed in terms of two aspects: the overall accuracy of the whole product relative to the central piece and the complexity of multiple component pieces (Verdine et al., 2014b).

Unstructured block play is a self-initiated, self-guided, and open-ended play activity. In other words, children can build whatever they want without instructions. To assess children's performance in free block building, researchers have coded children's construction behaviors, such as sharing with others, pauses for reflection, and satisfaction for self-directed play (Otsuka and Jay, 2017), or coded the end products in terms of complexity and the number and variety of blocks used (Caldera et al., 1999). Other researchers have focused on the developmental progression of block building. For example, Reifel (1984) found that children went through the following sequence: stacking, row construction, combination of stacking and row construction, piling (three dimensions with no interior space), enclosure (flat), enclosure (arches), enclosure (combination), and finally combination of many forms. Later on, Hanline et al. (2001) condensed the sequence into five stages by focusing on spatial dimensionality change: non-construction, linear construction, bidimensional construction, tridimensional construction, and representational construction.

Between the two extremes of structured and free block play lies semi-structured block play, in which an adult, such as a teacher, provides a prompt at the beginning but then lets children work freely with minimum involvement from the adult. The prompt can be as specific as constructing a specific house as shown on a poster (Casey et al., 2008) or as general as building a school with four walls and at least two rooms (Ramani et al., 2014; Schmitt et al., 2018). The adult can also ask children to show the story they hear by using blocks (Reifel and Greenfield, 1983). Researchers have grappled with a variety of ways to assess children's performance during semi-structured block building. Some researchers (Casey et al., 2012) have emphasized structural balance. Other researchers have focused on the number and type or even the symbolic meaning of structures. For example, Ramani et al. (2014) used four criteria: the combined number of blocks in height and in length, number of different columns and rows, meaningful use of the colors and shapes, and number of bridge formations. Still other researchers (Reifel, 1984; Hanline et al., 2001) have paid attention to developmental progression (as discussed earlier for free play). Finally, Casey et al. (2008) adapted an assessment tool developed for free block building to assess semi-structured construction. They added hierarchical integration to capture increasing structural complexity. Hierarchical integration occurs when children combine blocks to create more complex structures with vertical interior space, such as an arch or a bridge (Casey et al., 2008).

Although all three types of block-building activities have been used in the literature, semi-structured block building has several advantages over the other two when assessing children's block-building ability. First, unlike structured block play, semi-structured block play allows children to use their spatial skills and creativity to complete the task in any multiple of ways they prefer (Reifel and Greenfield, 1983; Ramani et al., 2014). Second, semi-structured play overcomes the drawbacks of unstructured free play which typically leads to simple structures and constant changes in children's building plans (Casey et al., 2008). Finally, semi-structured prompts can be easily adapted for use as an instructional strategy to enhance children's learning during free choice time (Schmitt et al., 2018).

Factors That Contribute to Children's Block-Building Ability

Researchers have examined various factors related to children's block-building ability. In terms of demographic factors, it is expected that children's block-building level increases with their chronological age (Hanline et al., 2001). The evidence regarding gender, however, has been mixed. Some research showed no significant gender difference in the complexity of block building (Hanline et al., 2001; Verdine et al., 2014b), but girls tended to build more house features, such as walls, windows, and doors, than did boys (Ramani et al., 2014). Other researchers, however, revealed that boys outperformed girls in block-building skills in China (Tian et al., 2018).

In terms of cognitive factors, Tian et al. (2019) recently proposed a conceptual model that abstract reasoning, numeracy, representational thinking, and spatial ability are the underlying cognitive mechanisms for block play. Among these cognitive capacities, spatial ability is the most crucial (Tian et al., 2019). Spatial ability includes several subcomponents. Based on their meta-analysis, Linn and Petersen (1985) concluded that spatial ability included spatial perception, mental rotation, and spatial visualization. Of the three subcomponents, mental rotation and spatial visualization involve a shared cognitive skill of forming and manipulation mental image (Hawes et al., 2017). A later factor-analysis by Carroll (1993) identified five major spatial abilities including visualization, spatial relations, flexibility of closure, perceptual speed, and closure speed. Finally, a more recent meta-analysis grouped the spatial abilities into two categories: small-scale spatial abilities (including allocentric spatial transformation, such as mental rotation along the object's central axis and object manipulation) and large-scale spatial abilities (including egocentric spatial transformation, such as environmental navigation and mental rotation along the body axis) (Wang et al., 2014). Most recently, Mix et al. (2016, 2017) reviewed a series of spatial tasks used to test subjects across a large age range from kindergarten to sixth grade and concluded that spatial ability included three dimensions: spatial visualization, form perception, and spatial scaling. Despite the variations across the above studies, two key subcomponents of spatial skills seem to be closely related to block building: spatial visualization and form perception. Spatial visualization is the ability to imagine and mentally manipulate figures or objects in space and it can be measured by mental rotation and perspective thinking tasks as well as through a particular type of block design task (using cubes with red and white sides to produce a 3-D structure according to a series of 2-D figure patterns). Form perception is the ability to recognize shapes, distinguish them from their backgrounds, and decompose them into parts, and this skill can be measured with tasks such as figure copying and visual spatial working memory (Mix et al., 2016, 2017).

Thus far, empirical evidence has been mixed in terms of the relationship between spatial visualization and block-building ability. In adult patients with cerebral disease, spatial visualization (perception of orientation or location) strongly predicted accuracy on the structured block play task (Capruso and Hamsher, 2011). Two studies of preschoolers, however, found no significant association between spatial visualization (assessed using Block Design) and block-building ability (Caldera et al., 1999; Casey et al., 2008). When spatial visualization was measured with a mental rotation task, a study of 9-year-old children found that 2-D mental rotation performance was significantly associated with block-building ability (Brosnan, 1998). Consistent with that finding, training with a structured block play game was found to improve 8-year-old children's 2-D letter mental rotation ability with associated changes in brain activation (Newman et al., 2016). However, another study that trained 5.6- to 6.7-year-old children on block building (with semi-structured storytelling block building or imitation of poster block building) did not lead to improvement in 3-D mental rotation (Casey et al., 2008). It seems possible that both age of the participants (older but not younger ones showed significant associations between visualization and block building) and the task (3-D mental rotation may be too difficult for young children (Levine et al., 2012) affect the outcome.

In contrast to the handful of studies on the association between spatial visualization and block building, little is known about the relationship between form perception and block-building play. Thus far, only two relevant studies have been conducted. Caldera et al. (1999) found that block-building ability was significantly associated with geometric figure abstraction ability [which is similar to the subcomponent of Mix et al. (2016, 2017) of form perception]. More recently, an intervention study showed that 7 weeks of semi-structured block intervention resulted in improved shape recognition for children aged from 38 to 69 months (Schmitt et al., 2018). Thus far, no systematic research has been conducted using various measures of form perception.

The Current Study

To expand the limited literature on the cognitive bases of block building, this study examined the associations between multiple measures of form perception and spatial visualization and preschoolers' block-building ability (see **Figure 1**). Four measures of form perception were used: 2-D shape naming, shape recognition, shape composition, and 3-D solid figure naming. This selection of measures was based on the standard conceptualization of form perception in geometry for early education (Sarama and Clements, 2009; Common Core State Standards Initiative, 2010; Sinclair and Bruce, 2015), according to which, form perception includes shape naming, 2-D and 3-D solid shape identification, and shape composition. For spatial visualization, we used two measures: 2-D mental rotation (because 3-D might have been too difficult for preschoolers, as discussed earlier) and cube transformation (2D-3D spatial transformation).

Block-building ability was assessed using semi-structured block construction because of its advantages over structured and free block play, as mentioned earlier. The index for block-building ability used the same complexity as used in previous studies (Hanline et al., 2001; Stannard et al., 2001).

Our main analyses focused on the relations between the six measures of spatial skills and block-building ability. We examined their bivariate relations (via Pearson product-moment correlations) as well as unique contributions (via multiple regression analysis). Finally, given the possible role of gender in spatial ability and block-building ability (as discussed earlier), we also explored potential interactions with gender.

MATERIALS AND METHODS

Participants

Participants were 66 second-year preschoolers (32 boys and 34 girls) from a public preschool in a middle-class neighborhood in Beijing. Children ranged in age from 3.4 to 5.2 years (M_{age} = 4.7 years, SD = 0.29). The protocol of this study was approved by the IRB of the Collaborative Innovation Center of Assessment for Basic Education Quality, Beijing Normal University. Parental consent was obtained for each child before the experiment. Children were allowed to terminate the experiment at any point during the experiment. No child made such a request. This study was based on the data from another study (Zhang et al., 2014).

Materials

Block Building Test

Casey's *Block Building Measure* (Casey et al., 2008) was used to assess children's block-building ability. Children were provided with 70 different shapes of unit blocks and asked to build a house with a ceiling that prevents raindrops from reaching the

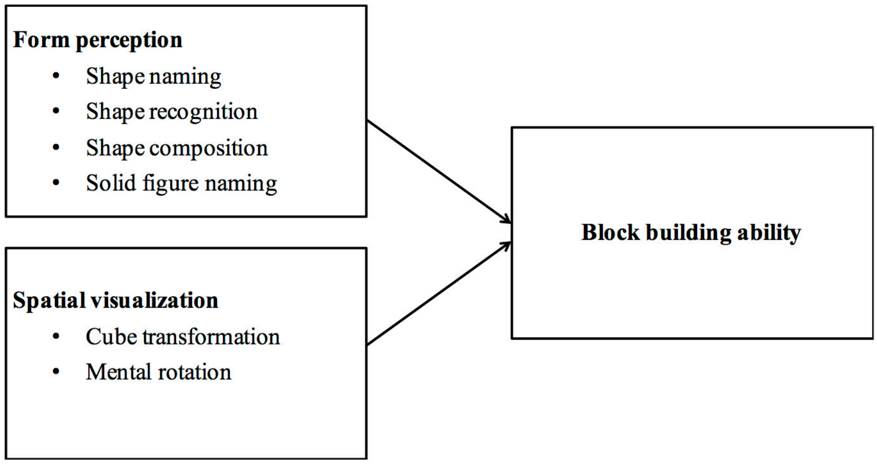

FIGURE 1 | Schematic model of spatial skills underlying block-buildings ability.

inside when it rains outside. Children were allotted 12 min to finish the house. This test has shown good reliability and validity (Casey et al., 2008). Children's block constructions were coded into 14 levels with scores ranging from 0 to 8.5: random placement (0), 1-d structure (1), 2-d with no internal space (2), 2-d with vertical internal space (3), 2-d with horizontal internal space (4), 2-d with horizontal internal space and no gaps (4.5), 3-d structure without internal space (5), 3-d structures with internal space and depth (6), series of arches (6.5), 3-d structure with irregular 1 block-high enclosure and roof (7), 3-d structure with regular 1 block-high enclosure and roof (7.5), 3-d structure with irregular 2-block high enclosure (8), 3-d structure with regular 2-block high enclosure (8.5), and 3-d horizontal closure structure with 2 block-high, roof and internal space (9) (Casey et al., 2008). **Figure 2** presents an example of the finished product scored as 9.

Form Perception Measures

Four tasks were used to measure form perception: shape naming, shape recognition, shape composition, and solid figure naming. The four tasks were scored separately. Because the four tasks had different ranges of scores, they were first standardized and then averaged to create an index of form perception. Reliability for the form perception subscores was Cronbach's $\alpha = 0.82$.

During the shape naming task, children were asked to say the name after being shown a series of ten shapes: square, parallelogram, trapezoid, semi-circle, pentagram, oval, and sector. Children received 1 point for each correctly named shape. The total score on this task could range from 0 to 7. This test was developed by Clements et al. (1999), who did not report reliability. It was also used by Verdine et al. (2016) to assess children's knowledge of shape names and they did not report reliability either. Cronbach's α in the current study was 0.60.

The shape recognition task was based on previous research (Clements et al., 1999; Schmitt et al., 2018). There are 10 picture boards, with each containing three target shapes (e.g., three rectangles) and a number of distractor shapes (e.g., triangles, parallelograms, and irregular shapes) (see **Figure 3**). Children were asked to point out all target shapes on each board. They were given 1 point for recognizing all three target shapes for each trial. The total score on this task could range from 0 to 10. This task has shown good reliability (0.73) in a previous study (Schmitt et al., 2018), although Cronbach's α in the current study was a little lower, at 0.57.

During the shape composition task, children were asked to compose new shapes of their choice from triangles that were provided to them. Children were first given two right triangles to compose a new shape, and then subsequently offered four right triangles to compose a new shape. After they finished each composition, children were asked to name the new shape. Two right triangles can be combined to form a new large triangle, a rectangle, or a parallelogram. Four right triangles can be combined to form a large triangle, a rectangle, a parallelogram, a trapezoid, or a square. Children received 1 point for correctly composing a shape and 1 point for correctly naming it. The total score on this task could range from 0 to 16. This test was developed by authors of the current study. Cronbach's α in the current study was 0.71.

In the solid figure naming task, children were presented with a cube, a cuboid, a cylinder, and a triangular prism and were asked to name these 3-D figures. Children received 2 points for correctly naming each figure. The total score on this task could range from 0 to 8. This test was developed by authors of the current study. Cronbach's α in the current study was 0.78.

Spatial Visualization Measures

The Counting and Coloring of Solid Cubes Test (CCSCT) was used to assess children's cube transformation from 2-D to 3-D. Li et al. (1997) developed the CCSCT based on previous research (Moore, 1986). This task included four figures of four or eight stacked cubes, and two of them had hidden cubes (hidden cubes are necessary to build the

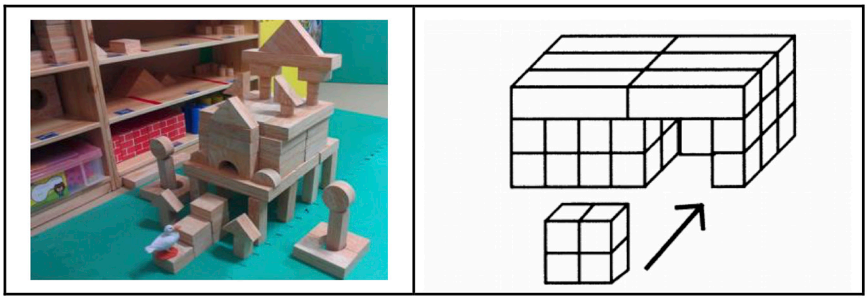

FIGURE 2 | An example of a finished product scored as 9 (on the left panel) and the defining characteristics of products scored as 9 (3-d horizontal closure structure with 2 block-high, roof and internal space) (on the right panel).

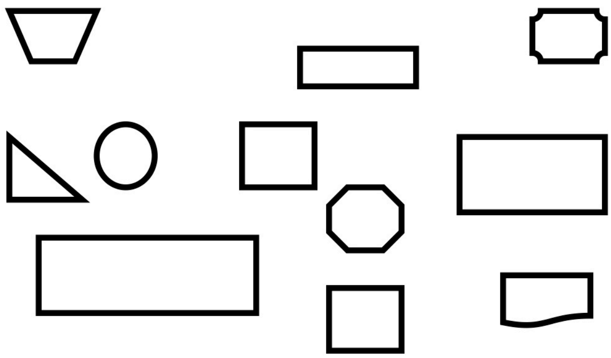

FIGURE 3 | A sample item of rectangle recognition from the shape recognition task.

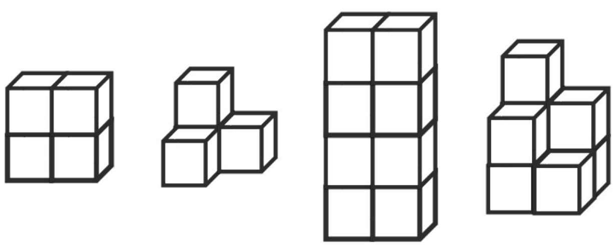

FIGURE 4 | The cube transformation task.

3-D construction but hard to see in the 2-D picture) (see **Figure 4**). First, children were asked to count the number of cubes in the picture by pointing at each of them, and then to paint all the surfaces of the same cube in the same color, and to paint cubes next to each other in different colors. This task was scored from 0 to 48. The original authors did not report the test's reliability. Cronbach's α in the current study was 0.84.

The Windows Test (WT) was used to assess children's 2-D mental rotation (Tzuriel and Egozi, 2010). This test includes three difficulty levels (WT1, WT2, and WT3). Based on the result of a pilot study, second-year preschoolers could not understand and complete WT2 and WT3, so only WT1 was used in this study. The standard figure in this instrument is composed of one triangle roof and nine square windows (three of which are black and six of which are white). Children were asked to find the position of the black windows in the contrast figure which was the original figure rotated 45°, 90°, 180° and with all windows being white. This task was scored from 0 to 18. Cronbach's α was 0.79 in the original study and 0.84 in the current study.

The total score for spatial visualization was calculated by averaging the standardized scores of cube transformation and mental rotation. Reliability for the total summary scores of overall spatial skills was Cronbach's α = 0.848.

Procedure

Children were tested individually in the fall (i.e., the first half of their second year in preschool). One experimenter administered the block-building test and coded the level of block building during the 15-min construction period. The finished product was also photographed, and the experimenter used the photos to verify the original scores after the test. Two research assistants (graduate students), who were not familiar with this study's goal, tested children's spatial skills. They strictly followed the instructions of the instruments. The total time for the testing of spatial skills ranged from 30 to 40 min.

Power Analysis

Power analyses were conducted using G*power for the two types of main analyses. For bivariate correlations aimed at exploring the associations between spatial skill and block-building ability, the sample sizes needed to yield a power of 0.80 and α = 0.05 (one-tailed, given the known positive correlations between spatial abilities and block-building ability). The score was 67 for $r = 0.30$ (medium effect size) and 23 for $r = 0.50$ (large effect size). For the regression analyses aimed at identifying unique contributors and potential interactive effects with gender, the sample sizes needed to yield a power of 0.80 and α = 0.05 for a hierarchical regression analysis, which was 77 for $f^2 = 0.15$ (medium effect size) or 36 for $f^2 = 0.35$ (large effect size) (fixed model, testing R^2 increase, with two control variables and three predictor variables, assuming there would be three significant correlates based on the bivariate correlations), and 68 for $f^2 = 0.15$

(medium effect size) or 31 for $f^2 = 0.35$ (large effect size) (fixed model, testing R^2 increase, with two control variables and two predictor variables). With 66 subjects, the current study was sufficiently powered for the planned bivariate correlations but slightly underpowered for final regression analyses to detect medium or smaller effects.

RESULTS

Correlations Between Spatial Skills and Block-Building Ability

Table 1 shows the Pearson correlations among the key study measures. The overall spatial ability was correlated significantly with the block-building ability, r (66) = 0.33, $p < 0.05$. Form perception was positively correlated with block-building ability, r (66) = 0.41, $p < 0.01$, but spatial visualization was not. Within form perception, significant correlates of the block-building ability included shape naming, r (66) = 0.33, $p < 0.01$, shape recognition, r (66) = 0.37, $p < 0.01$, and shape composition, r (66) = 0.37, $p < 0.01$. The one exception was that solid figure naming had no correlation with block-building ability. Neither of the two measures of spatial visualization (cube transformation and mental rotation) showed significant relation with block-building ability.

Regression Analysis of Form Perception and Spatial Visualization Predicting Block-Building Ability

Two sets of hierarchical regression were conducted to examine unique predictors of block-building ability. In the first set, we examined whether form perception and spatial visualization (as well as their interactions with gender and age) made unique contributions to block-building ability. Step 1 included two demographic variables: age and gender. Step 2 included two factors: form perception and spatial visualization. Step 3 included the interaction terms one at a time.

Results are shown in **Table 2**. Age was a significant predictor, but gender was not. Form perception made a unique contribution to explaining block-building ability, but spatial visualization did not. These two factors accounted for 9% additional variance. The interaction between form perception and gender was significant. Simple slope tests showed that form perception was significantly associated with block-building ability for girls, with a 1-unit difference in form perception being associated with a 0.73 points difference in block-building ability, $t = 3.66$, $p < 0.01$, but not for boys, $t = 1.21$, $p = 0.23$. **Figure 5** depicts the nature of the interaction of form perception and gender. The interaction between spatial visualization and gender was not significant. Nor were the two interaction terms with age.

Regression Analysis of Specific Spatial Skills Predicting Block-Building Ability

The second set of hierarchical regression was conducted to examine unique predictors (among the specific spatial skills) of block-building ability. Step 1 included two demographic variables: age and gender. Step 2 included the three significant correlates based on the bivariate analyses: shape naming, shape recognition, and shape composition. Step 3 included one of the interaction terms between the three significant correlates and gender or between them and age.

Results are shown in **Table 3**. Age was a significant predictor, but gender was not. On Step 2, of the three significant correlates based on the bivariate analyses (i.e., shape recognition, shape composition, and shape naming), the former two made unique contributions to explaining block-building ability, but shape naming did not account for a significant amount of unique variance. Step 2 accounted for 13% additional variance. On Step 3, the gender interaction terms of shape naming and shape recognition effects on block building were significant, suggesting that shape naming and recognition's effects on block-building ability varied by gender. Simple slope tests showed that, although shape naming was associated with block-building ability in the opposite direction (hence a significant interaction), the simple slope was not significant for either girls, $t = 1.46$, $p = 0.15$, or boys, $t = -1.79$, $p = 0.08$. Simple slope tests showed that shape recognition was significantly associated with block-building ability for girls, with a 1-unit difference in shape recognition being associated with a 0.57 points difference in block-building ability, $t = 3.47$, $p < 0.001$, but not for boys, $t = -0.17$, $p = 0.86$. **Figure 6** depicts the nature of the interaction

TABLE 1 | Correlations among key study variables.

	M ± SD	1	2	3	4	5	6	7	8	9	10
1. Block building skills	5.45 ± 2.11	–	–	–	–	–	–	–	–	–	–
2. Spatial ability	54.83 ± 18.27	0.33*	–	–	–	–	–	–	–	–	–
3. Form perception	15.98 ± 6.49	0.41**	0.77**	–	–	–	–	–	–	–	–
4. Spatial visualization	38.85 ± 15.44	0.12	0.82**	0.26*	–	–	–	–	–	–	–
5. Shape naming	3.58 ± 1.57	0.33**	0.65**	0.82**	0.24	–	–	–	–	–	–
6. Shape recognition	5.14 ± 1.97	0.37**	0.53**	0.65**	0.22	0.46**	–	–	–	–	–
7. Shape composition	5.86 ± 2.79	0.37**	0.59**	0.80**	0.17	0.57**	0.26*	–	–	–	–
8. Solid figure naming	1.41 ± 2.26	0.15	0.54**	0.74**	0.15	0.42**	0.22	0.58**	–	–	–
9. Cube transformation	27.41 ± 12.33	0.16	0.70**	0.26*	0.82**	0.21	0.18	0.21	0.17	–	–
10. Mental rotation	11.44 ± 5.92	0.04	0.64**	0.17	0.82**	0.18	0.18	0.07	0.08	0.35**	–

TABLE 2 | Hierarchical linear regression of form perception and spatial visualization predicting block building ability (*N* = 66).

	B	SE	*t*	*p*	*F*	*df*	*P*	Adj. R^2	Δ Adj. R^2
Step 1	–	–	–	–	7.03	63	0.002*	0.16	0.16
Age	3.03	0.82	3.68	0.000***	–	–	–	–	–
Gender	−0.27	0.48	−0.55	0.582	–	–	–	–	–
Step 2	–	–	–	– –	6.54	61	0.000***	0.25	0.09
Form perception	0.73	0.24	3.08	0.003**	–	–	–	–	–
Spatial visualization	0.01	0.25	0.04	0.972	–	–	–	–	–
Step 3a (interaction term was added one at a time)	–	–	–	–	6.90	60	0.000***	0.30	0.05
Gender*form perception	1.02	0.47	2.16	0.035*	–	–	–	–	–
Step 3b	–	–	–	–	5.52	60	0.000***	0.26	0.01
Gender*spatial visualization	−0.57	0.50	−1.56	0.252	–	–	–	–	–
Step 3d	–	–	–	–	5.57	60	0.000***	0.26	0.01
Age*form perception	−1.11	0.90	−1.23	0.223	–	–	–	–	–
Step 3e									
Age* spatial visualization	0.27	0.80	0.33	0.742	5.17	60	0.001***	0.24	−0.01

To simplify the presentation, only new variables for each step are shown because the effects of the variables from earlier steps did not change much in the subsequent steps.

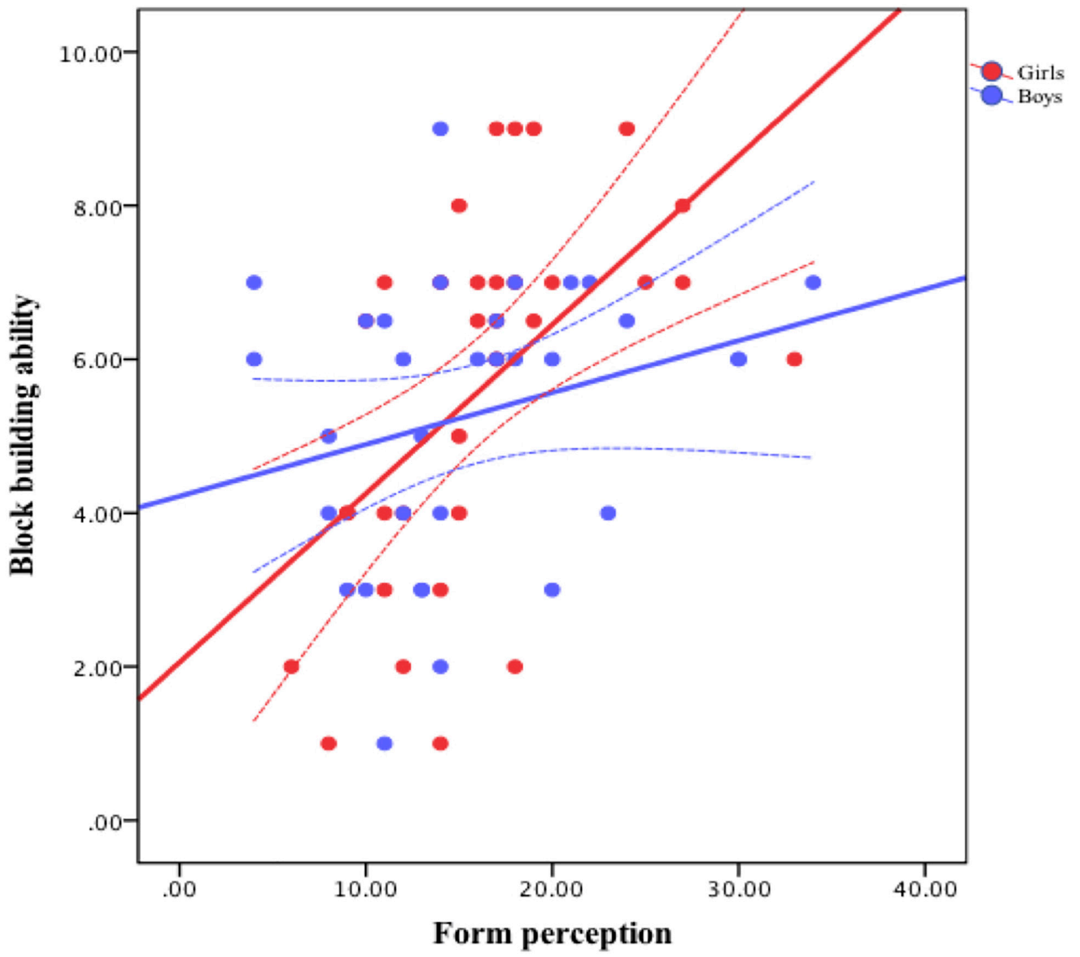

FIGURE 5 | The association between form perception and block building ability by gender.

TABLE 3 | Hierarchical linear regression predicting block building ability (*N* = 66).

	B	SE	*t*	*p*	*F*	*df*	*P*	Adj. R^2	Δ Adj. R^2
Step 1	–	–	–	–	7.03	63	0.002*	0.16	0.16
Age	3.03	0.82	3.68	0.000***	–	–	–	–	–
Gender	−0.27	0.48	−0.55	0.582	–	–	–	–	–
Step 2	–	–	–	–	6.26	60	0.000***	0.29	0.13
Shape naming	−0.07	0.30	−0.23	0.818	–	–	–	–	–
Shape recognition	0.57	0.26	2.19	0.033*	–	–	–	–	–
Shape composition	0.57	0.27	2.08	0.042*	–	–	–	–	–
Step 3a (interaction term was added one at a time)	–	–	–	–	6.90	59	0.000***	0.35	0.06
Gender*shape naming	−1.16	0.44	−2.64	0.011*	–	–	–	–	–
Step 3b	–	–	–	–	6.91	59	0.000***	0.35	0.06
Gender*shape recognition	−1.19	0.45	−2.65	0.010**	–	–	–	–	–
Step 3c	–	–	–	–	5.61	59	0.000***	0.30	0.01
Gender*shape composition	−0.64	0.46	−1.38	0.174	–	–	–	–	–
Step 3d	–	–	–	–	6.09	59	0.000***	0.32	0.03
Age*shape naming	−1.56	0.80	−1.95	0.056	–	–	–	–	–
Step 3e	–	–	–	–	5.16	59	0.000***	0.28	-0.01
Age*shape recognition	−0.25	0.68	−0.37	0.711	–	–	–	–	–
Step 3e	–	–	–	–	5.33	59	0.000***	0.29	0.00
Age*shape composition	−0.91	1.02	−0.89	0.377	–	–	–	–	–

To simplify the presentation, only new variables for each step are shown because the effects of the variables from earlier steps did not change much in the subsequent steps.

of shape recognition and gender. None of the interaction terms with age were significant.

DISCUSSION

The current study aimed at investigating the underlying cognitive mechanism of block-building complexity. We found that three measures of form perception (shape naming, shape recognition, and shape composition) were significantly correlated with block-building complexity, but the fourth measure (3-D shape naming) was not. In addition, neither of the two measures of spatial visualization (mental rotation and cube transformation) were a significant correlate. Finally, form perception and the specific skill of shape recognition had significant interactions with gender.

Our correlation results of form perception and block-building ability shows that block building relies on children's growing understanding of topological and geometrical knowledge (Hanline et al., 2001) and figure abstraction (Caldera et al., 1999). The more children know about wooden unit blocks containing a variety of shapes (Hsieh and Mccollum, 2018), the more they can manipulate different shapes, and the more complex their patterns of block building become (Stannard et al., 2001). Our quantitative results are consistent with Park et al. (2008) qualitative analysis that found three major actions (i.e., categorizing geometric shapes, composing a larger shape with smaller shapes, and transforming shapes) in free play with wooden unit blocks. The lack of a significant association between 3-D shape naming and block-building complexity was probably due to these young children's poor understanding of the names of 3-D shapes, with a mean of 1.44, suggesting a floor effect. Children of this age probably use 2-D names to describe 3-D shapes.

Interestingly, there was a gender difference in the association between form perception in general (and shape recognition in particular) and block-building complexity. It seems that girls may benefit more from shape recognition in the development of block-building complexity than boys. Previous research has shown that, compared to boys, girls include more symbolic features of constructions, such as doors and towers (Ramani et al., 2014), and pay more attention to unique shapes (Caldera et al., 1999). Boys seem to be able to build complex constructions regardless of whether they can recognize the shapes correctly. One possible interpretation of this gender interaction is that, compared to boys, girls had significantly higher verbal abilities in childhood (Toivainen et al., 2017) and were more likely to use strategies based on verbalization in the spatial tasks (Tzuriel and Egozi, 2007), so shape recognition (i.e., understanding the labels of shapes) played a more central role in girls' block building. In contrast, boys were less able to understand the labels (i.e., recognize) shapes, so their block-building ability was hence dependent not on their ability to recognize shapes but simply relied on their shape composition ability as found in this study.

Not surprisingly, we also found that the block construction complexity increased with the chronological age of children, consistent with previous research (Hanline et al., 2001). Interestingly, however, none of the interactions with age were significant. It seemed that within the age range studied, the spatial skills needed for block building were consistent. Future research should expand the age range and investigate the time points at which specific spatial skills may play different roles in block building.

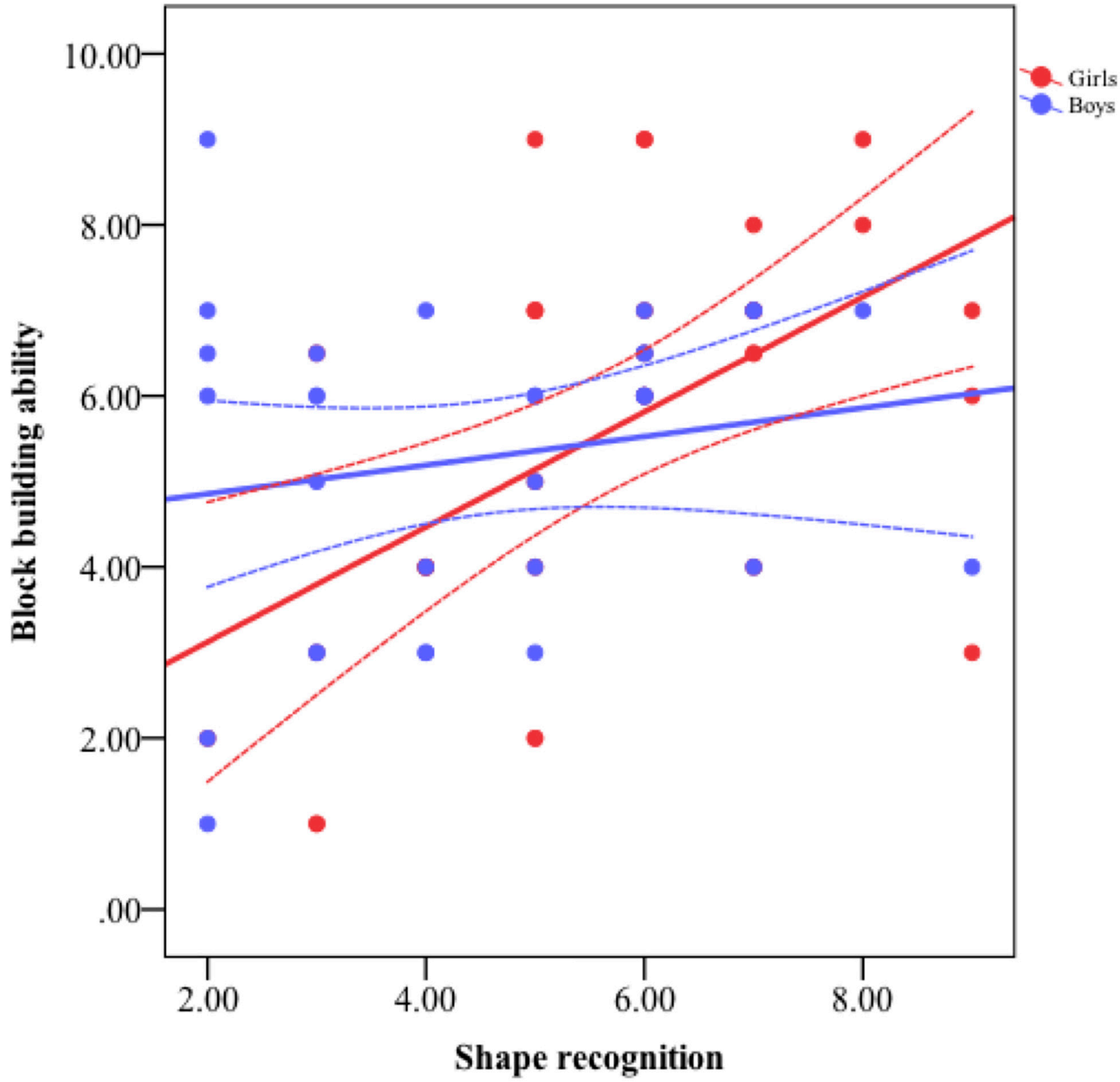

FIGURE 6 | The association between shape recognition and block building ability by gender.

Neither of the two measures of spatial visualization (cube transformation and mental rotation) were significantly correlated with block-building complexity, supporting the limited literature showing a lack of association between spatial visualization and block-building *complexity* in children (Caldera et al., 1999; Casey et al., 2008). Interestingly, a number of previous studies found significant correlations between spatial visualization and block-building *accuracy* (based on structured block-building tasks). It seems that different kinds of block play activities may require different skills and tap into different abilities (Ramani et al., 2014). Free play exposes children to imagination, creativity, problem-solving, and abstract thinking challenges, which can improve the ability of producing complex relations (Verdine et al., 2014b; Otsuka and Jay, 2017), whereas structured block building stimulates spatial visualization, patterning, and transformation (Ramani et al., 2014; Verdine et al., 2014b).

As mentioned earlier, block building has been found to be beneficial for children's cognitive development and their later school achievement. As a key preschool activity and a reliable measure of children's intellectual development, block building has gained more and more interest from researchers of early education. Our results provide new insights into the development of children's block-building complexity. Educators should pay attention to shape knowledge and their differential roles for boys vs. girls to enhance children's block play complexity.

The present study has several limitations that should be addressed in future research. First, the sample size is small and all participants came from one preschool, which limits the generalizability of our conclusion. Also due to the sample size, we did not further correct for multiple comparisons. Further research with a larger sample is needed to confirm the results. Second, we included only two measures of spatial visualization (2-D mental rotation and 2-D to 3-D transformation) and these tasks appeared to be somewhat difficult for these young children. More measures of spatial visualization with appropriate levels of difficulty for preschoolers are needed before we can firmly conclude that spatial visualization plays little role in block-building ability. Third, we studied only one age group. It is important to examine whether form perception and spatial visualization affect block building differentially at different age levels. Finally, as mentioned above, the spatial abilities related to block-building complexity may be different from those related to block-building accuracy. Therefore, different tasks are needed that can capture both accuracy and complexity in order to compare their differential cognitive mechanisms.

In summary, the current study investigated the relationships between block-building complexity and spatial skills including form perception (shape naming, shape recognition, shape composition, and solid figure naming) and spatial visualization (cube transformation and mental rotation). Form perception measures generally had significant relations with block-building complexity, but those of spatial visualization did not. There was also some evidence that shape recognition (and possibly shape composition) may be more relevant for girls than for boys.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Collaborative Innovation Center of Assessment for Basic Education Quality, Beijing Normal University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

XZ had overall responsibility for the research design, data collection, data analysis, and draft writing. CC was responsible for research design and draft editing, as well as interpreting all the data and results. TY was responsible for analyzing the data. XX was responsible for research design, participants' employment, and reviewing the manuscript. All authors contributed to the article and approved the submitted version.

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The Use of a Novel Term Helps Preschoolers Learn the Concept of Angle: An Intervention Study With Chinese Preschool Children

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Angle is an important concept in geometry. Young children have difficulty separating angle size from other dimensions such as the length of angle sides, perhaps due to whole-object bias in word learning. The present study used the pre-test–training–post-test design to investigate the effectiveness of two ways of separating angle from angle size in 3–6-year-old Chinese preschoolers. A total of 228 children were given a pre-test and 219 of them failed the crucial test. 168 of the 219 children were present at school during the training phase and were randomly assigned to three groups: the "toma" group (n = 57), which received training to call the whole angle figure as "toma" and angle size as angle size; the "angle/angle size" group (n = 56), which received the training of separating "angle" from "angle size"; and the control group (n = 55), which used "angle size" alone to represent both the overall angle figure and angle size. Results showed that the "toma" group improved significantly more than the other two groups, the latter of which did not differ from each other. These results suggest that it is insufficient to have two separate words/phrases (angle and angle size) for children to learn to differentiate angle from angle size, perhaps due to their shared usage of the word *angle*. Instead, the use of a novel term is necessary and sufficient to improve learning. Implications for preschool education are discussed.

Keywords: preschooler, angle, intervention, novel term, whole-object assumption

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INTRODUCTION

Angles are an important visual experience. As early as a few hours after birth, neonates already show sensitivity to the two fundamental properties of Euclidean geometry, angle and length (Schwartz et al., 1979; Cohen and Younger, 1984; Slater et al., 1991; Lourenco and Huttenlocher, 2008; Lindskog et al., 2019). Despite the early-developing sensitivity to angle, however, school children have great difficulty learning the concept of "angle size" (Clements and Battista, 1992; Mitchelmore and White, 2000). When comparing the size of angles, elementary and even middle school students are often confused by irrelevant properties such as the length of an angle's sides, the area within the sides, and the distance between the sides. For example, they would mistakenly judge that the angle formed by longer lines is larger than the same angle formed by shorter lines (Clements and Battista, 1989; Lindquist and Kouba, 1989; Lehrer et al., 1998; Huangpu, 2009).

Why do school children fail to take advantage of early sensitivity to angle to learn the concept of angle size? According to Van Hiele's model of geometric reasoning (Van Hiele, 1986), children learn to use a holistic processing approach to understanding geometric shapes. When learning a new concept such as angle, children make the whole-object assumption, i.e., a novel label is likely to refer to the whole object and not to its parts, substance, or other properties (e.g., Markman and Hutchinson, 1984; Landau et al., 1988; Hollich et al., 2007). When an adult points to an angle size and says "angle or angle size" in the classroom or in daily life, children map "angle size" to the entire angle figure. Therefore, they do not separate the size of an angle from its other dimensions such as length or area (Clements and Battista, 1989). What can educators do to help children to learn the concept of angle size? One way to force the children to separate angle size from other dimensions is to give separate labels for the angle size ("angle") and the whole angle figure ("toma"), as demonstrated by Gibson et al. (2015). Specifically, children in the experimental condition were given a label "toma" referring to the entire angle and "angle" referring to the size of an angle, and children in the control condition were given one label "angle" referring to both the whole angle and angle size as is done in daily English usage. Result showed that children in the experimental condition significantly improved in their understanding of the concept of angle size and the improvement was greater than that in the control condition.

Building on Gibson et al.'s (2015) finding that a novel term can help 4 year olds learn to differentiate angle size from angle, the current study aimed to expand this line of research in the following ways. First, we extended this research to a Chinese sample. Cultural differences in general and linguistic differences in particular between Chinese and Americans have been found to affect language learning (Tardif et al., 1997, 1999) and mathematical cognition even in preschoolers (e.g., Kelly et al., 1999; Zhou et al., 2007; Siegler and Mu, 2008; Xu et al., 2013). This study aimed to test whether the "toma" intervention would also be effective among a group of Chinese preschoolers. Second, in addition to the "toma" intervention condition and a control condition, we added a third condition that included another way of separating "angle (jiao)" and "angle size (jiaodu)" commonly used by Chinese elementary and middle school teachers. If the mere use of separate labels would be sufficient, the use of two labels "angle" and "angle size" should lead to improved learning of the concept of angle. On the other hand, the fact that both labels still include the word "angle" may not help children to learn the concept of angle. Third, previous studies have found significant gender differences in children's geometric and spatial cognition (Spelke, 2005; Davies and Uttal, 2007; Halpern et al., 2007; Tzuriel and Egozi, 2010; Tian et al., 2018). Gender difference was not examined in Gibson et al.'s study, perhaps due to its limited sample size (N = 30). This study used a much larger sample (N = 228) and investigated gender differences in children's understanding of angle and angle size and in the potential effects of the interventions. Fourth, age is another factor that was not examined in Gibson et al.'s study, which included only 4–5-year-olds (M_{age} = 4.86 years). Given the rapid changes in whole-object bias and mutual exclusivity bias in early childhood (Markman and Wachtel, 1988; Soja et al., 1991; Hall et al., 1993), we included a wider age range (from 3 to 6 years of age) to examine whether the effect of the "toma" intervention would be similar for children younger and older than those in Gibson et al. experiment.

MATERIALS AND METHODS

Participants

This experiment was carried out at two preschools in an average neighborhood in Beijing. Children were initially tested to assess their understanding of the concept of angle. Those who did not understand the concept served as the sample for experiment. The pre-test included 228 children from three grade levels (young, middle, and older preschoolers). The young (first-year) preschoolers included 72 children (44 boys, 28 girls, M_{age} = 3.65 years, SD = 3.15, age range: 3.25–4.25 years), the middle (second-year) preschoolers included 75 children (43 boys, 32 girls, M_{age} = 4.66 years, SD = 3.70, age range: 4.00–5.25 years), and the older (third-year) preschoolers (equivalent to American kindergarteners) included 81 children (49 boys, 32 girls, M_{age} = 5.66 years, SD = 3.52, age range: 5.00–6.25 years). Participation was voluntary and neither children nor teachers received compensation. Parental consent was obtained before the experiment. The experimental protocol was approved by the IRB of Capital Normal University.

Based on the pre-test, almost all children (219 of 228) lacked an understanding of angle size as a separate dimension from the angle figure (see **Table 1**). The subjects who lacked an understanding of angle served as the pool for the intervention. Due to illness and other reasons (vacation, celebrations, etc.), 51 children did not come to school to take part in the experiment. The rest of the children (N = 168) finished the experiment. The

TABLE 1 | Distribution of subjects with different pre-test scores on the length-inconsistent task.

	0 points	Above 0 points	Total
Boy			
Young	44	0	44
Middle	43	0	43
Old	44	5	49
Total	131	5	136
Girl			
Young	28	0	28
Middle	30	2	32
Old	30	2	32
Total	88	4	92
Total			
Young	72	0	72
Middle	73	2	75
Old	74	7	81
Total	219	9	228

"toma" group included 57 children (35 boys, 22 girls; 19 young preschoolers, 20 middle preschoolers, 18 older preschoolers), the "angle/angle size" group included 56 children (34 boys, 22 girls; 19 young preschoolers, 19 middle preschoolers, 18 older preschoolers), and the control group included 55 children (32 boys, 23 girls; 18 young preschoolers, 19 middle preschoolers, 18 older preschoolers).

The Conditions

For the "toma" condition, we used the Gibson intervention strategies. Children were taught that the label "toma (tuoma in Chinese)" represented the overall angle figure and the word "angle size (jiaodu)" referred to the measure of rotation of an angle figure (Note: Gibson et al. used "angle," which can be translated into either jiao or jiaodu. We used "angle size (jiaodu)" because of its clarity in Chinese.). For the "angle/angle size" condition, children were taught that the label "angle (jiao)" represented the overall angle figure and the word "angle size (jiaodu)" referred to the measure of rotation of an angle figure, which was the same as in the "toma" condition. In the control condition, children only heard the word "angle size" in reference to both the overall angle figure and the measure of rotation of an angle figure. We could have used "angle (jiao)" in reference to both concepts for the control condition or for an additional condition. However, the ultimate aim is to help children learn the concept of angle size (jiaodu), so we used this term because of its precision and clarity (see **Table 2**).

Pre-test and Post-test Task

We adapted Gibson et al.'s (2015) angle rotation comparison tasks. There were three types of angle rotation comparison tasks: *length-consistent*, *length-neutral*, and *length-inconsistent* trials, with 6 trials for each type and 18 trials in total (see **Figure 1**). On each trial, children were presented with a card depicting two angle figures and asked: "Can you tell me which one has the bigger angle size (jiaodu)?" Each angle figure was formed by two line segments that met at a single point. On the length-consistent trials, the larger angle size also had longer sides, and the smaller angle size had shorter sides. Children could judge correctly based on the length of the sides of the angles even if they were unable to properly compare the measurement of rotation of an angle figure. In other words, this task only assessed whether children had the general sense of larger or small geometric objects. On the length-neutral trials, the figure varied in angle size but not in length of the sides. This task controlled for one dimension (length) but no other dimensions (e.g., area), so it required a bit more sense of geometric shapes than the length-consistent task. On the length-inconsistent trials, the larger angle size had shorter sides than the smaller angle size. This is the crucial task that taps children's true understanding of the dimension of angle size.

All figures were arranged in the same orientation with a horizontal base and the vertex on the left side of the page. There were six pairs of angle figures (two pairs of acute angles, two pairs of obtuse angles, and two pairs of one acute angle vs. one obtuse angle) in each type of tasks. The pair of angles for each trial were arranged vertically, one at the top and the other one at the bottom. Three pairs of angle figures had the bigger angles at the top, and the other three pairs had the bigger angles at the bottom. Children were given 1 point for each correct answer and 0 points for wrong answers. Each type of tasks had a score range of 0–6 points.

Training

The training session consisted of three parts: introduction, description, and guided practice. The instructions were the same as those used by Gibson et al. (2015) except that they were given in Chinese.

In the introduction phase of training, all children were shown a picture of a single acute angle figure and then four pairs of angle figures (two pairs of acute angles and two pairs of obtuse angles). The angle figures within each pair had different side lengths but the same angle size. In the "toma" and "angle/angle size" experimental conditions, the experimenter pointed to the single acute figure and said, respectively, "This is a toma/angle. Can you say toma/angle." Then in the "toma" experimental condition, the experimenter pointed to each figure and said: "Here are two tomas. Here is a bigger toma and here is a smaller toma. Can you point to the bigger toma? Can you point to the smaller toma?" In the "angle/angle size" experimental condition, the experimenter pointed to each figure and said: "Here are two angles. Here is a bigger angle and here is a smaller angle. Can you point to the bigger angle? Can you point to the smaller angle?" Each of the four trials was repeated once and the experimenter provided feedback regardless of whether the child was correct or incorrect (i.e., "Right! This is the bigger toma/angle!" or "Oops! This is the bigger toma/angle"). In the control condition, the experimenter pointed to the single acute angle and said: "This is an angle size. Can you say jiaodu?" Then experimenter simply pointed to each figure and said: "Here are two angle sizes. Here is an angle size and here is the other angle size. Can you point to an angle size? Can you point to the other angle size?" Each of the four trials was repeated once and the experimenter provided encouragement each time the child correctly pointed to the two angle sizes.

TABLE 2 | The terms used in Gibson et al.'s and current studies.

Condition	Gibson et al.'s study		Current study	
	Overall angle figure	**Measure of rotation of an angle**	**Overall angle figure**	**Measure of rotation of an angle**
Toma	Toma	Angle	Toma (tuoma)	Angle size (jiaodu)
Angle/angle size	–	–	Angle (jiao)	Angle size (jiaodu)
Control	Angle	Angle	Angle size (jiaodu)	Angle size (jiaodu)

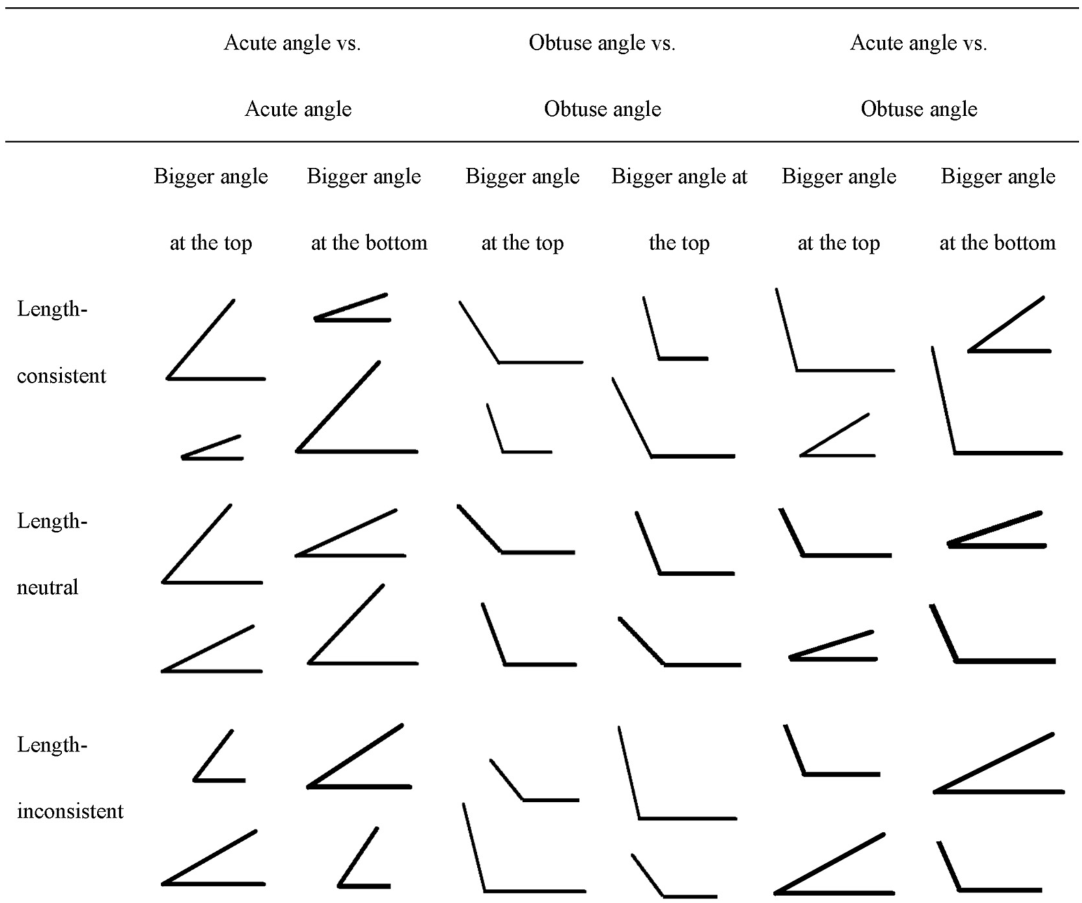

FIGURE 1 | Angle comparison task.

In the description phase of training, all children were shown a picture of a single angle figure with the arc of the angle highlighted by an arrow. The three groups of children were told, respectively: "Let's take a close look at the toma/angle/angle size. There are two lines (experimenter traces the sides) the top line opens up (experimenter traces the arrow) to form an angle size (experimenter points to the center of the figure)." This was repeated three times for each child.

In the guided practice phase of training, all children were given three length-consistent and three length-inconsistent trials. The order of presentation of the trials was the same for every child (one pair of acute angles, one pair of obtuse angles, and one pair of one acute angle vs. one obtuse angle in each type of trails). In the two experimental conditions, children were presented with the first pair of angles and asked: "Can you point to the bigger toma/angle?" After the children answered, experimenter gave feedback to them ("Right! This is the bigger toma/angle" or "Oops! This is the bigger toma/angle") and then told: "Now let's look at the angle size. This is the bigger angle size (experimenter points to center of the figure with larger angle size) and this is the smaller angle size (experimenter points to center of the other figure). Can you show me the bigger angle size?" Again, children received feedback (Right! This is the bigger angle size" or "Oops! This is the bigger angle size"). This process was repeated for all six trials. After going through all trials once, the same six trials were repeated a second time during which the children were only asked: "Can you show me the bigger angle size?" Again, all children received feedback regardless of whether or not they were correct. In the control condition, children saw the same six trials, but were not asked to identify the larger toma/angle. They were only told: "Here are two angle sizes. This is the bigger angle size (experimenter points to the center of one figure) and this is the smaller angle size (experimenter pointed to the center of the other figure). Can you show me the bigger angle size?" The six trials were repeated a second time, and children were only asked: "Can you show me the bigger angle size?" All children received feedback regardless of whether or not their responses were correct as was the case in the experimental conditions.

Procedure

The experimenters were two Chinese female postgraduate students. The pre-test, training, and post-test were all administered individually. The pre-test and post-test sessions lasted 3–5 min each, and the training session lasted 5–7 min. In the pre-test, length-consistent tasks were performed first, then length-neutral tasks, and finally length-inconsistent tasks. In each type of tasks, the tasks of two pairs of acute angles were conducted first, then the tasks of two pairs of obtuse angles, and finally the tasks of two pairs of one acute angle vs. one obtuse angle. In the post-test, only length-inconsistent task was used because children showed perfect or near-perfect performance on length-consistent and length-neutral tasks in the pre-test (see section "Results" for details). The training session was conducted 3 days after the end of the pre-test, and the post-test was conducted 3 days after the training.

RESULTS

In terms of the pre-test results, a 3 (age: young, middle, old) × 2 (gender: boy, girl) × 3 (type: length-consistent, length-neutral, length-inconsistent) mixed-design analysis of variance (ANOVA) revealed a significant main effect of type of task, $F(1.10, 243.25) = 6{,}322.87$, $p < 0.001$, $\eta_p^2 = 0.97$, reflecting children's better performance at length-consistent tasks and length-neutral tasks than length-inconsistent tasks (see **Figure 2** and **Table 1**). Children's performance on the former two tasks was near perfect and that on the third task was near zero. In other words, all children had a general sense of the geometric shape of an angle but few were able to separate the dimensions of angle size from the overall size of the angle figure. A significant main effect of age, $F(2, 222) = 4.42$, $p < 0.05$, $\eta_p^2 = 0.04$, and a significant Age × Type interaction effect, $F(2.19, 243.25) = 3.07$, $p < 0.05$, $\eta_p^2 = 0.03$, were found, reflecting older preschoolers' better performance on the difficult length-inconsistent task than middle and young preschoolers. There was no significant main effect of gender, $F(1, 222) = 0.21$, $p = 0.65$, $\eta_p^2 = 0.001$, nor was there significant interaction effect of Age × Gender × Type, $F(2.19, 243.25) = 0.69$, $p = 0.52$, $\eta_p^2 = 0.01$.

Given the results of the pre-test (near perfect scores on the length-consistent and length-neutral tasks), only the length-inconsistent task was administered at the post-test. Because the pre-test scores of all children on the length-inconsistent task were 0 points (as an inclusion criterion for the intervention part of the study), we only used the post-test scores as the dependent variable to examine the effect of the intervention. A 3 (age: young, middle, old) × 2 (gender: boy, girl) × 3 (condition: toma, angle/angle size, and control) ANOVA revealed a significant main effect of condition, $F(2, 150) = 19.25$, $p < 0.001$, $\eta_p^2 = 0.20$ (see **Figure 3**). The "toma" group performed significantly better than the other two groups, and the latter two groups did not differ from each other. A more detailed presentation of the condition effect is shown in **Figure 4**. More children in the "toma" group scored 5 or 6 points than did those in the other two conditions. In contrast, more children in the control and the angle/angle size groups scored 0 or 1 point than did those in the "toma" group. There was a main effect of age, $F(2, 150) = 13.60$, $p < 0.001$, $\eta_p^2 = 0.15$, with young preschoolers showing poorer performance than middle and old preschoolers, and the latter two groups not differing from each other. There was not a main effect of gender, $F(1, 150) = 4.02$, $p = 0.05$, $\eta_p^2 = 0.03$. Finally, there were no significant interactions between condition and age, $F(4, 159) = 2.39$, $p = 0.09$, $\eta_p^2 = 0.05$, between condition and gender, $F(2, 150) = 0.92$, $p = 0.40$, $\eta_p^2 = 0.01$, and among condition, age, and gender, $F(4, 150) = 1.24$, $p = 0.30$, $\eta_p^2 = 0.03$.

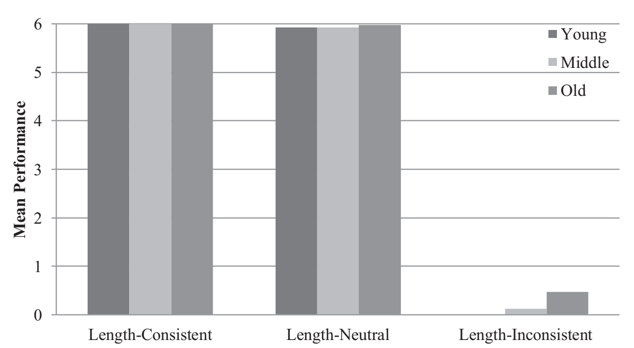

FIGURE 2 | Mean pre-test performance by age group and task type.

DISCUSSION

The current study investigated the effectiveness of two interventions on Chinese preschoolers' understanding of the concept of angle. Results showed that the novel term (toma) intervention based on Gibson et al. (2015) was effective but the "angle/angle size" intervention that is commonly used by Chinese teachers in the classroom was not, suggesting that children's learning of the concept of angle can be facilitated by two completely different labels (e.g., with a new term), but not by two separate but related labels, for angle and angle size. We further found that Chinese preschoolers showed the same error pattern as their Western partners, but weaker performance on the understanding of angle concept; that gender did not affect the development of the concept of angle and the intervention effect; and that the intervention was equally effective across the age groups included in this study. In the following paragraphs, we compare our results on Chinese children to Gibson et al.'s results on American children and discuss their contributions to our understanding of children's concepts of angle and angle size and their implications for preschool mathematics education.

First, our pre-test results revealed that Chinese preschoolers showed the same angle misconception and error pattern as American children did (Gibson et al., 2015). Chinese 3–6 year old children showed perfect or near-perfect performance on the length-consistent (mean proportion correct = 100%) and length-neutral tasks (mean proportion correct = 99%) but they almost completely failed on the length-inconsistent tasks (mean proportion correct = 3%, ranging from 0% for young preschoolers to 2% for middle schoolers and to 8% for old preschoolers). Gibson et al. (2015) also found that the length-consistent and length-neutral tasks were easier than the length-inconsistent task, but the accuracy rates were quite different from those found in the current study. The mean proportions of correct responses were 93, 84, and 25% for the three types of tasks, respectively, among their sample of American 4–5 year olds (corresponding to the middle group in our sample). Not

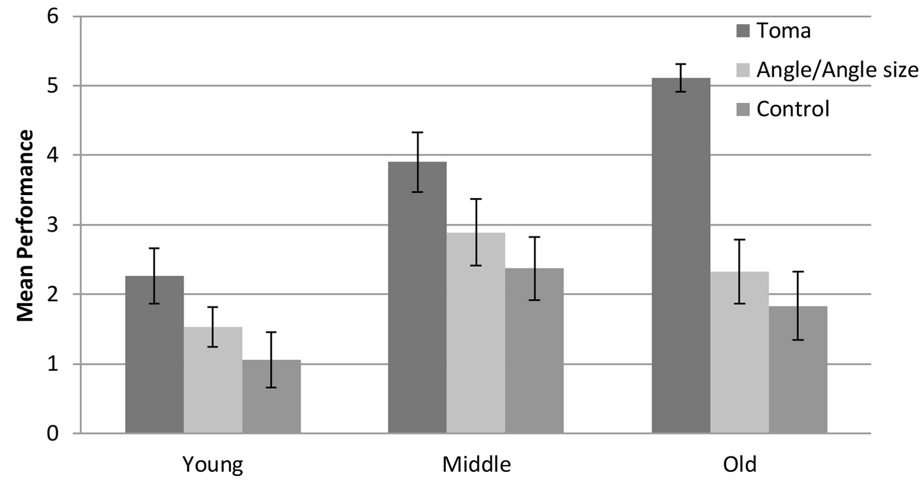

FIGURE 3 | Mean post-test performance on length-inconsistent tasks by condition and age group.

surprisingly, in both countries, children seem to have a general sense of the angle figure as an object and can judge its size by one or more of its dimensions (angle size, angle side length, or area), but have difficulty understanding angle size as a separate dimension from the angle figure, as shown in poorer performance when the length of the sides and angle size were inconsistent. This pattern of results is consistent with Van Hiele's model of the development of geometric reasoning. According to that model, young children use a holistic processing approach to understanding angles and do not focus on separate dimensions such as angle size and side length. It is worth noting that our study did not find gender differences in Chinese preschooler's angle misconception, which is consistent with some of the previous studies about children's spatial reasoning (e.g., Spelke et al., 2011), but not others (Spelke, 2005; Davies and Uttal, 2007; Halpern et al., 2007; Tzuriel and Egozi, 2010; Tian et al., 2018). Future research needs to investigate the conditions under which gender differences in children's geometry cognition and spatial reasoning occur.

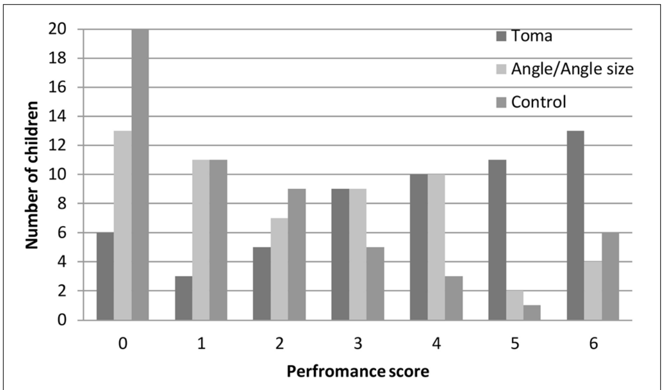

FIGURE 4 | Distribution of children's post-test scores on the length-inconsistent task by condition.

Despite the same pattern of task type differences in Gibson et al. (2015) and our studies, the children in our study appeared to perform somewhat better on the length-consistent and length-neutral tasks but much worse on the length-inconsistent tasks as compared to American children in Gibson et al.'s study. Chinese children even younger than the American preschoolers (the young preschooler group in our study) had no difficulty with the length-consistent and neutral tasks. In contrast, Chinese children even older than American preschoolers (the old preschooler group in our study) performed poorly on the length-inconsistent task. In other words, Chinese children's poorer performance on the length-inconsistent task cannot be attributed to their general sense (or holistic processing) of angle figures. What then would explain their poorer understanding of the concept of angle? Although it is perilous to compare results from different studies, one plausible explanation is that the preschool and kindergarten education guidelines in China emphasize knowledge about numbers, not geometry. The latter is limited to shape naming, recognition, matching, classification, and composition (Department of Basic Education of Ministry of Education of P. R. China. (Ed.)., 2002). Consequently, Chinese parents also pay more attention to mathematics instruction about number cognition such as counting, solving arithmetic problems, and magnitude comparison than to that about geometry (Pan et al., 2006; Zhou et al., 2006, 2007). In contrast, NCTM (1991, 2006) in the United States emphasizes that geometry and spatial reasoning is an important area of mathematic learning for early childhood. Izard and Spelke (2009) and Izard et al. (2014) even found that American 4 year old children were capable of comparing angles across two- and three-dimensional figures. Therefore, cross-country differences in early education practices might have contributed to Chinese preschoolers' better performance on number cognition as reported in the literature (e.g., Kelly et al., 1999; Zhou et al., 2007; Siegler and Mu, 2008; Xu et al., 2013) but weaker performance on the concept of angle found in this study and possibly other geometric knowledge beyond shape cognition.

Second, our study confirmed that the "toma" intervention was effective among Chinese children as it did for American children. Furthermore, it was equally effective for young, middle, and old preschoolers (as shown by the non-significant interaction between age group and condition). This result is consistent with the whole-object assumption about word-learning bias and the mutual exclusivity bias. According to the whole-object assumption, children tend to interpret a novel term as a label for the whole object and not its parts or properties (e.g., Markman and Hutchinson, 1984; Landau et al., 1988; Hollich et al., 2007). After learning a label for an object, children would have to understand that another label means something else due to the mutual exclusivity bias (Markman and Wachtel, 1988). Specifically, when children learn that "toma" represents the whole angle figure, they would not map "angle" onto the overall angle figure but instead onto a new property, which in the current case is the measure of rotation of an angle. In sum, a novel label helps children to separate the size of an angle from the overall angle figure.

Third, to investigate whether the mere use of two separate labels that refer to the whole figure of an angle and the size of an angle, respectively, would help children overcome the misconception of angle size, we used "angle (jiao)" and "angle size (jiaodu)" in the other experiment condition. These two terms are commonly used by elementary and middle school teachers in China. Results showed that this condition did not improve the learning of the concept of angle. One explanation is that "angle (jiao)" and "angle size (jiaodu)" are synonyms in Chinese vocabulary, so the separate label "angle" is not a novel enough word for Chinese preschoolers to be used to refer to the whole figure of an angle. In other words, the close proximity of the two words and/or the lack of novelty of the new word might have prevented children from separating the whole figure of an angle from the size of an angle.

Our results have important implications for preschool education. Our results suggest that using a novel term as a second label is very effective for teaching young children about angles by helping them attend to angle size as an independent dimension of the overall figure. This recommendation seems to counter the traditional practice of introducing one concept at a time used by Chinese preschool teachers and the common use of angle and angle size distinction by elementary and middle school teachers. Our findings suggest that children can gain a more accurate understanding of a concept by comparing easily confusable meanings with new terms, consistent with the thinking that analogy and structural alignment are powerful learning tools (e.g., Gentner and Markman, 1994, 1997). If Chinese teachers do not want to introduce a novel term and would rather continue using angle and angle size, they should consider using enriching or contextual information to help differentiate the two terms. For example, they can explain that "This is an angle, like a pair of scissors" rather than simply using the ostensive definition (e.g., "This is an angle"). Indeed, previous research has found that different introductory cues produce different learning outcomes (Hall et al., 1993; Congdon et al., 2018).

Finally, we note several limitations of the current study and discuss their implications for future research. First, our pre-test results seemed to show significant differences between Chinese and American preschoolers in their understanding of the concept of angle, but the conclusion needs to be substantiated with a cross-national study using exactly the same experimental and sampling procedure. Second, although we expanded Gibson et al.'s (2015) age range, our study still focused on preschoolers. Given the importance of learning the concept of angle in elementary school, future research should include elementary school students to examine the effectiveness the "toma" intervention and the "angle/angle size" intervention. Perhaps elementary school students may have a better appreciation of the distinction between angle and angle size to benefit from that intervention. Third, as mentioned earlier, our control condition used angle size (jiaodu) to label both angle and angle size. We could have used jiao to represent both. Even though the clearer label of jiaodu did not help children learn the concept of angle, future research nevertheless should consider including an additional control condition using jiao to refer to both the overall figure and angle size. Finally, although we did not find gender differences in this study, future studies, especially those with older children, can also explore demographic and individual differences (such as gender and cognitive abilities) in the effects of interventions.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the IRB of Capital Normal University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

XX had overall responsibility for the research design, data collection, data analysis, and draft writing. CC was responsible for research design, draft editing, as well as interpreting all the data and results. JM, XZ, and MJ were responsible for the data collection and analyzing the data. ZX was responsible for research design, participants' employment, and reviewing the manuscript. All authors contributed to the article and approved the submitted version.

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Exploring the Relationship Between Parental Involvement, Paper Folding Skills, and Early Spatial Ability: A Mediation Model

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Paper folding is a common activity in East Asian kindergartens, but its potential value to early spatial skills have not been empirically explored. This study aims to investigate whether and how paper folding skills can predict spatial ability (SA) in the early years. Altogether 101 preschoolers (N_{girl} = 45, M_{age} = 4.54, *SD* = 0.75) were randomly sampled from two Hong Kong kindergartens and invited to complete the map-use and the paper folding tasks. The paper folding task taps two levels of children's paper folding skills: Basic Folding Skill (BFS) and Advanced Folding Skill (AFS). The parents reported the demographic information and their involvement in spatial activities at home. The results indicated the following: (1) there was a significant age-related increase in the paper folding performance; (2) child age could significantly predict both BFS (β = 0.551, $p < 0.001$) and AFS (β = 0.627, $p < 0.001$), while parental involvement could only predict BFS (β = 0.246, $p < 0.001$); (3) after controlling for confounders, paper folding skills could significantly predict SA as measured by the map-use task; (4) BFS was found to mediate the relationship between parental involvement and SA. The educational implications of these findings are also discussed.

Keywords: spatial ability, folding paper, early development, parental involvement, origami

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INTRODUCTION

Paper folding activity (PFA) has a long history in China ("折纸") and Japan ("Origami") and has thus been listed as an Intangible Cultural Heritage of Humanity by UNESCO. It has become a popular and substantial part of Chinese and Japanese kindergartens' learning and teaching activities (Nishida, 2019). PFA is a kind of integrated learning experience requiring young children to systematically and strategically apply their mathematic and fine motor skills; thus, it has been widely regarded as a kind of art and craft activity in the early childhood classroom. However, its potential contribution to the early development of spatial skills has not been thoroughly explored (Dinehart and Manfra, 2013; Imaroonrak et al., 2018; Widayati et al., 2019). A recent study found that paper folding skills were highly correlated with spatial ability (SA) (Taylor and Hutton, 2019), indicating that there might be a predictive relationship between them. Therefore, for the first time, this study explored the possible predictive relationships between parental involvement (PI), PFA, and early spatial skills in the context of early education in Hong Kong.

Exploring the Relationship between Parental Involvement, Paper Folding Skills and Early Spatial Ability: A Mediation Model

Paper folding activity (PFA) has a long history in China (“折纸”) and Japan (“Origami”) and thus has been listed as the Intangible Cultural Heritage of Humanity by UNESCO. It has become a popular and substantial part of Chinese and Japanese kindergartens' learning and teaching activities (Nishida, 2019). PFA is a kind of integrated learning experience requiring young children to systematically and strategically apply their mathematic and fine motor skills; thus, it has been widely regarded as a kind of art and craft activity in the early childhood classroom. However, its potential contribution to early development of spatial

PFA in Early Educational Contexts

Paper folding activity refers to the action of folding paper into representative shapes with some specific skills, which involves visual-motor integration, considerable cognitive effort, and a relatively competent level of mathematical conceptualization (Wenciker and Flynn, 2004; Cakmak et al., 2014; Tenbrink and Taylor, 2015; Arsl and Işıksal-Bostan, 2016). Usually, paper folding skills could be divided into two levels: (1) the basic level, which requires children to fold the paper in half equally and fold along the midline of the paper and demands fine-motor skills and visual-motor integrations (Harte and Spencer, 2014; Imaroonrak et al., 2018); (2) the advanced level, which requires children to fold the paper from multiple directions with different angles and demands the children to mentally distinguish the folding step from the next step and complete the folding as planned. The advanced level depends more on high-level cognitive functions such as movement planning (Yao and Dai, 2008) and working memory (Sato et al., 2007; Zhang, 2017). This study aimed to develop a new paper folding task including these two levels.

Paper folding activity has been considered as an origami-based problem-solving context to facilitate mathematical learning and teaching during primary to high school (Wenciker and Flynn, 2004; Cakmak et al., 2014; Tenbrink and Taylor, 2015; Arsl and Işıksal-Bostan, 2016; Oberman, 2018). Some scholars believe that origami could provide some unique mathematical experiences and thus establish the linkage between mathematics and the arts, lending varying pedagogical support to the learning and teaching of math (Wenciker and Flynn, 2004). Some even believed that paper folding could serve as a teaching tool in mathematics classes (Boakes, 2009). Turkish teachers even believed that origami might be a beneficial and effective method in primary mathematics education (Arsl and Işıksal-Bostan, 2016).

However, in the early childhood context, PFA has been widely regarded as a learning activity to develop young children's fine motor skills and the sense of artistry (Dinehart and Manfra, 2013; Zhao, 2015; Nishida, 2019). The existing studies have widely explored its educational values on early arts and motor skills: (1) as an art education, PFA has been implemented in Japanese kindergartens for over 140 years, serving as a kind of symbolic art and craft culture (Nishida, 2019); (2) as an indicator of fine motor skills, PFA has been used to measure young children's fine motor skills (Dinehart and Manfra, 2013; Vidoni et al., 2014; Saraiva et al., 2019); and (3) as training of visual-motor integration, PFA has been proved to significantly improve the creativity and visual-motor integration (Imaroonrak et al., 2018; Widayati et al., 2019) in young children.

Recently, STEM education has become a global concern and has been linked with PFA in the early years (Taylor and Hutton, 2013; Lippard et al., 2019). For instance, Lippard et al. (2019) regarded folding activity as a pre-engineering play in early childhood classrooms and suggested that folding activity should be considered a learning context for early engineer education (EEE). Researchers have taken SA as one of the core skills required for EEE and STEM, as empirical studies have indicated that good spatial skills significantly predict achievement in STEM (Uttal et al., 2013; Stieff and Uttal, 2015). Recognizing the correlation between PFA and SA, researchers have suggested promoting STEM education by implementing PFA in kindergartens (Taylor and Hutton, 2013; Kuhl et al., 2019). However, all these suggestions should be better justified with empirical evidence about the complicated relationships between PFA and early spatial skills.

Spatial Ability in the Early Years

Spatial ability refers to the capacity of understanding, reasoning, and remembering the spatial relations among objects or space. It has been documented as a fundamental cognitive skill with three major constructs (Uttal et al., 2013; Mix et al., 2016; Burte et al., 2017; Rittle-Johnson et al., 2019): (1) spatial visualization, which is the ability to imagine and mentally transform spatial information; (2) form perception, which is the ability to copy and distinguish shapes from other shapes, including symbols; and (3) visual-spatial working memory, which is the ability to hold the locations of different objects, landmarks, and so on in working memory. There are significant age, gender, and individual differences in the early development of spatial skills (Voyer et al., 1995; Astur et al., 2004; Parsons et al., 2004; Newcombe, 2010; Uttal et al., 2013; Rittle-Johnson et al., 2019). For example, some scholars (Peters, 2005; Maeda and Yoon, 2013) have had different views on the gender difference in SA, and Levine et al. (2016) argued that the gender gap in SA could be bridged if there was appropriate training. Therefore, it is important to ascertain the contributors from the family and preschool to better design appropriate training programs of SA (Rittle-Johnson et al., 2019).

The gender gap in SA has triggered another debate surrounding the 'nature-nurture controversy' in child development (Casey, 1996; Kass et al., 1998; Hoffman et al., 2011). On the one hand, Halpern (1992) indicated that hormones could have provided men with a slight advantage to foster SA, driving them to be willing to engage in related activities and reinforcing their SA from infancy to adulthood. On the other hand, Kass et al. (1998) argued that strong social encouragement to engage both boys and girls in spatial tasks could help narrow the gender gap in SA. Therefore, Tosto et al. (2014) conducted a comparison study with 4,174 pairs of 12-year-old twins and found that the environmental factors explained about 67% of the variation in SA, implying that SA could be 'nurtured.' Very recently, however, Rimfeld et al. (2017) duplicated the study of twins but found a greater effect of a genetic component on general SA (69%) than the environmental component (23%). They concluded that the genetic contribution to SA was generated from various kinds of genes, each making a small contribution. In Chinese children, studies have also identified significant gender differences in early SA. For example, Seng and Tan (2002) found there were cultural and gender differences in spatial abilities. Chan (2007) found differentiated gender differences: there were modest gender differences in visual arts favoring girls, while there were variations in visual orientation favoring boys. These mixed results have raised more questions in terms of how SA could be nurtured in the school and family contexts, which will be explored in this study with the newly developed map-use task. In particular, this study was focused on the relationship between PI in young children's spatial-related activities at home and children's performance on the PFA and map-use tasks.

In this study, the map-use task was developed from the one designed by Bluestein and Acredolo (1979) to evaluate early spatial skills for the following reasons. First, it is technically challenging to measure SA in young children because there is a lack of consensus on the definition and age-appropriate content (Rittle-Johnson et al., 2019). Second, two challenging problems should be solved before designing the age-appropriate measurement: (1) how to incorporate all the domains of SA into one single indicator, as different spatial tasks could only gauge different aspects of SA (Rittle-Johnson et al., 2019); and (2) how to make it workable with young children, as the existing spatial measures include paper-and-pencil tasks, the manipulation of objects, or computer-based tasks that are not applicable for young children (Ilen, 2016). Therefore, some scholars have tended to use the map-use task to evaluate young children's SA (Blades and Spencer, 1986; Freundschuh, 1990; Liben et al., 2013). Third, the map-use task mainly evaluates the ability to locate places in the room, to indicate one's own position in the room, to plan routes on maps, and so on. All these abilities could reflect (and would be affected by) the spatial visualization and spatial working memory, the two major constructs of SA (Gilmartin and Patton, 1984; Blades and Spencer, 1986; Sandberg and Huttenlocher, 2001). Finally, the existing studies by Blades and Spencer (1986) have confirmed that this task could apply to 3- to 5-year-old children. Therefore, this map-use task was revised and adopted in this study.

Folding Activity, Spatial Ability, and Parental Involvement

The relationship between folding activity and SA has been explored from two divergent perspectives: (1) folding activity supports SA; and (2) folding activity is integrated into SA. In particular, the first view has been widely employed to study early spatial development. For example, the studies on young Japanese and American children (Yuzawa et al., 1999), middle school students (Boakes, 2009), and primary students (Cakmak et al., 2014) have jointly confirmed the first view that folding activity could improve SA. Yuzawa and Bart (2002) specifically noted that the experience of origami facilitated young children's spatial learning such as size comparison. However, the second view was also supported by many psychologists who tended to use the concept 'mental folding skill' to reflect a certain aspect of SA (Milivojevic et al., 2003; Wright et al., 2008; Harris et al., 2013). For example, both Milivojevic et al. (2003) and Wright et al. (2008) employed mental folding skills as an indicator of spatial skills in adults. Harris et al. (2013) developed a mental folding test and found it applicable and reliable for young children. The mental folding task in these studies, however, mainly involved evaluating specific spatial skills (i.e., spatial transformation), leaving out most of the other domains in a physical PFA such as visual-motor integration. Thus, it should not be regarded as equivalent to the typical PFA in an early childhood setting. In this study, PFA is not a mental folding skill but a physical activity to fold papers into the target figure, which may correlate with spatial skills. Therefore, this study explored whether PFA predicts early SA.

Parental involvement has been documented to have a significant impact on children's development and later academic achievement (Fan and Chen, 2001; Jeynes, 2006, 2007; Lomax-Bream et al., 2007; Lau et al., 2012; Castro et al., 2015). According to Jeynes (2006), East Asian kindergartens, as faithful practitioners of the Froebel model, have greatly promoted PI in early educational practices. Therefore, considering PI in early SA development is suitable for the Hong Kong context (Jeynes, 2006; Lau et al., 2012). However, little is known about whether PI in spatial-related activities can enhance children's SA and whether children's performance on PFA can play a role in this relationship. There has been no consensus on the relationship between PI and SA due to the nature-versus-nurture debate of SA (Casey, 1996; Kass et al., 1998; Hoffman et al., 2011). Some researchers have held the belief that SA is predetermined by nature, and nurturing factors, such as PI, might thus play non-significant roles (Halpern, 1992). In contrast, some other scholars believed that SA could be influenced by educational factors including PI (Tosto et al., 2014). The recent study by Rimfeld et al. (2017) indicated that both the natural base and the environmental components during the nurturing process could contribute to the development of SA, implying that the effects of PI on SA might not be so direct. In addition, the link between PI and folding skills has been rarely explored. Therefore, this study is dedicated to exploring whether and how PI could predict children's SA through the potential mediation of folding paper.

The Current Study

The literature review has indicated the following relationships among PI, folding skills, and SA: (1) folding skills in early years may be influenced by PI (Fan and Chen, 2001; Jeynes, 2007; Castro et al., 2015); (2) folding skills might correlate with the SA (Boakes, 2009; Cakmak et al., 2014); and (3) PI might influence the SA, while the effect of which might not be direct (Tosto et al., 2014; Rimfeld et al., 2017). Theoretically, it is reasonable to hypothesize that the effect of PI on SA might be mediated by paper-folding skills. Therefore, an empirical exploration is needed urgently to test this hypothesis.

To achieve this end, first, this study has developed a paper folding task and analyzed its reliability and constructs with Chinese preschoolers. The malleability of paper folding skills was also examined with a focus on age and gender differences in the early years. It particularly ascertained whether the widely reported age and gender effects could be found in the two levels of paper folding tasks. Second, this study has also explored parent involvement's influences on early folding performance with those confounding variables being controlled for. Last, the predictive relationships among PI, paper folding performance (PFP), and spatial skills were investigated using a mediation model. In particular, the following four research questions guided this study:

(1) What are the reliability and potential constructs of the paper folding task newly developed in this study?

(2) Are there any age and gender differences in the folding performance in Hong Kong preschoolers?
(3) How does PI predict early folding performance after controlling for age, gender, and family SES?
(4) Does PFP mediate the relationship between PI and spatial skills?

MATERIALS AND METHODS

Participants

This study was part of a larger study examining early child development in Hong Kong. Altogether 101 children ($N_{girl} = 45$) aged from 3.08 to 5.92 ($M_{age} = 4.54$, $SD = 0.75$) were randomly sampled from two kindergartens in Hong Kong. Both kindergartens were non-profit-making organizations, providing whole-day and half-day programs with the same story-based curriculum. The Story Approach of Integrated Learning is the dominant curriculum widely used by most of Hong Kong kindergartens, allowing teachers to intergrade different learning activities into an interesting story (Li and Chau, 2010; Li et al., 2012). All the participating children were right-handed and not diagnosed with any developmental delay. The research consent forms were signed and obtained from the principals and parents in advance of data collection. Before the formal test, the first author observed and trained the participants to confirm whether they have experience of doing similar tasks. Only the children without previous exposure to the tasks were included in this study.

Measures

Map-Use Task

The map-use task was adapted from the classical experimental task developed by Bluestein and Acredolo (1979), who asked young children to identify the pictures on the map and point to the referents accordingly. This map-use task is a comprehensive test of the three constructs of young children's SA (Mix et al., 2016; Burte et al., 2017; Rittle-Johnson et al., 2019): (1) spatial visualization is the ability to imagine and mentally transform spatial information; (2) form perception is the ability to copy and distinguish shapes from other shapes, including symbols; and (3) visual-spatial working memory is the ability to hold the location information of different objects, landmarks, etc. in working memory. The Cronbach's Alpha for all the four scoring items for map-use skills was 0.67, indicating acceptable reliability.

The map-use test was conducted in the setting, as shown in **Figure 1**. The experimenter instructed the participating child as follows: "*This is the map of this room. Please have a look at this map: you are here, and the bear is over there. Please, according to this map and find the toy bear in the room.*" It was conducted during individual sessions with one experimenter following the same procedure and protocol as follows.

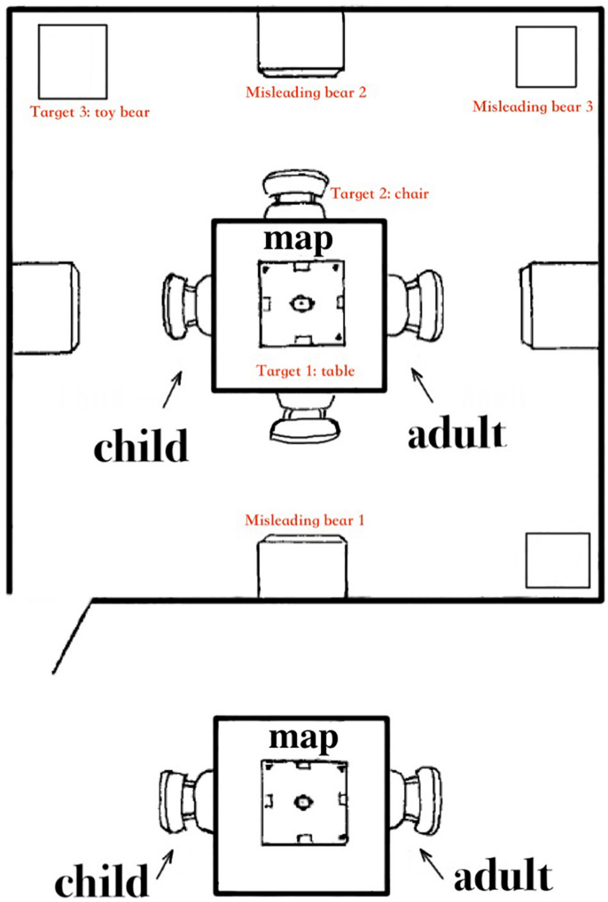

FIGURE 1 | The setting of the map-use task.

Step 1: the child was guided by the examiner to walk around in the room starting from the door, while the examiner introduced the major referents in the room matching with the map (the door and the equipment).
Step 2: the child was asked to read the map and to point out the location of the testing table in the room (scoring item 1), which mainly required the child to have the cognitive foundation of visual-spatial working memory to hold the location information of different objects and landmarks in mind and to recognize them.
Step 3: the child was asked to point out the location of the particular chair in the room (scoring item 2), which mainly demanded spatial visualization so that the child could imagine and mentally match the spatial information in the room with that on the map.
Step 4: the child was asked to stand outside the room and then find the toy bear as indicated by the map. In this step, three similar toy bears were placed in the room, including the target one and three distracting ones, to control the chance probability. When the setting was ready, the child was asked to return to his seat in the room, look at the map on the table, and go to find the toy bear (scoring item 3). To complete the task, the child's form perception was mainly involved in this step, which facilitates the child to copy and distinguish the targeted symbol on the map from the misleading ones.
Step 5: two separate goals were contained in this step, including the child's behavioral result of getting the right bear and the child's correct reflection about this behavior.

After the child got the toy bear, the experimenter asked the child to reflect whether he or she got the right bear as indicated on the map (scoring item 4). If the child answered no, he or she would then be given a second chance to find the toy bear. Then, the examiner would repeat the question asking young children to confirm whether the bear was taken from the target place marked on the map. When the child doubted his or her choice in the second time, the task was terminated, and the performance of the second time would serve for scoring. In this step, there were possible four levels of performance: (1) the child got the wrong bear but did not know it was wrong; (2) the child got the right bear but doubted his or her choice; (3) the child got the wrong bear, and realized it was wrong; (4) the child got the right bear and confirmed his or her choice. More specifically, level (1) shows that the child cannot accomplish the two separate goals, while level (4) indicates two accomplishments, and level (2) or level (3) demonstrates only one accomplishment.

The scoring process started from step 2 (scoring item 1) when the child executed the task and ended at step 5 (scoring item 4), resulting in a maximum score of 5. Specifically, from step 2 to step 4, one point was scored for each step completed, while zero point was scored if the child failed to complete that step. For step 5, different points were scored for the four levels of performance: zero points for level (1), one point for level (2) or level (3), and two points for level (4).

Paper Folding Task

In this study, we developed the paper folding task to examine children's PFP based on the two criteria: first, it should be equal to the daily folding activity in kindergartens (aged 3–5), involving the fine motor skill and visual-motor integration; second, it should involve different levels of folding competence. Accordingly, 'folding a paper tiger,' similar to one of the most popular paper folding tasks 'folding a paper plane' in Chinese and Japanese kindergartens, was developed for this study (see **Figure 2**). With the help of both the verbal instructions provided by the experimenter and the demonstrative flow diagram, the participating child went through 11 steps to take different folding actions, which could be classified into two levels of folding performance: the basic level (Basic Folding Skills, BFS) and the advanced level (Advanced Folding Skills, AFS).

As shown in **Figure 2**, BFS includes three basic folding steps and skills: Step 1 involved folding in half into a triangle; Step 2 involved folding to align the centerline; and Step 3 involved folding the target shape as shown. AFS includes the following folding actions and skills: Step 4 involves rotating the paper as shown; Step 5 involves folding down, resulting in an upside-down triangle; Step 6 involves folding up, resulting in an upside-down triangle; Step 7 involves turn-over as shown; Step 8 involves, after the turn-over, folding up, resulting in an upside-down triangle; Step 9 involves, after turn-over, folding down to make an upside-down triangle; Step 10 involves folding the two sides, resulting two hidden triangles; and Step 11 involves adding the facial characteristics of the tiger as shown. For each step, the child was allowed to have one chance to receive a cue or prompt given by the examiner. If the child failed to complete a certain step even after receiving a cue, the task would end. For each step completed, the child gets two points for successful completion without prompts, 1 point for successful completion with prompt, and 0 for failing to complete. The reliability and construct validity of this task were examined.

Parent Survey

The parents of participating children were invited to complete a parent questionnaire, which aimed to survey the demographic information and PI. The demographic information part included the monthly household income and education degrees of the parents. The PI part used a five-point Likert scale containing eight items to evaluate the frequency of parent-child activity related with SA: how often do you (1) do crafts with your child; (2) read or use a map with your child; (3) teach your child spatial relations with the reference of his or her own body; (4) teach your child spatial relations with the reference of other objects; (5) teach your child to recognize, compare and name the shapes; (6) teach your child to remember or describe the routes from home to school; (7) ask your child to guide you to somewhere familiar/playing blocks or puzzles together; and (8) play puzzle or block building with your child? The Cronbach's Alpha of the survey was 0.84 showing good reliability of the scale.

Procedures

All the tasks were administered in a classroom within the kindergartens that participants were familiar with. One examiner conducted all the tasks for each participant individually. It took a total of 15–20 min on average for each participant to complete the two tasks (5–10 min per task). Before the formal task, the first author (the examiner) invited each participant to 'participate in classroom play' and briefed them about the related information. After the participant settled down, the examiner instructed the tasks' rules and encouraged the participant to complete the task as required. To avoid the order bias, for each of the two kindergartens, half of the participants conducted the task by order of map-use task first and then the folding task, and the other half of them conducted the task in the opposite order. Participants were allowed to quit during the task for any reason.

Data Analysis

First, the reliability and construct validity of the paper folding task were examined using the factor analysis. Second, the age and gender effects in the map-use and paper folding tasks were explored by MANOVA analysis with age (3) and gender (2) as independent variables and SA and folding skills as dependent variables. Third, the relationships between the study variables were explored using the correlation analysis. Fourth, the possible contributors to young children's folding performance and its predictive power of map-use performance were investigated by two sets of hierarchical regression analyses. Last, based on the above analyses, a bootstrapping analysis

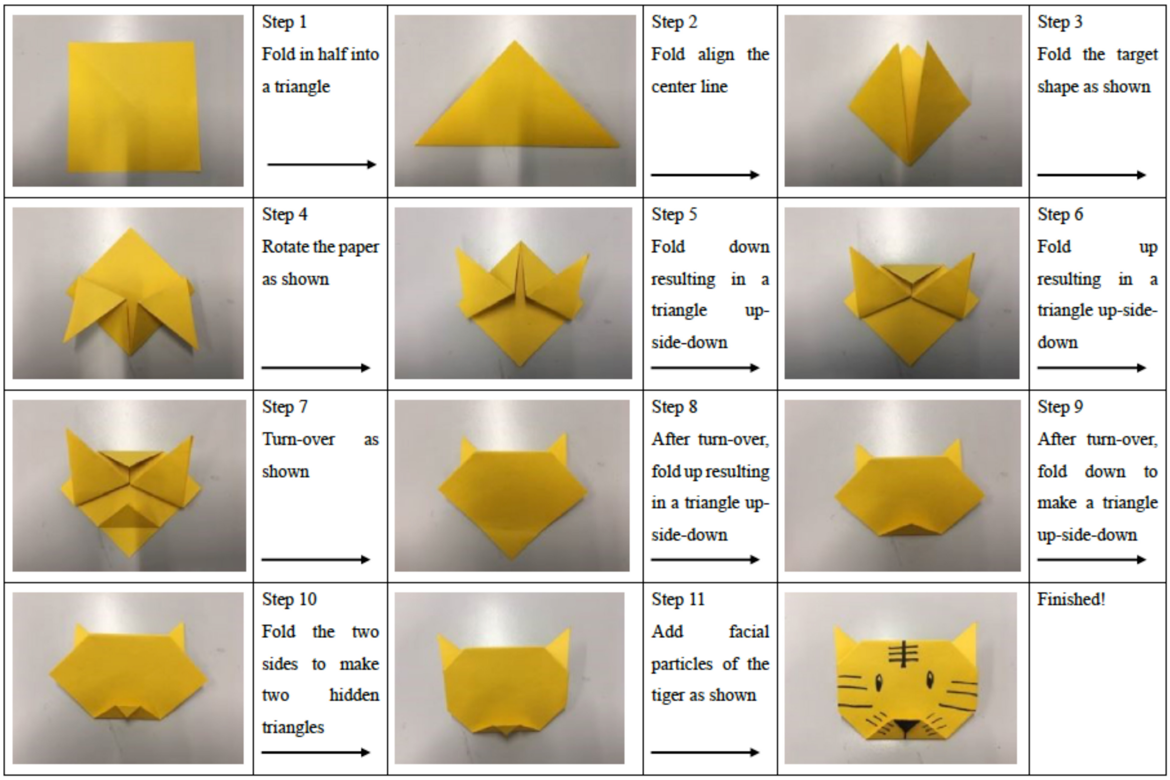

FIGURE 2 | The folding task (folding a tiger).

using IBM SPSS Statistics version 23.0 and macro-program PROCESS 3.2 was conducted to test the mediation effect of the paper-folding performance. The bias-corrected bootstrap method with 5,000 resamples was employed to calculate the 95% confidence intervals (CI).

RESULTS

Reliability and Exploratory Factor Analysis (EFA) of the Folding Task

The Cronbach's Alpha for all the 11 folding steps was 0.92, indicating excellent reliability. Principle component analysis was conducted on the sample to explore the construct validity of the folding task. First, the adaptability of the predicted data was tested, and the results indicated that the data were suitable for exploratory factor analysis, KMO = 0.914, Bartlett spherical test $\chi^2 = 664.748$ ($df = 55$, $p < 0.001$). Second, Principal Component Analysis with the Varimax rotation method yielded a two-factor model for the folding task, which could explain 9.81 and 56.04% of the variance, respectively, accounting for 65.86% of the total variation (see **Table 1**). The eigenvalues for the two constructs were 1.08 and 6.17. The factor loadings of the two constructs ranged between 0.62 and 0.87, and no cross-loading was above 0.30. These results indicated that the newly designed folding task could be used for the targeted sample with the two-level constructs of BFS and AFS.

TABLE 1 | Exploratory factor analysis and confirmatory cluster structures for the paper folding task.

Item	Factor1	Factor2
Basic Folding Skill		
Step 1	0.870	
Step 2	0.802	
Step 3	0.667	
Advanced Folding Skill		
Step 4		0.683
Step 5		0.723
Step 6		0.624
Step 7		0.710
Step 8		0.682
Step 9		0.785
Step 10		0.791
Step 11		0.710
Eigenvalue	1.079	6.165
Explained Variance	9.814%	56.041%
Total Explained Variance	65.855%	

KMO = 0.914; Approx. Chi-Square (df) = 664.748 (55), p < 0.001.

Age and Gender Differences in Folding Performance and Spatial Ability

First, the descriptive analysis showed that there was an increasing trend in folding performance from age 3–5 ($M_{aged3} = 7.154$;

SD = 5.583; $M_{aged\ 4}$ = 14.625; SD = 5.504; M_{aged5} = 18.086; SD = 3.293) and a growing trend in SA of the participating preschoolers (M_{aged3} = 2.039; SD = 1.455; $M_{aged\ 4}$ = 3.200; SD = 1.548; M_{aged5} = 3.943; SD = 1.130) (**Table 2**). Second, MANOVAs was employed to examine the age and gender effects as well as age × gender effects in both the SA and folding skills. The results showed that there were significant age effects in both SA ($p < 0.001$) and folding skills ($p < 0.001$). In contrast, no significant gender effects or age × gender effect were found for either tasks ($p_s > 0.05$). Specifically, for the SA, the *Post Hoc* Tests indicated that there were significant age differences in early SA between children aged 3 and 4 ($p < 0.01$), and between children aged 3 and 5 ($p < 0.001$), but no significant age difference was found between children aged 4 and 5. For the folding skills, the *Post Hoc* tests showed that for the AFS level, a significant age difference was found between each two age groups ($p_s < 0.001$). However, there were no significant age differences between the 4-year-olds and the 5-year-olds for the BFS level. All these results jointly indicated a significant age difference in the PFP, while the 4-year-old and 5-year-old children had no performance differences at the BFS level.

Hierarchical Regression Analyses Predicting Paper Folding Performance

First, to explore the variables associated with early folding performance, we conducted Spearman correlation analysis on the variables involved (**Table 3**). The correlation matrix indicated that there were significant positive associations between folding performance and the following factors: map-use skills ($r = 0.505$, $p < 0.01$) and child age ($r = 0.644$, $p < 0.01$). Next, to explore the possible predictors of the two levels of folding performance in the early years, we entered the child age, household income, parents' educational levels, and PI in the three-step hierarchical regression model (**Table 4**). The results showed that: (1) child age could significantly predict both Basic (β = 0.551, $p < 0.001$) and Advanced (β = 0.627, $p < 0.001$) levels of folding; (2) and PI only predicted the BFSs in early years but could not predict the variation in AFSs (β = 0.246, $p < 0.001$). This finding indicated that PI might play a vital role in developing children's BFSs in the early years.

Path Analysis of Parental Involvement, Two-Level Folding Performance, and Spatial Ability

First, to determine the predictive power of paper-folding performance to the SA in the early years, we conducted four-step hierarchical regression analyses with map-use skills as the dependent variable. The results are shown in **Table 5**. In Step 1, we entered age and gender to control for their effects. In Step 2, household income, father's education level, and mother's education level were entered. In Step 3, we entered PI to control for its effects. In Step 4, the folding performance was entered by full folding skills (FS), BFS, and AFS, respectively. The change in R^2 between the four steps indicated that (1) the children's age and gender could jointly explain 21.9% of the variation in map-use performance. Additionally, age was found to be the

TABLE 2 | Mean, SD, and age difference in the paper folding and map-use tasks.

	3;6		4;6		5;6			
	N = 26		*N* = 40		*N* = 35			
Task	***Mean***	***SD***	***Mean***	***SD***	***Mean***	***SD***	***F***	***p*-Value**
Map-use	2.039	1.455	3.200	1.548	3.943	1.130	14.001**	0.000
Folding (Whole)	7.154	5.583	14.625	5.504	18.086	3.293	38.230**	0.000
BFS	3.654	1.917	5.400	1.105	5.829	0.382	25.967**	0.000
AFS	3.500	4.188	9.225	4.875	12.257	3.128	33.353**	0.000

***p < 0.001. BFS, Basic Folding Skills; AFS, Advanced Folding Skills. Post Hoc Tests indicated no significant age difference between the 4-year-old and 5-year-old children during the BFS part (p = 0.284).*

TABLE 3 | Correlations among the study variables.

	1	2	3	4	5	6	7	8
(1) Map	–							
(2) Folding	0.505**	–						
(3) Parent Involvement	0.118	0.184	–					
(4) Child Age	0.467**	0.644**	−0.041	–				
(5) Child Gender	0.072	0.011	−0.042	0.078	–			
(6) Mother Education	0.047	−0.071	0.154	−0.072	0.096	–		
(7) Father Education	−0.02	−0.004	−0.021	−0.058	0.121	0.493**	–	
(8) Household Income	−0.014	−0.036	−0.01	−0.072	−0.092	0.546**	0.291**	–

*N = 101. **p < 0.01 (two-tailed).*

TABLE 4 | Summary of hierarchical regression analyses predicting paper folding skills.

	Level 1: Basic Folding Skills				Level 2: Advanced Folding Skills			
	β	R^2	ΔR^2	*F for models*	β	R^2	ΔR^2	*F for models*
Step 1		0.302	–	21.186***		0.391	–	31.446***
Child gender	−0.050				−0.033			
Child age	0.551***				0.627***			
Step 2		0.305	0.003	8.331***		0.395	0.004	12.411***
Household income	0.057				0.144			
Father education	0.030				0.734			
Mother education	−0.047				−0.616			
Step 3		0.362	0.057	8.895***		0.409	0.013	10.825***
Parent involvement	0.246**				0.119			

$^{**}P < 0.01$; $^{***}P < 0.001$.

TABLE 5 | Summary of hierarchical regressions predicting spatial ability (map-use).

	Beta	R^2	ΔR^2	*F*		Beta	R^2	ΔR^2	*F*		Beta	R^2	ΔR^2	*F*
Step 1		0.219	–	13.759***	Step 1		0.219		13.759***	Step 1		0.219		13.759***
Gender	0.036				Gender	0.036				Gender	0.036			
Age	0.464***				Age	0.464***				Age	0.464***			
Step 2		0.227	0.008	5.593***	Step 2		0.227	0.008	5.593***	Step 2		0.227	0.008	5.593***
SES	−0.028				SES	−0.028				SES	−0.028			
Dad Edu	−0.045				Dad Edu	−0.045				Dad Edu	−0.045			
Mom Edu	0.116				Mom Edu	0.116				Mom Edu	0.116			
Step 3		0.242	0.014	4.993***	Step 3		0.242	0.014	4.993***	Step 3		0.242	0.014	4.993***
PI	0.123				PI	−0.123				PI	−0.123			
Step 4		0.308	0.066	5.901***	Step 4		0.303	0.061	5.774***	Step 4		0.294	0.052	5.531***
FS	0.344***				BFS	0.310**				AFS	0.297*			

N = 101. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. Dad/Mom Edu, Father/Mother education degree obtained; PI, parental involvement in teaching children's spatial knowledge in daily life; FS, folding skills; BFS, basic folding skills; AFS, advanced folding skills.

most significant predictor of this SA; (2) household income, father education, and mother education could jointly explain 0.8% of the variation in children's performance in using a map. However, none of them was a significant predictor; (3) parent involvement could only explain 1.4% of the variation in children's map-use skills. However, it was not the significant predictor of the map-use skills; (4) full folding skills as the significant predictor of the map-use skills could explain 6.6% of the variation in map-use skills, while, specifically, BFS (6.1%) could explain more variation in map-use skills than the AFS (5.2%). The findings indicated that folding performance could serve as a significant predictor of SA when controlling for child age, gender, SES, and PI.

Second, based on the literature review and the correlation matrix, we conducted the mediation analysis using the Bootstrap (model 4, sampling 5000 times) method to examine the direct and indirect effects of PI and Paper Folding Performance (PFP, BFS, and AFS, respectively) on SA. As shown in **Table 6**, the results indicated that in the significant full model: (1) PI had no significant direct influence on SA (β = 0.0081, 95% CI ranged from −0.1744 to 0.1906); but (2) the indirect effect of PI → BFS → SA was significant (β = 0.4798, 95% CI ranged from −0.2511 to −0.0299). No significant results were found in other paths and other indirect effects (see **Table 6**). All these findings jointly support the mediating role of BFS in this model in which PI indirectly influenced SA through BFS. The final model for this sample is presented in **Figure 3**.

TABLE 6 | Direct and indirect effects of parental involvement on spatial ability in early years.

Paths	Full	
	Effect	95% CI
Paper Folding Performance as Mediator		
Parental Involvement → Spatial Ability	−0.0400	[−0.3149, 0.2349]
Parental Involvement → Paper Folding Performance →Spatial Ability	−0.1439	[−0.3298, 0.0067]
Basic Folding Skill as Mediator		
Parental Involvement → Spatial Ability	0.0081	[−0.1744, 0.1906]
Parental Involvement → Basic Folding Skill →Spatial Ability	−0.1259	[−0.2511, −0.0299]
Advanced Folding Skill as Mediator		
Parental Involvement → Spatial Ability	−0.0479	[−0.2260, 0.1302]
Parental Involvement → Advanced Folding Skill →Spatial Ability	−0.0698	[−0.1847, 0.0197]

All the raw scores were transformed into z score to indicate Parental Involvement level, spatial ability, and paper folding performance.

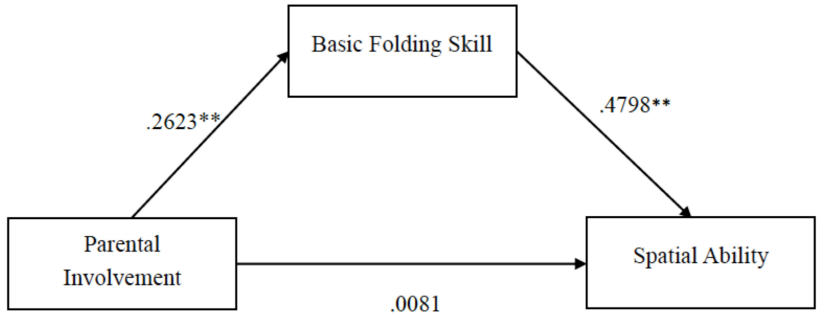

FIGURE 3 | The confirmed mediation model.

DISCUSSION

The primary objective of this study was to explore the predictive relationship between PI, PFP, and SA in Chinese preschoolers. The results indicated a mediation of BFS between PI and early spatial skills.

Developmental Patterns of Paper Folding Skills and Spatial Skills

This study has developed and validated a paper folding task that could be used for young children aged 3–5. Factor analysis results have yielded two constructs: the BFS and the AFS. The psychometric results indicated that it has satisfactory reliabilities and construct validity thus could be used as a reliable measure to evaluate young children's paper folding skills. This two-construct model is consistent with the existing studies (Wenciker and Flynn, 2004; Cakmak et al., 2014; Tenbrink and Taylor, 2015; Alebna et al., 2016).

First, this study found a significant age difference in both BFS and AFS, indicating a developmental trend of paper folding skills in the early years. This finding suggests that folding skills are malleable during the preschool years and develop from age 3 to 5. However, no significant age-related increase was found between children aged 4 and 5, suggesting that children may acquire the BFS at age 4 and maintain it to age 5. In contrast, a significant age-related increase was found in AFS between age 4 and age 5, indicating that the AFS might still develop during the 2 years. Along with the development of folding skills, significant age effects were also found in the map-use performance, implying a developing trend of SA during early childhood. Nevertheless, all these findings have jointly indicated an age-related increase in the early years, providing sound evidence to support the malleability of both abilities (Taylor and Hutton, 2013; Lippard et al., 2019).

Second, this study found no significant gender differences in both paper folding and map-use performance. This finding has provided empirical evidence to challenge the belief that spatial abilities should be biologically determined by gender-related hormones (Halpern, 1992; Rimfeld et al., 2017). This finding, however, is inconsistent with that reported by Seng and Tan (2002) and Chan (2007), who both found some significant gender differences in SA. This discrepancy might be caused by the differences in the spatial tasks, indicating that more empirical studies with consistent measures and tasks should be conducted to further explore the gender differences in SA.

Predictors of Paper Folding Performance

This study found that PI could predict the variation in BFSs, after controlling for age and gender. This finding indicated that PI might play a critical role in developing young children's BFSs (instead of advanced skills) in the early years. This is consistent with the existing studies that have found that interactive parenting enhanced children's fine motor skills (Gutman and Feinstein, 2010). Other studies have also found that parenting behaviors could predict young children's cognitive development (Rubin et al., 2002). The PFA requires the integrated involvement of both cognitive and fine motor skills; thus, it should be affected by PI, as found in this study. However, the impact of PI on PFP could only be found in developing basic skills. Those advanced skills in PFP could not be predicted by PI, indicating that there might be some intrinsic or even genetic factors contributing to its development. This possibility, however, cannot be ruled out in this study, warranting further studies.

The Mediating Role of Paper Folding Performance

This study found that the BFS played the mediating role between PI and early SA. This finding has highlighted the important role of PFA in promoting early SA, providing empirical evidence to support the new trend to treat the PFA as a learning context for EEE (Taylor and Hutton, 2013; Lippard et al., 2019). Also, the finding that PFA could predict early SA has provided empirical evidence to support Taylor and Hutton (2013) to promote STEM education through implementing folding activity in early childhood settings. However, this study also found the AFS did not play any roles in the relationship between PI and Early Spatial Ability. This finding indicated that PI could only predict young children's BFSs, thus indirectly facilitating their SA. In addition, this study found that PI could not predict the AFS, indicating that these skills might be influenced by other confounding factors, such as cognitive level, which is more genetic-oriented thus could not be facilitated by the 'nurturing' measures. Therefore, well-designed experimental or large-scale longitudinal studies should be conducted in the future to confirm the cause-effect relationships between them and to evaluate the intervention effects. This study, however, can only confirm the predictive relationship using the cross-sectional data.

CONCLUSION, LIMITATIONS, AND IMPLICATIONS

This study has achieved the following conclusions. First, significant age differences were found in the PFP and early SA, indicating that both of them were still developing in the early years. No significant age differences were found in the BFSs between the 4-year-old and 5-year-old children. Second, no significant gender differences were found in the PFP and early SA, challenging the belief that there are gender differences in Chinese children's SA. Third, PI could significantly contribute to the BFS level of the paper folding task in Chinese preschoolers. Fourth, paper folding skills could significantly predict SA after controlling for age, gender, SES, parental education levels, and PI. Last, BFSs played a mediating role in the relationship between PI and early SA.

This study, however, has some limitations. First, a cross-sectional study cannot explore the cause-effect relationships between PI and children's SA. Well-designed experimental or large-scale longitudinal studies should be conducted in the future to confirm the causality. Second, the paper folding task was newly developed and validated in this study, and the map-use task was adapted from Bluestein and Acredolo (1979). They should be further validated by a large-scale sample in the future.

Nevertheless, this study has some implications for future directions and parental education. First, the finding that there were predictive relationships between PI, paper folding, and SA implies that PFA might potentially facilitate the development of spatial abilities thus deserves further studies. Second, the finding that there were no significant age differences in the BFSs between the Age 4 and Age 5 groups implies that more attention should be paid to younger children's training under Age 4. Third, the finding that there were no significant gender differences in paper folding and map-use implies that the traditional stereotype about gender difference should be abandoned, and early childhood education should not be gendered. Last but not least, the finding that PI might have an indirect impact on early spatial development implies that parental education programs should consider including the promotion and training of paper folding skills. This is especially convenient and workable in the contexts with well-established family kindergarten partnerships, such as in Hong Kong (Jeynes, 2006; Lau et al., 2012).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethical Committee of the Education University of Hong Kong. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

DW and JS designed the study and drafted the whole manuscript together. DW collected and analyzed the data under the supervision of JS. Both authors contributed to the article and approved the submitted version.

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Neural Correlates of Mental Rotation in Preschoolers With High or Low Working Memory Capacity: An fNIRS Study

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This study explored the differentiated neural correlates of mental rotation (MR) in preschoolers with high and low working memory capacity using functional near-infrared spectroscopy (fNIRS). Altogether 38 Chinese preschoolers (M = 5.0 years, SD = 0.69 years) completed the *Working Memory Capacity* (WMC) test, the *Mental Rotation* (MR), and its Control tasks (without MR). They were divided into High-WMC (N_1 = 9) and Low-WMC (N_2 = 18) groups based on the WMC scores. The behavioral and fNIRS results indicated that: (1) there were no significant differences in MR task performance between the High-WMC (M_{mr} = 23.44, SD = 0.88) and Low-WMC group (M_{mr} = 23.67, SD = 0.59); (2) the Low-WMC group activated BA6, BA8, BA 9, and BA 44, whereas the High-WMC group activated BA8, BA10 and BA 44 during mental rotation; (3) significant differences were found in the activation of BA44 and BA9 between the High-WMC and Low-WMC groups during mental rotation; and (4) the High-WMC and Low-WMC groups differed significantly in the activation of BA 9 and BA10 during the control tasks, indicating that both areas might be responsible for the group differences in working memory.

Keywords: neural network, mental rotation, working memory, Chinese preschoolers, functional near-infrared spectroscopy

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INTRODUCTION

Mental rotation (MR) has been extensively employed to evaluate early cognitive development (e.g., Hoppe et al., 2012), as it is a cognitive process in which participants have to form a mental image of the target assemblage and align it with the other assemblage by rotating this image (Shepard and Cooper, 1982, for a review; Zacks, 2008, for a meta-analytic review). This cognitive process is based on the processing of visual or object working memory (Hyun and Luck, 2007), thus has substantially involved the frontal cortex (BA 9, BA10), premotor cortex (BA 6), parietal cortex (BA 40, BA 44) (Cohen et al., 1996; Jordan et al., 2001; Schöning et al., 2007). All these studies, however, were conducted with adult participants. Recently, Wu et al. (2020) examined the neural correlates of MR in preschoolers using functional near-infrared spectroscopy (fNIRS) and found that BA6, BA9, BA44 were involved in the MR processing. But the role of working memory in preschoolers' MR has not been explored, even though it is substantially engaged in mental rotation (Gauthier et al., 2002; Hyun and Luck, 2007). Therefore, this study will fill the gap by duplicating and extending the MR tasks by Wu et al. (2020) to explore the relationship between working memory and mental rotation.

The Neural Correlates of Mental Rotation

Using fMRI, Cohen et al. (1996) found that the frontal cortex (BA 9, BA 44, BA 46), premotor cortex (BA 6), and parietal cortex (BA 7, BA 40) were significantly activated during mental rotation, and some adult cases showed noticeable activation in BA 39 and BA 19. Later, Richter et al. (2000) conducted an fMRI study with Shepard and Metzler's classic task and found a bilateral involvement of the superior parietal lobule, lateral premotor area, and supplementary motor area in the very act of mental rotation. They also found activation in the left primary motor cortex, which seemed to be associated with the right-hand button press at the end of the task period. This was verified by Windischberger et al. (2003), who found that the button pressing caused activation in the primary motor cortex (BA 4) and supplementary motor area (SMA, BA 6) while the parietal cortex (BAs 5, 7, 39, 40) and mesial regions rostral to the supplementary motor area were recruited for the actual mental rotation process.

Harris and Miniussi (2003) employed repetitive transcranial magnetic stimulation (rTMS) and found that the right superior posterior parietal lobe might play an essential role in mental rotation. However, this study could not rule out the role of the left posterior parietal lobe in mental rotation. Accordingly, Kucian et al. (2007) investigated the maturing neural network for mental rotation by comparing brain activation in 20 children and 20 adults using fMRI. They found that adults exhibited more robust activation in the left intraparietal sulcus compared to children. This finding suggests a shift of activation from a predominantly right parietal activation in children to a bilateral activation pattern in adults.

Later, Milivojevic et al. (2008) studied the brain regions involved in mental rotation by assessing the fMRI activation during a letter-digit judgment task. They found that the mental rotation was sub-served by a bilateral frontoparietal network. Therefore, they suggested that the hemispheric asymmetries found in the parity-judgment tasks might reflect visuospatial processing other than mental rotation itself, which could be sub-served by a bilateral frontoparietal network. Later, Zhang et al. (2009) investigated the interactive cortical networks involved in Chinese Character MR tasks using the Partial directed coherence (PDC) analysis. They found that during MR of Chinese character (1) cortical interactive networks changed according to task difficulty, and (2) the right hemisphere played an initiating role in bilateral cortical activation. However, all these neuroimaging studies have not explored the role of working memory in mental rotation, especially in the preschoolers who are gradually acquiring the cognitive ability of mental rotation. Therefore, this study will address this research gap with near-infrared spectroscopy technology.

Working Memory and Mental Rotation in Preschoolers

Neuroimaging studies have consistently found that mental rotation would involve spatial or object working memory (Gauthier et al., 2002; Hyun and Luck, 2007). Initially, Carpenter et al. (1999) found an extensive activation of both dorsal and ventral stream areas during an MR task compared to a control task. However, only the dorsal stream activation was strongly dependent on the degree of rotation. Later, Hyun and Luck (2007) found that prefrontal areas (BA 9 and BA 10) appeared to be involved in both spatial and object working memory and especially to be responsible for the control and manipulation of information in working memory, rather than being the "storeroom" of the spatial and object information. As mental rotation requires both the storage and manipulation of spatial and object information, precisely the neural function of prefrontal areas (BA 9 and BA 10), we tend to believe that BA 9 and BA 10 might play a critical role in the processing of mental rotation tasks. Therefore, this study will explore the role of BA 9 and BA10 in mental rotation processing in a group of Chinese preschoolers.

Preschoolers' mental rotation, however, has been rarely explored by neuroimaging studies. Most of the existing studies simply adopted the traditional behavioral paradigms. For instance, Frick et al. (2013) assessed individual differences in children's mental rotation abilities between 3.5 and 5.5 years of age. They found that: (1) children's error rates and response times increased linearly with increasing angular disparity by the age of 5 years; (2) 4-year-olds were found to respond at a chance for all angular disparities; (3) both manual and observational experience increased the response accuracy of 5-year-olds, but there was no effect on 4-year-olds. These results indicated that the mental rotation paradigm's successful application should be restricted to children 5 years or older. To challenge this age limitation, Krüger et al. (2014) developed a new research paradigm allowing for the measurement and interpretation of reaction time with 3- to 6-year-olds. They presented a stimulus configuration on a touchscreen and asked preschoolers to bring a rotated stimulus into an upright position using the shortest path. They found that the 3- and 4-year-olds performed reliably above the chance level, but only 5- and 6-year-olds could correctly complete the tasks.

Naseer and Hong (2015) conducted a systematic review and found that fNIRS showed a significant advantage in studying the prefrontal cortex due to no hair in detecting the cognitive tasks like mental arithmetic, music imagery, so on. In extracting features related to the desired brain signal, the mean, variance, peak value, slope, skewness, and kurtosis of the noised-removed hemodynamic response were used. Therefore, they believed that fNIRS would be more widely used to monitor the occurrence of neuro-plasticity after neuro-rehabilitation and neuro-stimulation. Recently, Wu et al. (2020) examined MR's neural correlates in preschoolers using fNIRS and the mental rotation paradigms developed by Krüger et al. (2014). They found that the 48 Chinese preschoolers (M = 66.15 months) could complete the behavioral tasks and be classified into Low and High MR performance groups. And the fNIRS results indicated that BA 44 might be one of MR's core neural correlates in preschoolers, and BA 6 and BA 9 might also be involved in MR processing under a compensatory mechanism. However, the major finding that BA44 was the "neural correlate" (core brain area) of mental rotation might be confounded by other factors, such as it is also in charge of hand movements (Gallagher et al., 2002). Future studies should control hand movements using a control task to reaffirm the precise contribution of BA44 in MR. Also, limited by the research design, Wu et al. (2020) study did not explore working memory's role, leaving a research gap to be filled by this study. Therefore, we have endeavored to address the following questions in this study:

1. Are there any relationships between the preschoolers' performance in the working memory and mental rotation tasks?
2. Are there any significant differences in the neural correlates of mental rotation between the preschoolers with high and low working memory capacity?
3. What are the brain areas involved in the mental rotation according to the fNIRS evidence?

MATERIALS AND METHODS

Sample

Altogether 42 right-handed preschoolers participated in this study before the outbreak of COVID-19 in late January 2020. Parents of these children were informed verbally of the purpose of the research and the fNIRS experiments' safety before they signed the written consent form. The University Ethics Committee approved the experiment and ethical clearance. Among the 42 children, four failed to complete the tests and were thus excluded, resulting in a final sample of 38 children (aged between 4 and 6.3 years, $M = 5.0$ years, $SD = 0.686$ years).

Instrument

Working Memory Capacity (WMC) Test

The Missing Scan Task (MST) (Roman et al., 2014) was adopted in this study. MST has been validated by Roman et al. (2014) as a workable and reliable measure of working memory in preschool children (3–6 years in age). Recently, Jusienė et al. (2020) have adopted MST to test 190 preschool children's working memory and further verified it with sound psychometric properties. Among 65 Beanie Babies (small animal-shaped bean-filled bags), 15 were chosen and used as test stimuli in this study. Examples of animals in the test set included turtle, pig, cow, and duck. Each Beanie Baby was named by the participant (i.e., turtle, pig, cow) to prevent the need to learn new vocabulary; therefore, the participating child could consistently label this animal and did not refer to another animal the same set by the same name. To assess their existing knowledge of the animal names in the stimulus set, we asked the participants to name pictures of each Beanie Baby animal before carrying out the MST. If the participant did not recognize the animal, it would not be included in the test set.

Mental Rotation (MR) Tasks

The MR task in this study was modified from the version developed by Krüger et al. (2014), containing 24 pictures. As shown in **Figure 1**, the test and target stimuli were physical pictures printed on paper cards and test books. One stimulus was not rotated (target stimulus, left side) while the other one was rotated clockwise to one of the following angles: 45°, 90°, 135°, 225°, 270°, or 315° (test stimulus; right side). As many of the participants had no experience using a PC desktop, no screen task was employed in this study. In the training and testing sessions, the paper card with a picture of a duck was presented to the participants to show how to rotate it and make it stand up (using the shortest path). All the test and target materials were presented to the participants on a table.

Control Tasks

To control for the effects of hand movement and movement planning, a set of tasks was conducted to ask the participants to perform a manual rotation movement similar to that in the MR task but without a decision about the movement's direction. The stimulus material consisted of a clock-like schematic drawing. As shown in **Figure 2**, the small hand of the "clock" was always set to 12 o'clock (target position). The big hand was set between 12 and 6 o'clock (starting position). The angle between the two watch

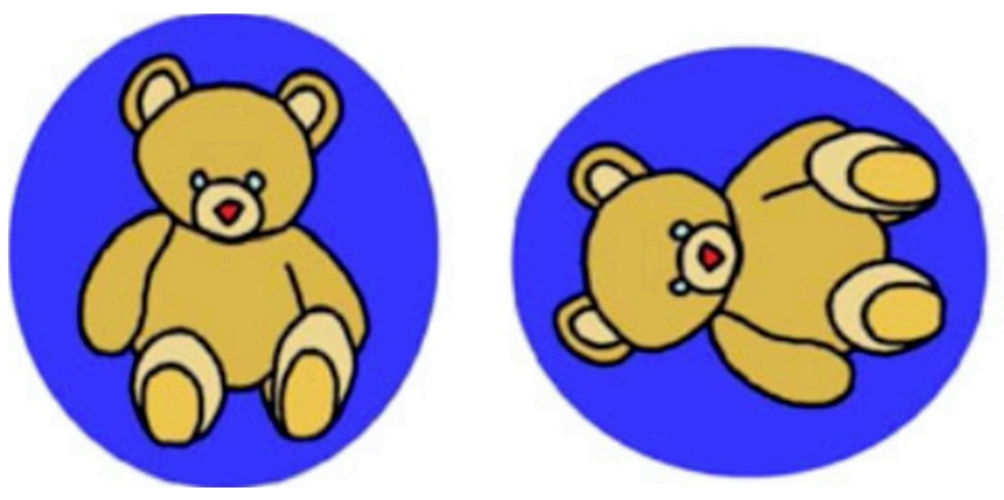

FIGURE 1 | The mental rotation (MR) task.

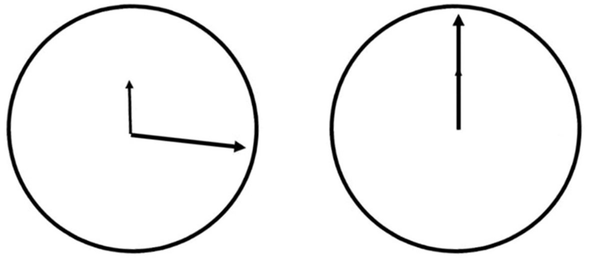

FIGURE 2 | The control task.

hands varied in 14 different degrees (80° and 160° for training; 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°, 165°, and 180° for testing). The big hand could be moved toward the small watch hand (target position) counter-clockwise only.

Procedure

Cap Placement

First, the participants were informed about the fNIRS experiment in terms of an invitation to play games. The participants were encouraged to report any uncomfortable feelings so that the technician could adjust the cap for them. The participants were allowed to quit anytime during the experiment. Once the participants gave their consent to participate, the experimenter read a picture book with them while an experienced technician assisted them in putting on the fNIRS cap.

Second, the technician performed the cap placement, hair manipulation, and tossing and the installation of optodes (based on the 10/20 system). The cap placement procedure involved making general head measurements to decide the cap's size to be used for each participant. Both small (S) and extra-small (XS) fNIRS caps accompanied by the fNIRS instrument (Oxymon Mk III, Artinis, Netherlands) were used for the Chinese preschoolers in this study. The cap is a highly stretchable soft headwear covering the entire head, with prefixed locations for optodes, much like an EEG cap. It has digitized optode positions to illustrate the brain areas being studied. Additional colorful hairbands were used to keep the cap in place and to prevent slipping. As the cap placement procedure took approximately half an hour, children were engaged in storybook reading with an experienced preschool teacher during this period.

Working Memory Assessments

The participant with the fNIRS cap sat across from the experimenter, where a small cardboard house was placed on the table facing the participant. Out of the participant's line of sight, a back-pack was placed under the table, which contained the 15 animal-shaped Beanie Babies. The experimenter explained to the participant that they were going to play a memory game. The experimenter brought out two randomly selected Beanie Babies and placed them on the table in front of the participant. The two animals represented a memory set size of two and were used as the training and practice set for each child. The participant was asked to name and remember the two animals, as "they would go inside the house where the participant would not be able to see them anymore," and when they came back out of the house, one of the animals would be missing. Each child was given approximately 10 s to look at the animals in the memory set and name them before the experimenter placed them inside the house. Two or three seconds later, one Beanie Baby was brought back (chosen at random), and the participant was asked, "which one is missing?" The participant had to display an understanding of the instructions before proceeding with the MST. If the participant were unable to demonstrate an understanding, he/she would not continue with the MST. All the children reported in this study have completed the practice set and proceeded to the test sets.

The memory set size began with three animals and increased in length by one animal each time when the participant correctly reported the missing item. After one correct trial at a given set size was completed, the memory set size was increased by one item. If the participant incorrectly named the missing animals, the same memory set size was tested again with a new test item. In both training and test trials, the participants were shown the missing animal after each trial regardless of the answer's correctness. The MST concluded when the participant either failed to correctly name the missing animal on two trials of the same memory set size or successfully completed a set size of 10. The animals in each memory set were always novel and were randomized for each set size without replacement. The presentation order was also randomized for each child. Working memory capacity (WMC) was defined as the most extended set size that the participant could correctly scan with no errors.

MR Task

The training session of the MR task consisted of four trials. The experimenter explained to children how the first trial should be performed with the following instructions: "*Here is an upright bear [experimenter pointing the target stimulus on the left] and here is a duck falling on its side [pointing the duck on the right]. Now let us help this bear get back on its feet as soon as possible. We can help him get up this way [rotating the test stimulus via the shortest route]. However, if you do it like this [rotating the test stimulus via a more distant route], the bear will be unhappy. So, please do not do it this way.*" The participants were then asked to perform the remaining three training trials, during which the experimenter corrected them upon any mistakes. When a child made a mistake, i.e., chose the more distant route, the experimenter would repeat the original instructions and ask the participant to repeat the corresponding trial. If the participant made the same mistake again, he/she would be asked to perform all training trials again.

The test session of the MR task consisted of 24 trials (24 different stimulus pairs) divided into three task blocks (8 trial/block), each of which preceded a rest block (see **Figure 3**). In each trial, a target (unrotated) stimulus was presented on the left side of the table while a test stimulus, rotated to one of the six angles mentioned above, was presented on the right side of the table. The trials were randomized in each block. No trials were repeated. As in the training session, the participants were instructed to rotate the test stimulus to match the target stimulus. No help or further instructions were given.

Control Task

The control task's training consisted of four trials with the large hand starting randomly at either 80° or 160°. At the start of the training phase, the experimenter showed children the stimulus material and explained that it would be the participant's task to move the large watch hand to the small watch hand. Then the experimenter solved the first trial for the participant by "dragging" the large hand counter-clockwise to the small hand. Afterward, children were asked to do so by themselves, but the experimenter offered assistance and answered their questions. If children made a mistake, the instruction was repeated.

The control task test consisted of 36 trials divided into three blocks, each of which preceded a rest block (see **Figure 3**). The set of stimuli was the same in every block and consisted of 12 different angles (15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 150°, 165°, and 180°) presented in random order. Precisely as in the training session, children were always asked to move the big hand to the small hand, but no help or further instructions were given.

Data Acquisition, Processing, and Analysis

In this study, a multiple-channel fNIRS system (OxyMon Mk III, Artinis, Netherlands) was used to simultaneously measure the concentration changes of oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total hemoglobin (HbT) in the participants. Two wavelengths in the near-infrared range, namely 760 and 850 nm, were used to measure the changes in optical density, which were then converted into changes in the concentration of HbO and HbR using the modified Beer-Lambert law.

Seventeen fNIRS channels were used and located following the international 10/20 system for EEG, with a 2.5 cm distance between adjacent emitter-detector pairs. The regions of interest (ROIs) were located at Brodmann Areas (BAs) 6, 8, 9, 10, 40, and 44 (see **Figure 4**). Previous studies have shown that these areas might be activated during cognitive shifting, mental rotation, and other preschoolers' cognitive activities (Moriguchi and Hiraki, 2009; Wu et al., 2020). Ten channels were located in the right frontal cortex, and seven channels were located in the prefrontal cortex (see **Figure 4**). In particular, the channels 1 and 9 were located at BA 6, channel 10 at BA 8, the channels 11, 12, 14, 16 at BA 9, and channels 13, 15, 17 at BA 10, channel 4 at BA 40, and channels 2, 3, 5, 6, 7, 8 were located at BA 44 in the right inferior frontal cortex.

A subject-specific differential pathlength factor (DPF) constant was calculated based on the age of each subject (Duncan et al., 1996). And the sampling rate was set at 50 Hz for data acquisition. As DPF value is sensitive to age and wavelength, the wavelengths of near-infrared light used to collect the data collected were fixed in this study. In particular, we calculated the DPF value of each child according to the formula ($DPF = 4.99 + 0.067^{*}Age^{0.814}$), which is more conducive to the data's accuracy. After screening the data, the trials contained deformity or noisy data were treated as the incorrect trials and were discarded in advance of the formal analysis. The raw optical intensity data series were converted into changes in optical density (OD). The discrete wavelet transform was applied to every channel data series to remove motion artifacts, with the tuning parameter (α) of wavelet filtering set at 0.1. To reduce slow drifts and high-frequency noise, a bandpass filter (third-order Butterworth filter) with cut-off frequencies of 0.01–0.3 Hz (Delpy et al., 1988) was then applied to the data. The OD data were then converted into concentration changes of HbO and HbR. Among the three NIRS parameters measured, the concentration of HbO was found to be the most sensitive to changes in regional cerebral blood flow, which provided the strongest correlation with the blood oxygen level-dependent signal (Moriguchi and Hiraki, 2009). Thus, a change in the HbO concentration was considered to be the best indicator of brain activity. In the following analysis, only HbO concentration was calculated. Based on the previous research (Moriguchi and Hiraki, 2009), HbO concentration was converted into *z*-scores. The *z*-score was calculated using the mean value, and the *SD* of the HbO concentration changes during the rest phase.

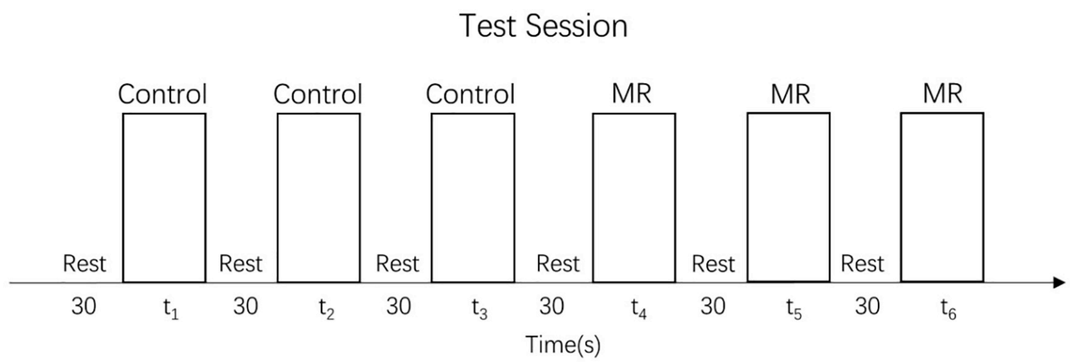

FIGURE 3 | Test session.

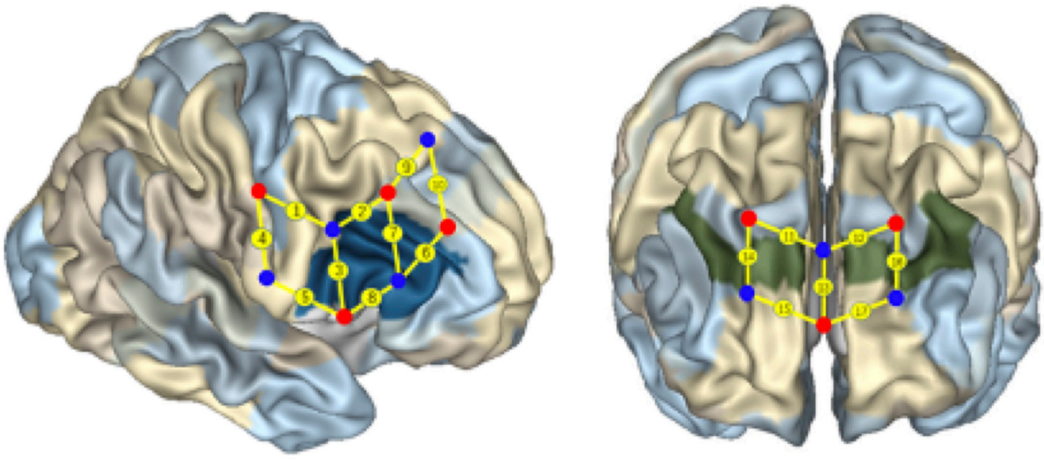

FIGURE 4 | Localization of regions of interest. The numbers on small spheres on the brain map indicate the 17 channels. The channel localization was based on the upper central probe, which was anchored at Fz according to the international 10–20 system and was located at the midpoint between channels numbers 11 and 12. The channels 1 and 9 were located in BA 6, the channel 10 was located in BA 8, the channels 11, 12, 14, 16 were located in BA 9, and the channels 13, 15, 17 were located in BA 10, the channel 4 was located in BA 40, the channels 2, 3, 5, 6, 7, and 8 were located in the right IFC (BA 44).

Individual data were processed using MATLAB 2013b (Mathworks, MA, United States) (Huppert et al., 2009) and analyzed using *the Homer2 NIRS* processing package. The mean of z-scores (HbO) was calculated for each control task block and each MR task block separately for each participant. Then, the mean of z-scores (HbO) was calculated by averaging across the three task blocks for each participant. Finally, the mean of z-scores (HbO) across all channels were compared using *t*-tests between the High and Low groups using SPSS. The General Linear Model (GLM) analysis used to predict z-scores (HbO) in each channel was conducted in *R* ($Y_{\Delta HbO} = aX_{time} + b$).

RESULTS

Behavioral Results

All 38 participants completed the *Working Memory Assessment* (WMC scored between 3 and 10, $M_{age} = 5.0$, $SD = 1.95$). They were divided into high-WMC and low-WMC groups based on their WMC scores. Altogether nine participants were scored at least 0.5 *SD* higher than the mean, thus were included in the High-WMC group, whereas 18 were scored at 0.5 *SD* lower than the mean were included in the Low-WMC group, and the other 11 children were around the mean level, thus were excluded from this study. The MR task score of the High-WMC group ($M_{mr} = 23.44$, $SD = 0.882$) was slightly lower than that of the Low-WMC group ($M_{mr} = 23.67$, $SD = 0.594$), $p = 0.084$. No significant age difference was found between the High-WMC and Low-WMC groups, $t = 0.29$, $p = 0.774$. Next, Spearman correlation analysis was conducted between the WMC and MR scores. A significant negative correlation was found in the Low-WMC group ($r = -0.55$, $p < 0.05$). In contrast, no significant correlation was found in the High-WMC group and Total samples, as shown in **Table 1**. This result indicated that generally, the MR task's performance was not significantly correlated with their working memory capacity.

T-Tests Results

First, a set of two-sample (independent groups) *t*-tests was conducted to determine any significant difference in the mean HbO increase between the High and Low-WMC groups in the control task. As multiple channels were involved in this type of *t*-tests, all the results were corrected for multiple comparisons using the false discovery rate (FDR), and the adjusted significant level of *p*-value was set at 0.05. The results indicated a significant between-group difference in BA 9 (ch 12) ($t = 3.085$, $p < 0.01$), BA 10 (ch 13) ($t = 2.416$, $p < 0.05$), BA 10 (ch 15) ($t = 3.079$, $p < 0.01$). As shown in **Table 2**, a significant increase in HbO was observed in BA 9 and BA 10 in the Low-WMC group compared to the High-WMC group.

Next, a set of two-sample (independent groups) *t*-tests was conducted to determine any significant difference in the mean HbO increase between the High and Low-WMC groups in the MR task. The results indicated a significant between-group difference in BA 44 (ch 7) ($t = -2.349$, $p < 0.05$), BA 44 (ch 8) ($t = -2.206$, $p < 0.05$), BA 9 (ch 14) ($t = -2.261$, $p < 0.05$),

TABLE 1 | Descriptive and correlational statistics of the low-MWC ($N_1 = 18$) and high-WMC ($N_2 = 9$) groups.

	Working memory	Mental rotation	WM/MR correlation	Sig (2-tailed)
	Mean (SD)	Mean (SD)		
High-WMC	7.89 (1.69)	23.44 (0.88)	0.46	0.212
Low-WMC	3.56 (0.51)	23.67 (0.59)	−0.55*	0.018*
Total	5.0 (1.95)	23.29 (1.41)	−0.23	0.168

*$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

TABLE 2 | Comparison of increases in HbO between the low-MWC (N_1 = 18) and high-WMC (N_2 = 9) groups in the control task.

	Group	Mean	*SD*	*T*-value	*p*-value
Channel 1	Low	−0.463	1.381	1.681	0.105
	High	−1.472	1.644		
Channel 2	Low	−0.559	2.067	−1.124	0.272
	High	0.279	1.148		
Channel 3	Low	−1.248	1.725	0.359	0.722
	High	−1.530	2.283		
Channel 4	Low	−0.909	1.610	−0.291	0.774
	High	−0.719	1.570		
Channel 5	Low	−0.542	2.067	0.181	0.858
	High	−0.698	2.203		
Channel 6	Low	−0.078	1.055	−0.970	0.341
	High	0.306	0.762		
Channel 7	Low	−0.982	1.233	−0.357	0.724
	High	−0.794	1.413		
Channel 8	Low	−1.285	2.182	−0.863	0.396
	High	−0.514	2.201		
Channel 9	Low	−0.024	0.608	−0.551	0.586
	High	0.099	0.379		
Channel 10	Low	1.412	1.928	1.605	0.121
	High	0.241	1.445		
Channel 11	Low	0.220	1.604	1.684	0.105
	High	−0.900	1.685		
Channel 12	Low	0.122	1.234	3.085	0.005**
	High	−1.553	1.514		
Channel 13	Low	0.188	1.325	2.416	0.023*
	High	−1.138	1.382		
Channel 14	Low	−0.665	2.195	−0.287	0.776
	High	−0.427	1.639		
Channel 15	Low	0.214	1.375	3.079	0.005**
	High	−1.880	2.158		
Channel 16	Low	0.148	1.130	1.136	0.267
	High	−0.622	2.428		
Channel 17	Low	−0.331	1.260	0.672	0.508
	High	−0.669	1.177		

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.*

TABLE 3 | Comparison of increases in HbO between the low-MWC (N_1 = 18) and high-WMC (N_2 = 9) groups in the MR task.

	Group	Mean	SD	*T*-value	*p*-value
Channel 1	Low	−1.185	2.433	−0.790	0.437
	High	−0.292	3.380		
Channel 2	Low	−1.319	2.328	−1.907	0.068
	High	0.773	3.324		
Channel 3	Low	−2.077	1.858	−1.022	0.317
	High	−1.215	2.451		
Channel 4	Low	−1.524	2.296	−1.059	0.300
	High	−0.610	1.666		
Channel 5	Low	−1.328	2.025	−1.224	0.232
	High	−0.094	3.215		
Channel 6	Low	0.593	1.565	0.707	0.486
	High	0.170	1.220		
Channel 7	Low	−1.943	2.342	**−**2.349	0.028*
	High	−0.202	1.486		
Channel 8	Low	−2.502	2.233	**−**2.206	0.037*
	High	−0.538	2.064		
Channel 9	Low	−0.118	0.689	−0.128	0.899
	High	−0.087	0.304		
Channel 10	Low	1.665	2.869	0.110	0.914
	High	1.534	3.032		
Channel 11	Low	−0.355	2.128	−0.202	0.842
	High	−0.157	2.893		
Channel 12	Low	0.461	1.266	2.027	0.053
	High	−0.900	2.244		
Channel 13	Low	−0.375	2.342	−0.643	0.526
	High	0.162	1.209		
Channel 14	Low	−1.136	2.585	**−**2.261	0.034*
	High	0.741	1.691		
Channel 15	Low	−0.016	2.256	0.720	0.478
	High	−0.612	1.438		
Channel 16	Low	0.353	2.399	2.149	0.044*
	High	−1.452	1.865		
Channel 17	Low	0.132	1.606	0.157	0.876
	High	0.006	2.573		

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.*

BA 9 (ch 16) (t = 2.149, $p < 0.05$). As shown in **Table 3**, the High-WMC group had significantly more increase in HbO than the Low-WMC group in BA 44 (ch 7 and 8) and BA 9 (ch 14), indicating more brain activation in these areas. However, a significantly less increase in BA 9 (ch 16) was observed in the High-WMC than the Low-WMC group.

Third, a set of paired-samples t-tests was conducted to determine whether there were significant differences in the mean HbO increase between the MR and control tasks in the Low-WMC group. As shown in **Table 4**, no significant differences were found between the control and MR tasks in all the channels, $ts > -1.834$, $ps > 0.084$.

Fourth, a set of paired-samples t-tests was conducted to determine whether there were significant differences in the mean HbO increase between the MR and control tasks in the High-WMC group. As shown in **Table 5**, a significant increase in HbO was found in BA 10 (ch 13) when comparing the MR task against the control one, t = 2.584, $p < 0.05$.

Modeling HbO Increase for High and Low-MWC Groups in MR and Control Tasks

A set of GLM analyses was conducted to model the change in HbO in the 17 channels based on *experiment time* for the High and Low = WMC groups, respectively. First, the changes in HbO during the MR and control tasks were analyzed for the Low group. As shown in **Table 6** and **Figure 5**, during the MR task, significant HbO increase was observed in BA 6 (ch 9) [β = 0.41, ΔR^2 = 0.26, F = 29.16 (for the model), t = 5.40 (for β), $ps < 0.001$], BA 8 (ch 10)[β = 0.84, ΔR^2 = 0.70, F = 353.92 (for the model), t = 18.81 (for β), $ps < 0.001$], BA 9 (ch 12) [β = 0.69, ΔR^2 = 0.47, F = 133.77 (for the model), t = 11.57 (for β), $ps < 0.001$], and BA

TABLE 4 | Comparison of increases in HbO of the low-WMC group between the control and MR task.

MR−control	Paired differences		T-value	p-value
	Mean	Std. deviation		
Channel 1	−0.722	2.474	−1.239	0.232
Channel 2	−0.760	2.508	−1.286	0.216
Channel 3	−0.829	1.918	−1.834	0.084
Channel 4	−0.616	2.315	−1.128	0.275
Channel 5	−0.785	2.162	−1.542	0.142
Channel 6	0.671	1.627	1.749	0.098
Channel 7	−0.961	2.730	−1.494	0.154
Channel 8	−1.217	3.427	−1.507	0.150
Channel 9	−0.095	0.788	−0.510	0.617
Channel 10	0.253	2.970	0.361	0.722
Channel 11	−0.575	2.633	−0.926	0.367
Channel 12	0.338	1.939	0.740	0.469
Channel 13	−0.563	2.600	−0.919	0.371
Channel 14	−0.470	2.700	−0.739	0.470
Channel 15	−0.229	2.654	−0.366	0.719
Channel 16	0.206	1.744	0.500	0.623
Channel 17	0.463	2.152	0.913	0.374

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

TABLE 5 | Comparison of increases in HbO of the high-WMC group between the control and MR task.

MR−control	Paired differences		T-value	p-value
	Mean	Std. deviation		
Channel 1	1.180	2.674	1.324	0.222
Channel 2	0.494	2.604	0.569	0.585
Channel 3	0.315	0.884	1.068	0.316
Channel 4	0.109	1.525	0.215	0.835
Channel 5	0.604	2.596	0.698	0.505
Channel 6	−0.136	0.768	−0.531	0.610
Channel 7	0.592	0.986	1.803	0.109
Channel 8	−0.024	2.322	−0.031	0.976
Channel 9	−0.186	0.476	−1.175	0.274
Channel 10	1.293	2.696	1.439	0.188
Channel 11	0.743	3.132	0.712	0.497
Channel 12	0.653	2.237	0.875	0.407
Channel 13	1.301	1.510	2.584	0.032*
Channel 14	1.167	2.366	1.480	0.177
Channel 15	1.268	2.473	1.538	0.163
Channel 16	−0.830	2.527	−0.986	0.353
Channel 17	0.675	2.017	1.005	0.344

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

44 (ch 6) [β = 0.40, $\Delta R^2 = 0.16$, $F = 28.39$ (for the model), $t = 5.33$ (for β), $ps < 0.001$]. Meanwhile, significant decreases were found in the other channels including BA 6 (ch 1), BA 40 (ch 4), BA 44 (ch 2, 3, 5, 7, and 8), BA 9 (ch 11, 14, and16), BA 10 (ch 13, 15, and 17), $Fs > 16.45$ (for the models), $ts < -4.06$ (for β), $ps < 0.001$. All these results jointly indicated that **BA6, BA8, BA9, and BA 44** were significantly activated during the MR task in this Low-WMC

TABLE 6 | Predicting increase in HbO for the low group ($N_1 = 18$) in the MR task.

	β	ΔR^2	F-value	T-value
Channel 1	−0.590	0.343	78.865***	−8.881***
Channel 2	−0.915	0.836	762.619***	−27.616***
Channel 3	−0.794	0.628	252.429***	−15.888***
Channel 4	−0.491	0.236	47.090***	−6.862***
Channel 5	−0.788	0.618	242.561***	−15.574***
Channel 6	0.401	0.155	28.394***	5.329***
Channel 7	−0.506	0.251	51.031***	−7.144***
Channel 8	−0.687	0.468	132.096***	−11.493***
Channel 9	0.406	0.159	29.158***	5.400***
Channel 10	0.840	0.703	353.924***	18.813***
Channel 11	−0.927	0.858	898.024***	−29.967***
Channel 12	0.689	0.471	133.768***	11.566***
Channel 13	−0.900	0.809	630.593***	−25.111***
Channel 14	−0.968	0.936	2193.944***	−46.840***
Channel 15	−0.928	0.860	912.931***	−30.215***
Channel 16	−0.833	0.692	335.364***	−18.313***
Channel 17	−0.316	0.094	16.455***	−4.056***

*$p < 0.05$; **$p < 0.01$; *** $p < 0.001$.

group. During the control task, as shown in **Table 7** and **Figure 6**, significant HbO increase was observed in BA 9 (ch 12) [β = 0.51, $\Delta R^2 = 0.26$, $F = 51.88$ (for the model), $t = 7.21$ (for β), $ps < 0.001$], and BA 9 (ch 16) [β = 0.73, $\Delta R^2 = 0.53$, $F = 167.78$ (for the model), $t = 12.95$ (for β), $ps < 0.001$]. Meanwhile, significant decrease in HbO was observed in BA 44 (ch 2, 3, 5, 7, and 8), BA 40 (ch 4), BA 8 (ch 10), BA 9 (ch 11 and 14), BA 10 (ch 13 and 15), $Fs > 39.35$ (for the models), $ts < -6.27$ (for β), $ps < 0.01$. BA 9 was significantly activated during the control task in the Low-WMC group. After controlling for the activation of BA 9 in the control tasks, we could conclude that **BA6, BA8, and BA 44 were significantly activated during the MR task in this Low-WMC group.**

Second, the changes in HbO during the control and MR tasks were analyzed for the High-WMC group. During the MR task, as shown in **Table 8** and **Figure 5**, significant increase in HbO were observed in BA 8 (ch 10) [β = 0.87, $\Delta R^2 = 0.75$, $F = 456.59$ (for the model), $t = 21.37$ (for β), $ps < 0.001$], BA 10 (ch 13) [β = 0.35, $\Delta R^2 = 0.12$, $F = 21.17$ (for the model), $t = 4.60$ (for β), $ps < 0.001$], BA 10 (ch 17) [β = 0.86, $\Delta R^2 = 0.74$, $F = 416.19$ (for the model), $t = 20.40$ (for β), $ps < 0.001$], and BA 44 (ch 2) [β = 0.336, $\Delta R^2 = 0.12$, $F = 21.90$ (for the model), $t = 4.68$ (for β), $ps < 0.001$]. Meanwhile, significant HbO decrease was observed in BA 6 (ch 9), BA 9 (ch 11, 14, and16), BA 10 (ch 15), BA 40 (ch 4), and BA 44 (ch 3, 5, 7, and 8), $Fs > 14.69$ (for the models), $ts < -3.83$ (for β), $ps < 0.001$. All these results jointly indicated that **BA8, BA10, and BA 44** were significantly activated during the MR task in this High-WMC group. During the control task, as shown in **Table 9** and **Figure 6**, significant HbO increase was observed in BA 6 (ch 1) [β = 0.32, $\Delta R^2 = 0.09$, $F = 16.35$ (for the model), $t = 4.04$ (for β), $ps < 0.001$], BA 9 (ch 11) [β = 0.55, $\Delta R^2 = 0.30$, $F = 65.61$ (for the model), $t = 8.10$ (for β), $ps < 0.001$], BA 44 (ch 3) [β = 0.32, $\Delta R^2 = 0.10$, $F = 16.71$ (for the model), $t = 4.09$ (for β), $ps < 0.001$], BA 44 (ch 8) [β = 0.37, $\Delta R^2 = 0.13$,

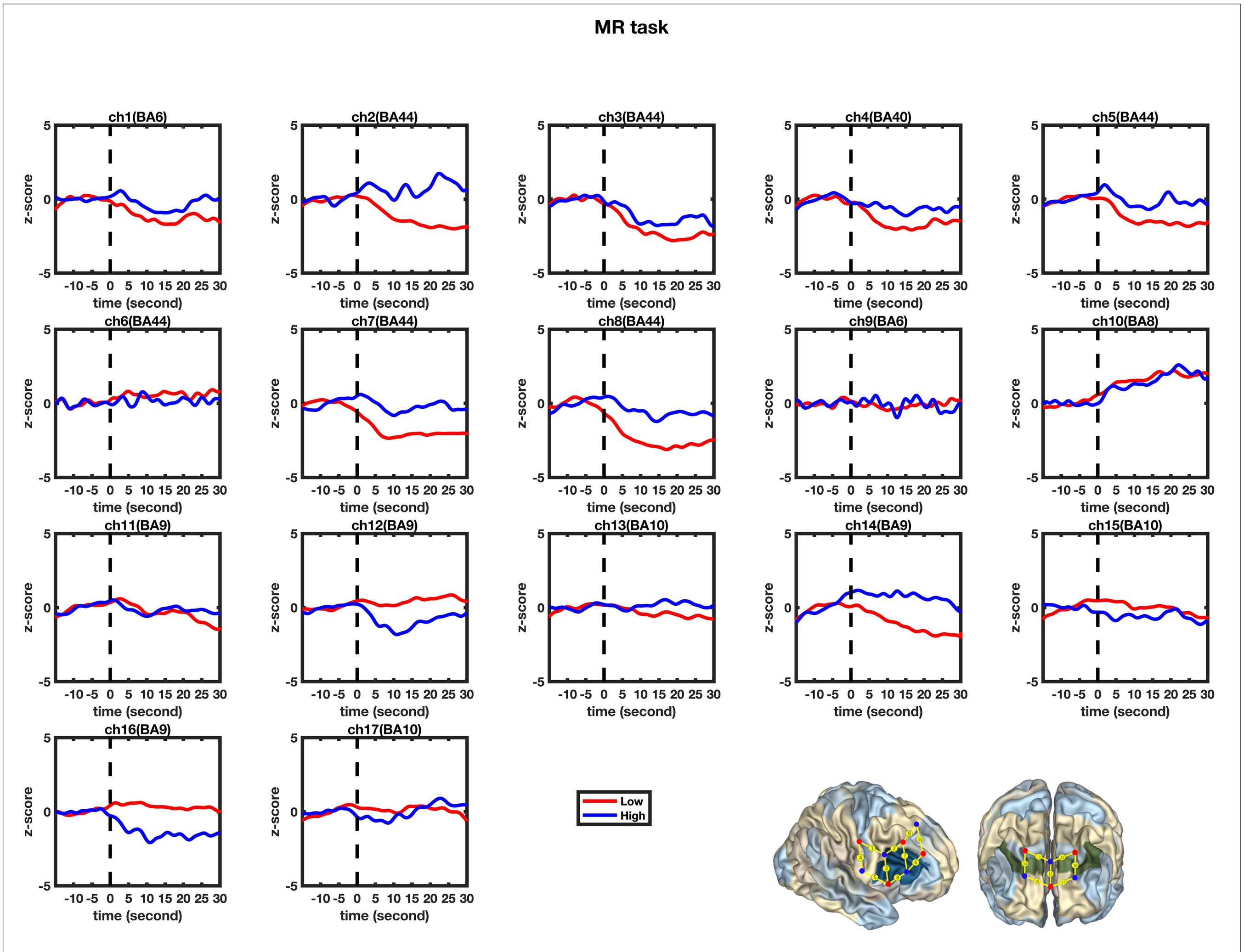

FIGURE 5 | Temporal changes in the HbO concentration in the 17 channels during the mental rotation tasks. From left to right are channels 1–17. The HbO data for Low-MWC (N_1 = 18) and High-WMC (N_2 = 9) are shown in the blue and red lines, respectively.

$F = 23.92$ (for the model), $t = 4.89$ (for β), $ps < 0.001$]. Meanwhile, significant decrease in HbO was observed in BA 8 (ch 10), BA 9 (ch 16), BA 10 (ch 13, 15, and 17), BA 40 (ch 4), and BA 44 (ch 2, 5, and 6), $Fs > 11.14$ (for the models), $ts < -3.34$ (for β), $ps < 0.01$. BA6, BA9, and BA 44 were significantly activated during the control task in the High-WMC group. After controlling for the activation of BA6, 9, 44 in control tasks, we could conclude that BA8 and BA10 were significantly activated during the MR task in this High-WMC group.

DISCUSSION

Neural Correlates of Mental Rotation in the Low-WMC Group

First, this study found no significant differences in the activation of the 17 channels between the Low group's control and MR tasks. This result indicated that the Low-WMC group activated the same brain areas to complete both the control and MR tasks. As the MR task required the successful processing of mental rotation, whereas the control task did not, this result indicated that mental rotation's neural correlate might be involved in completing both MR and control tasks in this Low group. In addition, when they performed the MR task, they demonstrated significant deactivation in BA 40 and BA 44, indicating that both BA 40 and BA 44 might play a critical role in completing the mental rotation task. This finding is consistent with that of Wu et al. (2020).

Second, the GLM analysis found that BA6, BA8, BA9, and BA 44 were significantly activated during the MR task in the Low-WMC group, whereas only BA9 was significantly activated during the control task. After controlling for the effect of BA9 in the control task, we could conclude that BA6, BA8, and BA 44 were significantly activated during the MR task in the Low-WMC children.

All these findings jointly indicated that: (1) BA 9, as one of the neural cores of executive function, was consistently involved in the processing of both MR and control tasks; (2) BA

TABLE 7 | Predicting increase in HbO for the low-WMC Group (N_1 = 18) in the control task.

	β	ΔR^2	*F*-value	*T*-value
Channel 1	0.063	0.004	0.594	0.770
Channel 2	−0.961	0.923	1784.655	−42.245***
Channel 3	−0.760	0.574	201.923	−14.210***
Channel 4	−0.898	0.806	618.974***	−24.879***
Channel 5	−0.876	0.766	489.510***	−22.125***
Channel 6	0.031	−0.006	0.145	0.381
Channel 7	−0.833	0.691	334.929***	−18.301***
Channel 8	−0.476	0.221	43.299***	−6.580***
Channel 9	0.075	−0.001	0.844	0.919
Channel 10	−0.458	0.205	39.346***	−0.6.273***
Channel 11	−0.931	0.865	959.229***	−30.971***
Channel 12	0.509	0.255	51.877***	7.209***
Channel 13	−0.809	0.653	281.010***	−16.763***
Channel 14	−0.897	0.804	610.320***	−24.705***
Channel 15	−0.889	0.788	556.363***	−23.587***
Channel 16	0.729	0.528	167.783***	12.953***
Channel 17	−0.013	−0.007	0.026	−0.161

*$p < 0.05$; **$p < 0.01$;***$p < 0.001$.*

44 was substantially involved in mental rotation (but not in the control task) in Low-WMC children, demonstrating that BA 44 could be one of the core neural correlates for the manipulation of mental rotation; and (3) BA6, BA8, and BA 40 might also be involved in the mental rotation for the Low-WMC group.

Neural Correlate of Mental Rotation in the High-WMC Group

First, this study found a significant HbO increase in BA10 (when comparing the MR against the control task) in the High-WMC group. This result indicated that the High-WMC group had to activate BA10 more significantly to complete the mental rotation task than their brain activation during the control task. Second, the GLM results indicated that BA8, BA10, and BA 44 were significantly activated during the MR task, whereas BA6, BA9, and BA44 were significantly activated during the control tasks. Therefore, we can conclude that: (1) BA 44 has been substantially involved in the processing of both the MR and control tasks, demonstrating that BA 44 is one of the core neural correlates for the manipulation of mental rotation; (2) BA8 and BA10 were significantly activated during the MR task in the High-WMC group; (3) BA6 and BA9 were responsible for the manipulation of the control task, which requires visual-spatial information processing, movement planning, hand movement (Krüger et al., 2014).

The Roles of BA9, BA10, and BA 10 in Working Memory and Mental Rotation

This study found two different patterns of neural correlates of MR for the Low-WMC and High-WMC preschoolers, respectively. The Low-WMC group tended to activate BA6, BA8, and BA44 when processing the MR tasks, whereas the High-WMC activated BA8, BA10, and BA 44. The comparison of Low-WMC and High-WMC patterns indicated the significant differences in the activation of BA9 and BA44. This finding implies that BA9 and BA44 might play essential roles in the collaboration between mental rotation and working memory.

First, BA 44 functions significantly in binding the language elements, selecting information among competing sources, generating/extracting action meanings, and cognitive control mechanisms for the syntactic processing of sentences (Aron et al., 2004). Also, BA 44 is responsible for both hand movements (Rizzolatti et al., 2002) and cognitive shifting in the Dimensional Change Card Sort (DCCS) task in preschool children (Moriguchi and Hiraki, 2009; Wu et al., 2020). In this study, hand movement is critical to successfully completing all these MR tasks, as the children should make appropriate hand movements to return the stimuli to the correct place. Therefore, we added a control experiment and found that BA44 was consistently involved in MR and control tasks in the High-WMC group (but not in the Low group). This nuanced difference indicated that BA44 should be responsible for the mental rotation rather than hand movement in this study. All the participants were right-handed, and we only tested the right hemisphere BA44. This finding has provided empirical support to that of Wu et al. (2020) that BA44 should be regarded as one of the core neural correlates of mental rotation in preschoolers.

Also, in the High-WMC group, BA 10 was a significant activated area for the mental rotation. BA10 is extensively involved in cognitive processing in the human brain, but its function is poorly understood. A meta-analysis found that it involved working memory, episodic memory, and multiple-task coordination (Gilbert et al., 2006). Therefore, this finding indicates that working memory is substantially involved in MR tasks; thus, BA 10 plays a significant role in mental rotation. This is consistent with that of Hyun and Luck (2007), who found that prefrontal areas (BA 9 and BA 10) were responsible for the control and manipulation of information in working memory and provides partial evidence to support our hypothesis that BA 9 and BA 10 might play a critical role in the processing of mental rotation tasks.

Last, this study found that the High and Low-WMC groups differed significantly in BA 9 during mental rotation. BA 9 is widely involved in attributing intention, theory of mind, working memory, spatial memory, recognition, recall, and planning (Brunet et al., 2000; Gallagher et al., 2002; Leung et al., 2002; Pochon et al., 2002; Raye et al., 2002; Zhang et al., 2003). In the mental rotation, the High-WMC group had significantly more activation in BA9 than the Low-WMC group, indicating that BA9 might be relevant to the between-group differences in working memory capacity. This finding implies that BA9 might also play an essential role in preschoolers' working memory and mental rotation, which is also consistent with that of Wu et al. (2020).

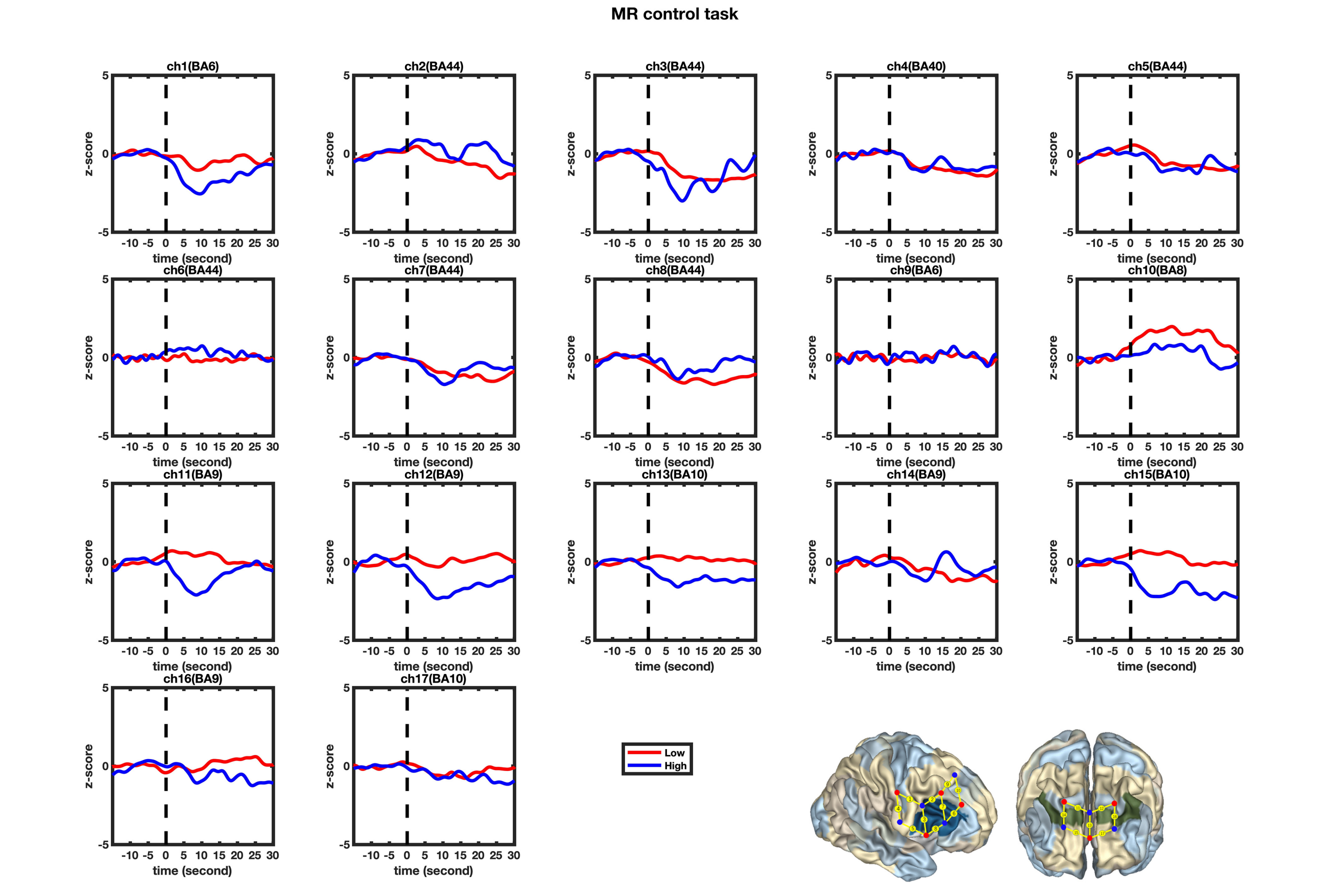

FIGURE 6 | Temporal changes in the HbO concentration in the 17 channels during the Control tasks. From left to right are channels 1–17. The HbO data for the Low-MWC (N_1 = 18) and High-WMC (N_2 = 9) are shown in the blue and red lines, respectively.

TABLE 8 | Predicting increase in HbO for the high-WMC group (N_2 = 9) in the MR task.

	β	ΔR^2	*F*-value	*T*-value
Channel 1	−0.147	0.015	3.263	−1.806
Channel 2	0.359	0.123	21.903***	4.680***
Channel 3	−0.591	0.345	79.493***	−8.916***
Channel 4	−0.496	0.241	48.184***	−6.941***
Channel 5	−0.426	0.176	32.874***	−5.734***
Channel 6	0.021	−0.006	0.064	0.253
Channel 7	−0.330	0.103	18.111***	−4.256***
Channel 8	−0.630	0.393	97.391***	−9.869***
Channel 9	−0.400	0.154	28.175***	−5.308***
Channel 10	0.869	0.754	456.594***	21.368***
Channel 11	−0.396	0.157	27.461***	−5.240***
Channel 12	0.100	0.003	1.491	1.221
Channel 13	0.354	0.119	21.174***	4.601***
Channel 14	−0.806	0.646	273.464***	−16.537***
Channel 15	−0.301	0.084	14.698***	−3.834***
Channel 16	−0.574	0.325	72.593***	−8.520***
Channel 17	0.859	0.736	416.189***	20.401***

**p* < 0.05; ***p* < 0.01; ****p* < 0.001.

TABLE 9 | Predicting increase in HbO for the high-WMC group (N_2 = 9) in the MR control task.

	β	ΔR^2	*F*-value	*T*-value
Channel 1	0.315	0.093	16.350***	4.043***
Channel 2	−0.612	0.370	88.648***	−9.415***
Channel 3	0.318	0.095	16.708***	4.088***
Channel 4	−0.569	0.320	71.006***	−8.427***
Channel 5	−0.405	0.158	28.989***	−5.384***
Channel 6	−0.799	0.636	261.558***	−16.173***
Channel 7	0.119	0.008	2.131	1.460
Channel 8	0.373	0.133	23.923***	4.891***
Channel 9	−0.128	0.010	2.467	−1.571
Channel 10	−0.633	0.396	98.696***	−9.935***
Channel 11	0.554	0.302	65.605***	8.100***
Channel 12	0.145	0.015	3.200	1.789
Channel 13	−0.265	0.064	11.143**	−3.338**
Channel 14	−0.050	−0.004	0.376	−0.613
Channel 15	−0.482	0.227	44.842***	−6.696***
Channel 16	−0.743	0.549	182.532***	−13.510***
Channel 17	−0.823	0.675	309.806***	−17.601***

**p* < 0.05; ***p* < 0.01; ****p* < 0.00.

CONCLUSION, LIMITATIONS, AND IMPLICATIONS

In summary, this study found two patterns of neural correlates of mental rotation for the preschoolers with low and high working memory capacity. The Low-WMC group tended to activate BA6, BA8, and BA44, whereas the High-WMC group activated BA8, BA10, and BA 44 when processing the MR tasks. The significant differences in the activation of BA9 and BA44 between the Low and High-WMC patterns indicated the two areas might play essential roles in the collaboration between mental rotation and working memory. In addition, the High-WMC group has demonstrated significant activation in BA 10, indicating that BA10 might be specifically responsible for the mental rotation when completing the MR tasks. In contrast, the Low-WMC group had no significant activation in any studied areas compared to the control task. All these findings jointly indicate that BA9 and BA10 might play a vital role in processing both working memory and mental rotation, and BA44 might be one of the core neural correlates of mental rotation in preschoolers (Wu et al., 2020).

This study has some limitations. First, other brain regions, especially left frontal areas, might also contribute to mental rotation development. However, with minimal channels, this study could only focus on the right IFC and inferior prefrontal areas. Second, the younger (3-year-olds) and older (7-year-olds) should have been included in this study to examine whether the neural network of mental rotation could be matured and adultlike in primary school years. Last, this study found a significant negative correlation between WMC and MR scores in the Low-WMC group. Is this finding caused by sample bias or developmental differences? This cross-sectional study with a small sample was incapable of address this question. Further studies with more samples of varying ages should be conducted in the future. Therefore, we need to address all these limitations by investigating brain activation using various tasks and longitudinal designs in the future.

Nevertheless, the findings of this study do have some implications for future studies. First, preschoolers can complete the mental rotation tasks, and future studies can further explore the neural correlates of mental rotation using this research paradigm. Second, BA44 has been substantially involved in processing both the MR and control tasks in the High-WMC group, indicating that the role of BA 44 might be more complicated and deserves further exploration. Third, the critical roles of BA 9 and BA 10 in the processing of working memory and mental rotation should be further explored and verified with more experiments. Therefore, more empirical evidence could be provided to confirm the neural correlates of working memory in preschoolers.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the ethics committee of the Faculty of Medicine, Shenzhen University, China. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

JY, DW, JL, and SX collected the data. DW and HL designed the experiment. JY and CC analyzed the data. JY, HL, DW, and CC drafted the manuscript. All authors contributed to the article and approved the submitted version.

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A Corpus-Based Comparison of the Pragmatic Use of *Qian* and *Hou* to Examine the Applicability of Space–Time Metaphor Hypothesis in Early Child Mandarin

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The Universal Space–Time Mapping Hypothesis suggests that temporal expression is based on spatial metaphor for all human beings. This study examines its applicability in the Chinese language using the data elicited from the Early Childhood Mandarin Corpus (ECMC) (Li and Tse, 2011), which collected the utterances produced by 168 Mandarin-speaking preschoolers in a semistructured play context. The unique pair of Chinese words, *qian* (前/before/front) and *hou* (后/after/back), which can be used to express either time (before/after) or space (front/back) in daily communication, was the unit of analysis. The results indicated that: (1) there was a significant age effect in the production of "qian/hou," indicating that the period before the age of 4.5 may be critical for the development of temporal and spatial expression; (2) the pair was produced to express time (before/after) much earlier than space (front/back), indicating that the expression of time might not necessarily be based on the spatial metaphor; and (3) the pair was used more frequently to express time (before/after) than space (front/back) by the preschoolers, thus challenging the hypothesis.

Keywords: spatial metaphor, temporal sequencing, temporal expression, early acquisition, corpus-based

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INTRODUCTION

Space and time are the two fundamental and interrelated dimensions of human cognition and language production, with spatial terms being often used to describe the occurrence, sequence, and duration of events (Majid et al., 2013). This is because temporal relationships are abstract and invisible and thus have to be encoded into spatial terms using spatial metaphors, as suggested by the Conceptual Metaphor Theory (Lakoff and Johnson, 1980, 1999) and the Universal Space–Time Mapping Hypothesis (Fauconnier and Turner, 2008). Thus, it is widely accepted that temporal expression is based on spatial metaphor, and the concept of space is a precondition of temporal expression in all languages (Boroditsky, 2000). This theory has been confirmed by studies on the English language (Lakoff, 1994; Gentner et al., 2002; Zhang, 2003; Bender and Beller, 2014). However, recent studies have challenged this theory with evidence from other languages such as Amazonian (Sinha et al., 2011), Chinese (Chen, 2007), Japanese, and Marathi (Shinohara and Pardeshi, 2011). Chinese, featuring a pair of words—"*qian 前* " (before/front) and "*hou 后*" (after/back) that could be used to express both temporal (before/after) and spatial (front/back) concepts, provides a perfect case for empirically examining the applicability of this hypothesis (Yang and Xue, 2011; Tsung and Zhang, 2019). If the pair of words were used much earlier to express time rather than space, we could conclude that time expression might not necessarily be based on space metaphor. Accordingly, the premise of this theory would not be established; neither does the theory itself. Therefore, this study elicited the utterances with this pair of words from the Early Childhood Mandarin (Chinese) Corpus (ECMC) (Li and Tse, 2011) and analyzed their developmental patterns to test the hypothesis.

The Space–Time Metaphor Hypothesis

Space and time are highly intercorrelated in human cognition and language; thus, their relationship has long been a philosophical inquiry topic, psychological exploration, and psycholinguistic study (Bottini and Casasanto, 2013). Lakoff and Johnson (1999) proposed the Space–Time Metaphor Theory to understand the asymmetric and sequential relationship between space and time and have empirical support from some metaphorical languages such as English. In English, the temporary expression is based on the spatial metaphor, using the words whose primary meaning is spatial—denotatively, developmentally, or historically (Clark, 1973). It is thus widely believed that the concept of space is acquired and expressed before that of time (Clark, 1973; Bowerman, 1996; Lan, 1999; Boroditsky, 2000). The space–time mappings and the asymmetry in the language (Lakoff and Johnson, 1999) have been verified with behavioral findings in psycholinguistics (Boroditsky, 2000), cognitive development (Casasanto et al., 2010), and psychophysics (Casasanto and Boroditsky, 2008; Bottini and Casasanto, 2010; Merritt et al., 2010). Bottini and Casasanto (2013) suggested that preschool and primary school children could ignore irrelevant temporal information when making judgments about space. Still, they might have difficulty ignoring spatial information when making judgments about time. This implies that the spatial system is acquired earlier than the temporal system.

This Space–Time Metaphor Hypothesis, however, has been challenged by many researchers with languages other than English. For example, Boroditsky (2001) compared Mandarin (the spoken form of Chinese) and English speakers' conceptions of time and space. She found that English might prefer using the horizontal spatial metaphors to express time, for instance, "the good days ahead of us." In contrast, the Chinese language tends to use vertical metaphors to express time, "the month above" means last month. Then, she concluded that English speakers conceived time differently from Mandarin speakers, indicating that language is a powerful tool in shaping habitual thoughts about abstract domains. However, this finding has been challenged by Chen (2007), who found that Chinese speakers used the horizontal spatial metaphors more often than the vertical metaphors and concluded that Chinese and English speakers shared the same way of thinking about time. Moreover, Kemmerer (2005) found that the temporal and spatial concepts could be represented and processed separately in the modern adult brain, thus challenging the Space–Time Metaphor Theory. However, these studies only tested adult subjects who had gone beyond the critical period of language acquisition. Although adults can process and express conceptions of time and space separately and independently, young children may not be able to do so. Therefore, we need to examine this theory using authentic data on young children.

Matching Space–Time Concepts in *qian* (前) and *hou* (后) in Mandarin

Mandarin Chinese is the spoken form of Modern Standard Chinese (MSC) (Li, 2014), which provides an ideal arena for testing the cross-linguistic applicability of the Space–Time Metaphor Theory. MSC features three pairs of words that can express both time and space: *shang (上)- xia (下)*, *zuo (左)- you (右)*, *qian (前)- hou (后)*. Among them, the pair of *qian (前)* and *hou (后)* has the strongest sense of space (Chen, 2007; Yang and Xue, 2011) thus has been widely used to express either the spatial contrast (FRONT/BACK) or the temporal sequencing (BEFORE/AFTER) (Gentner et al., 2002; Zhang, 2003). In particular, *qian* (前) signifies "before" in temporal sequencing and "in front of" in spatial sequencing, whereas *hou* (后) signifies "after" in temporal sequencing and "back" in spatial sequencing. Zhang (2003) has summarized the five types of temporal sequencing that could be expressed by the pair of *qian* (前) and *hou* (后) in MSC:

(1) Temporal adverbs:
 (a) *yiqian 以前* (before), *congqian 从前* (before)
 (b) *yihou 以后* (after), *jinhou 今后* (after)
(2) Temporal adjective prefixes:
 (a) *qianren前人* (predecessors), *qianqi前妻* (ex-wife)
 (b) *houji后记* (postscript), *housheng后生* (young man)
(3) Temporal postpositions:
 (a) *wanfanqian晚饭前* (before dinner)
 (b) *wanfanhou晚饭后* (after dinner)
(4) Temporal prepositions:
 (a) *qianbanye前半夜* (the first half of the night)
 (b) *houbanye后半夜* (late night)
(5) Proverbs:
 kongqianjuehou空前绝后 (unprecedented)
 qianyinhouguo前因后果 (cause and effect)

In the above examples, the words *zhi qian* (之前), *zhi hou* (之后), *ran hou* (然后), and *zui hou* (最后) are used to convey relative temporal sequencing. In contrast, *qian mian* (前面) and *hou mian* (后面) can be used to express both spatial and temporal sequencing relations. Moreover, these temporal terms include words that refer to the future, such as *zhi hou* (之后), *ran hou* (然后), and *zui hou* (最后), and a set of words that refer to the past using the term *zhi qian* (之前). If the pair of words was widely used to express time much earlier than that of space in young children's natural utterances, we would have to reject the premise of the Space–Time Metaphor Hypothesis—temporal expression based on space concepts. Therefore, the following research questions guided this study:

(1) Are there any age differences in Mandarin-speaking preschoolers' production of temporal and spatial expressions using the pair of *qian* (前) and *hou* (后)? If yes, what are the developmental patterns?

(2) Do Mandarin-speaking preschoolers use the pair of *qian* (前) and *hou* (后) to express time earlier than that of space? If yes, what is the pattern of this preference?

In particular, we have the following hypotheses:

Hypothesis I: There will be a significant age effect in the pragmatic use of the target pair of words: *qian* (前) and *hou* (后).
Hypothesis II: The same words *qian* (前) and *hou* (后) will be used to express space much earlier than time.
Hypothesis III: The pair will be used more frequently to express space than time.

MATERIALS AND METHODS

The Corpus

Li and Tse (2011) established the largest corpus on early child Mandarin, which includes 504 Chinese preschoolers aged from 2.5 to 5.5 years and randomly sampled from Beijing (N_{BJ} = 168), Hong Kong (N_{HK} = 168), and Singapore (N_{SG} = 168). Using Age (four groups), Gender (two), Society (three), and Language (Mandarin, Cantonese, and English) as the study variables, this corpus allows scholars to explore the age and gender differences in early psycholinguistic development and to conduct cross-linguistic and cross-society comparisons. So far, this corpus has generated six academic publications, exploring Chinese and English interrogative development in Beijing, Hong Kong, and Singapore preschoolers (Li et al., 2015, 2017, 2019), early acquisition of aspect markers and temporal adverbs in Mandarin- and Cantonese-speaking preschoolers (Tse et al., 2012; Liang et al., 2019), and early acquisition of Cantonese classifiers (Li and Wong, 2014). This study was based on the ECMC in Beijing (Li and Tse, 2011), which comprises 42 h of conversations between 168 Mandarin speakers aged from 2 to 5 years, with 21 boys and 21 girls in each age group. All participants were randomly sampled from eight preschools in Beijing, where Mandarin is the official and daily used language in China and the spoken form of Modern Standard Chinese (Li, 2014). All of the participants, their families, and the teachers spoke Mandarin.

Communication Task

The participants were randomly paired (boy/girl, boy/boy, or girl/girl), and each pair was encouraged to play and talk with each other for 30 min in the same play context set up in the participants' classroom. The context was furnished with toys, including cooking materials, food and fruits, furniture and electrical appliances, and hospital materials and vehicles. During playtime, their conversations were videotaped using a high-definition digital camera with two separate microphones and observed uninterruptedly by the researchers. The conversations were transcribed and checked by experienced research assistants (RAs). The spatial and temporal sequencing expressions were first identified by the RAs and then confirmed by a panel of Chinese linguists. Because the context was the same for every child, the children had equal chances of producing spatial and temporal expressions, thus ensuring an ideal setting for making comparisons.

Coding System

The coding book was developed by the second author, verified by the first author, and reviewed by an independent psycholinguist. It was used to code all of the expressions collocated by the words *qian* (前) and *hou* (后) into four subtypes of time and one subtype of space: Time A for ran hou (然后), Time B for zui hou (最后), Time C for zhi hou (之后), and Time D for zhi qian (之前). Specifically, ran hou (然后) in Chinese also serve as a conjunction with the meaning of "and," therefore, we excluded all the ran hou (然后) with conjunction meaning but only included the ran hou (然后) with the meaning of time. All of these terms are temporal sequencing expressions of future/past relations. A pair of space–term types for hou mian (后面) (Space A) and qian mian (前面) (Space B) was used to code expressions of spatial sequencing in terms of front/back relations (**Table 1**). All of the data were coded by the same RA to ensure 100% coherence in the coding based on the coding system.

RESULTS

One hundred eighty-three cases of the use of the localizers *qian* (前) and *hou* (后) were elicited from the ECMC (Li and Tse, 2011). The pair of words was uttered by 72 Mandarin speakers across the four age groups (aged 2.5, 3.5, 4.5, 5.5), with 22 girls and 40 boys using the words correctly and 10 children misusing the terms. All of the usages were analyzed and placed within the typology shown in **Table 1**: (1) temporal expression: 然后 (then), 最后 (at last), 之后 (after), 之前 (before); and (2) spatial expression: 后面 (back) and 前面 (in front of). This section reports the results of the detailed statistical analyses.

Among the 183 cases of temporal and spatial expression, 66.12% was Time A, ran hou (然后), which means "then," "afterward," "after that," "and then," etc. The second most commonly used expression (15.3%) was Space A, hou mian (后面), which means "behind," "at the back," "in the rear," "back," etc. The third most commonly used expression (9.84%) was Time B, zui hou (最后), which means "at last," "last," "final," "ultimate," etc. The fourth most commonly used expression (8.74%) was Time C, zhi hou (之后), which means "later," "after," "afterward," etc. The two least used terms, Time D "之前" (zhi qian, before) and Space B "前面" (qian mian, in front of), were related to the Chinese term "前." The difference between the use of "前" and "后" may

TABLE 1 | Inventory of temporal and spatial expression with qian/hou in the corpus (*N* = 168).

	Temporal Expression				Spatial Expression	
	Time A	**Time B**	**Time C**	**Time D**	**Space A**	**Space B**
Chinese	然后	最后	之后	之前	后面	前面
Pinyin	*ran hou*	*zui hou*	*zhi hou*	*zhi qian*	*hou mian*	*qian mian*
English	then	at last	after	before	back	in front of
Percentage	66.12	9.84	8.74	2.73	15.3	2.8

be associated with the participants' cognitive level, which will be discussed in the next section.

Age Differences in Temporal and Spatial Expression

As shown in **Table 2**, the number of participants who used the pair to express time varied across the age groups, with 10, 2, 20, and 29 cases from the age groups of 2.5, 3.5, 4.5, and 5.5, respectively. A set of chi-square tests was conducted to test the age differences, and a significant age effect was found for temporal expression [χ^2 (3) = 3.79, $p < 0.05$] and Time A (*ran hou*) [χ^2 (3) = 3.64, $p < 0.05$]. Non-significant differences were found for the other temporal and spatial expressions [χ^2s (3) < 2.05, *ps* > 0.12]. In particular, about 69% of the 5.5 age group participants used temporal expressions, indicating that the 5–6-year-olds used this type of expression maturely and pragmatically. In contrast, only 4.8% of the participants in the 3.5 age group used temporal expressions. In addition, about 23.8% of the 5.5 age group participants used spatial expressions, indicating that most participants did not use the spatial expression. Similarly, only 7.1% of the participants in the 2.5 age group used spatial expressions. Furthermore, a jump from 11.9 to 23.8% was found in the spatial expression, which occurred between age groups 4.5 and 5.5, indicating that around age 5 may be a critical developmental period for spatial expression.

In particular, in the 2.5 age group, 10 participants used temporal expressions: five for Time A (然后), two for Time B(最后), and three for Time C and Time D (之后/之前), whereas only three of this group used *qianmian* (前面) to express a spatial relationship, and no child used *houmian* (后面) in the communication. For example, one 2-year-old correctly used "*zhi qian* (之前)" in the utterance "*dan gao zai kao zhi qian*" (蛋糕在烤之前; English: before baking the cake) (Time D) to express the meaning of "before baking the cake." In the 3.5 age group, two children used temporal expressions: one for Time A (然后) and one for Time B (最后), and no child used Time C/D (之后/之前). Only four participants used *qianmian* (前面) to express a spatial relationship, and no child used houmian (后面) in the communication. In the 4.5 age group, 20 children used temporal expressions: 14 for Time A (然后), four for Time B (最后), and two for Time C/D (之后/之前). Only five children used *qianmian* (前面) to express a spatial relationship, and two used *houmian* (后面) in communication. In the 5.5 age group, 29 children used temporal expressions: 17 for Time A (然后), five for Time B (最后), and seven for Time C/D (之后/之前). Eight participants used *qianmian* (前面) (Space B) to express a spatial relationship, and two used *houmian* (后面) (Space A) in the communication.

Last, the analysis revealed two critical developmental periods. First, in the 4.5 age group, almost half (47.5%, 69%) of the children used temporal expressions, indicating that age 4 may be a critical developmental period for temporal expression development. Second, in the age groups before age 4.5, no child used a spatial expression with *houmian* (后面), indicating that age 4 may be a critical developmental period for this type of spatial expression. Therefore, this study's results jointly indicated that age 4 might be a critical developmental period for temporal and spatial expressions. And Hypothesis I has been supported by the data of this study.

A 2 (gender) × 2 (expression) chi-square test was conducted to examine the gender differences in temporal versus spatial expression. The results indicated no significant gender difference, $\chi^2(1) = 1.645$, $p = 0.147$. For details, see **Table 3**.

Preschoolers' Pragmatic Preference for Temporal Expression

Further analysis revealed that more temporal expressions were used within each age group than spatial expressions (**Figure 1**). The only exception was the 3.5 age group, which produced relatively more spatial than temporal expressions. In particular, in the 2.5 age group, seven children (16.7%) talked about the future, three (7.1%) talked about the past, three (7.1%) talked about the front, and none talked about the back. In the 3.5 age group, two children (4.8%) talked about the future, four (9.6%) talked about the front, and none talked about the past and the back. In the 4.5 age group, 18 children (42.9%) talked about the future, two (4.8%) talked about the past, three (7.1%) talked about the front, and two (4.8%) talked about the back. In the 5.5 age group, 22 children (52.4%) talked about the future, seven (16.7%) talked about the past, eight (19%) talked about the front, and two (4.8%) talked about the back. Significantly more Mandarin-speaking preschoolers preferred to talk about the future (time), and very

TABLE 2 | Age differences in the temporal and spatial expressions with qian/hou.

	In Chinese	Aged 2.5 (*N* = 42)		Aged 3.5 (*N* = 42)		Aged 4.5 (*N* = 42)		Aged 5.5 (*N* = 42)		χ^2
		n	%	*n*	%	*n*	%	*n*	%	
Time		10	23.8	2	4.8	20	47.6	29	69	3.79*
A	然后	5	11.9	1	2.4	14	33.3	17	40.5	3.64*
B	最后	2	4.8	1	2.4	4	9.6	5	11.9	0.27
C/D	之后 / 之前	3	7.1	0	0	2	4.8	7	16.7	1.16
Space		3	7.1	4	9.6	5	11.9	10	23.8	1.53
A	前面	3	7.1	4	9.6	3	7.1	8	19	0.46
B	后面	0	0	0	0	2	4.8	2	4.8	2.02

**p < 0.05; % = n/N.*

TABLE 3 | Gender differences in the temporal and spatial expressions with qian/hou.

English	Chinese	Boy (*N* = 84)		Girl (*N* = 84)	
		n	%	*n*	%
Temporal word		30	35.7	20	23.8
Time A	然后	21	25	16	19
Time B	最后	6	7.1	6	7.1
Time C/D	之后 / 之前	9	10.7	3	3.6
Spatial word		15	17.9	6	7.1
Space A	前面	3	3.6	1	1.2
Space B	后面	14	16.7	5	5.9

% = n/N.

few talked about the back (space) (**Figure 2**). This "future-preference" phenomenon might be linked to early cognitive development and warrants further study. All these findings indicated that Hypotheses II and III should be rejected in this study.

DISCUSSION

Time and space are two fundamental dimensions of human cognition and language, and their acquisition and expression have been a fascinating and important research topic. As the first comparison of temporal and spatial expressions using the same pair of words, *qian* (前) and *hou* (后), this study found significant age differences and remarkable developmental patterns in early child Mandarin. The findings did not support all the hypotheses (except for Hypothesis I). This section will discuss the major findings and their implications for future studies.

The Developmental Pattern of Pragmatic Use

This study revealed a significant age effect in temporal expressions production, particularly Time A (*ran hou*). This finding suggested that the period between 2.5 and 5.5 might be critical for acquiring temporal expressions, especially future expressions, among Chinese preschoolers. However, no significant age differences were found in the production of spatial expressions, indicating that the period between 2.5 and 5.5 might not see any remarkable development in this regard. It was found that only a few children in the 5.5 age group (23.8%) were able to produce spatial expressions, indicating that the children in this age group were only beginning to develop their capacity to produce spatial expressions. Therefore, we could conclude that the Mandarin-speaking preschoolers began to produce temporal expression between the ages of 2.5 and 5.5, whereas they only began to produce spatial expression around age 5.5. This finding implies that Chinese children might acquire spatial expression capacity later than that for temporal expression. However, this finding needs to be further explored and verified with longitudinal studies.

Pragmatic Preference for Temporary Expression

This study found that although the same pair of words could be used to express time and space, the participants preferred to express time (84.70%) more than space (15.30%). This finding implies that young Mandarin speakers might prefer to use the pair of Chinese words to express time, given that the research setting equally invited both temporal and spatial expressions. This finding could provide empirical evidence to support Boroditsky; Boroditsky's (2000; 2001) hypothesis that "thinking about time does not necessarily require access to spatial schemas." In addition, this finding has also provided alternatives to challenge the idea that spatial expression is the precondition or foundation for temporal expression (Wallentin et al., 2005; Kranjec et al., 2010). Nevertheless, it is also important to note that Boroditsky (2000, 2001) used an adult sample and experimental design, whereas this study used a sample of young children and a corpus design, which provided naturalistic and authentic data on early child language acquisition. In particular, this study found that even though children did not produce any spatial expressions using *qian* (前) and *hou* (后), they could use the related temporal expressions. This finding implies that temporal expression using the same words as a morpheme might not necessarily be an adaptive use of spatial metaphor.

This study has also provided new evidence to support Kemmerer's (2005) hypothesis that the time and space domains might be represented and processed separately and independently in the brain. This separation in brain processing implies that temporal expressions' processing may not necessarily depend on spatial expressions. If Kemmerer's Hypothesis were true, Mandarin-speaking preschoolers would have developed their temporal and spatial expressions separately. Accordingly, the temporal expression of *qian* (前) and *hou* (后) would not be constrained by the spatial expression. Accordingly, it is natural and understandable that the Mandarin-speaking preschoolers in this study produced the temporal expression more and earlier than the spatial ones. However, because the corpus used in this study only included young children aged 2–5 years, leaving very younger children (0–2 years old) understudied. Thus, the possibility of the early production of spatial expression using the pair of qian/hou could not be ruled out, thus warranting future studies on this topic.

Temporary Expression Produced Earlier Than Spatial Expression

This study found that the 2.5 age group produced considerably more temporal sequencing expressions than the spatial ones, indicating that young Mandarin speakers tended to produce temporal expressions more and earlier (**Figures 1**, **2**). This production difference in the early years indicated that the temporal expression might have occurred earlier than the spatial expression of *qian/hou*. Accordingly, this finding has provided new evidence to support Boroditsky; Boroditsky's (2000; 2001) statement that thinking about time does not necessarily require access to spatial schemas, as temporal language is not adapted from spatial sequencing. In addition, Boroditsky (2001) has

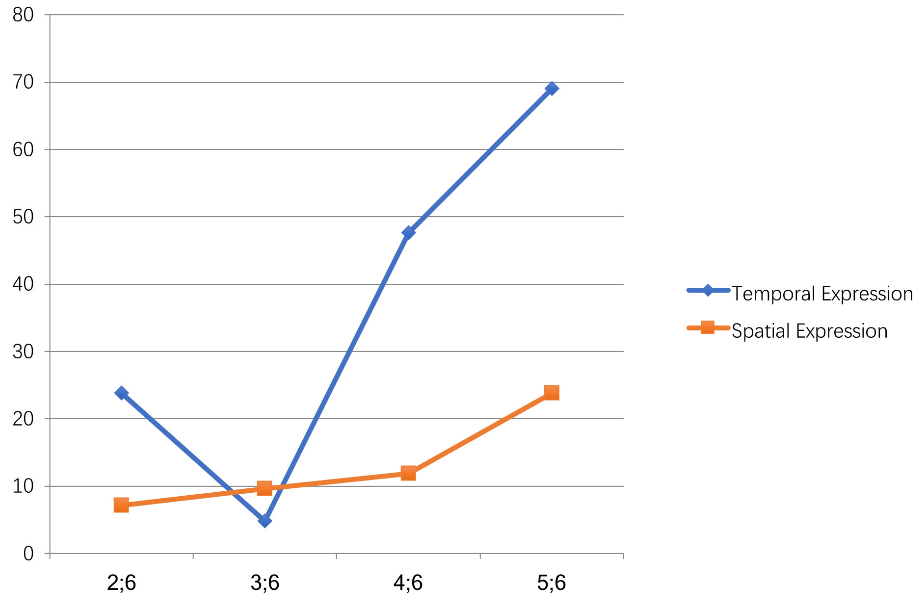

FIGURE 1 | Developmental trends of temporal and spatial expression with qian/hou.

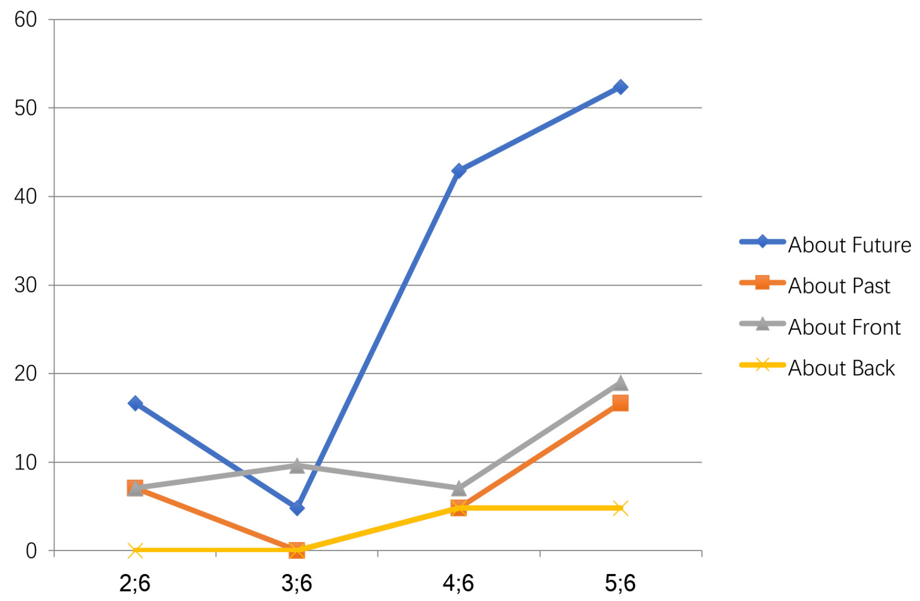

FIGURE 2 | Age differences in the pragmatic functions of Qian/Hou.

attributed temporal expression preference in her experiments to the adults' experiences as she believed that the concept was before the language. Experiences in different cultural and linguistic contexts will cause different conceptualization and expression of time and space. Chinese people's view of time and space might be different from that of English speakers. Therefore, Boroditsky's study on adults might not control the confounding effects of culture and sociolinguistic contexts. In contrast, this corpus-based study was designed to examine the language acquisition of young Mandarin speakers who had far less experience in using language than adults. Therefore, this study could provide authentic evidence on language acquisition during the early years, demonstrating the true relationship between temporal and spatial expression. According to this study, when the young children did not produce any spatial expressions using *qian/hou*, the related temporal expressions had been produced. This finding implies that temporal expressions using the same words as a morpheme might not be the adaptive use of spatial metaphor, thus challenging the Universal Space–Time Mapping Hypothesis.

CONCLUSION, LIMITATIONS, AND IMPLICATIONS

The pair of Chinese words qian/hou could be used to express either time or space, thus providing an ideal case to test the cross-linguistic applicability of the Space–Time Metaphor Hypothesis. First, this corpus-based study found a significant age effect in the pragmatic use of the target pair of words, indicating that the period before the age of 4.5 might be critical for developing temporal and spatial expression. Second, the pair was used to express time (before/after) much earlier than space (front/back), indicating that t might not necessarily be based on the spatial metaphor. Third, the pair was used more frequently to express time (before/after) than space (front/back) by the preschoolers, thus challenging the hypothesis.

This study has some limitations. First, as the corpus collected only a sample of the entire target language (rather than the whole), the sample size must be increased and data should be gathered from more typical everyday settings to gain a more representative sample. Second, the sample was cross-sectional rather than longitudinal, making the evidence less robust for understanding the long-term developmental trend. Third, it would be perfect if similar corpus data could be collected from adult participants; otherwise, we could not judge whether the pragmatic preference for temporal expression would be a norm in Mandarin-speaking. Last, the younger children (0–2 years old) should also be included in this study, as they might have also produced the spatial and temporal expressions using qian/hou words.

Nevertheless, as the first comparison of temporal and spatial expressions using the same pair of words, this study has initiated a new experimental paradigm for studying the complicated relationships among cognition, language, and pragmatics in the early years. This study might not provide sound evidence to overthrow the Space–Time Metaphor Hypothesis completely but has provided an exceptional case to challenge the universal applicability of this hypothesis. This study's finding has at least indicated that the Space–Time Metaphor Hypothesis might not be applicable in early child Mandarin. Therefore, more cross-linguistic and cross-contextual studies are urgently needed.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: the dataset is confidential. Requests to access these datasets should be directed to dandan.wu4@students.mq.edu.au.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethical Committee of the Faculty of Education in The University of Hong Kong. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

LT and DW completed the whole manuscript writing. DW designed the study and analyzed the data by the guidance of the LT. Both authors contributed to the article and approved the submitted version.

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Spatial Language of Young Children During Block Play in Kindergartens in Urban China

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Spatial language is an important predictor of spatial skills and might be inspired by peer interaction and goal-oriented building behaviors during block play. The present study investigated the frequency, type and level of children's spatial language during block play and their associations with the level of block play by observing 228 young children in classrooms equipped with unit blocks and allowing free play on a daily basis. The findings showed that during block play, young children used more words about spatial locations, deictic terms, dimensions, and shapes and fewer words about spatial features or properties and spatial orientations or transformations. Spatial locations were used most frequently, and young children tended to use vertical location words to represent the corresponding location. Most young children used gestures in conjunction with spatial deictic terms. Among shape words, tetragon words were frequently used, and the representation of spatial shapes showed alternatives, collective tendencies and gender differences. The use of spatial language during the play process had a significant positive correlation with age, the construction structure, and form of block building.

Keywords: block play, spatial language, use, representation, features

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INTRODUCTION

Spatial skills in the early years may predict young children's later academic performance in mathematics, science, engineering, and technology learning (Wai et al., 2009; Newcombe and Frick, 2010; Vasilyeva and Lourenco, 2010; Zhu, 2017) and are an important domain of children's mathematics learning and development (Wai et al., 2009; Verdine et al., 2014; Lauer and Lourenco, 2016; Verdine et al., 2017; Simoncini et al., 2020). Spatial language is the language used to communicate spatial information to others and represent the location and spatial relationship of objects (Pang et al., 2008). It is also the internal process of thinking, reasoning, and operation of spatial information, which is one of the important forms of children's external spatial representation (Pang et al., 2008). The use of spatial language enables children to pay attention to and process spatial information (Shusterman and Spelke, 2005), so it may improve the effect of spatial reasoning (Levinson, 2001) and promote the development of spatial skills. Variations in spatial skills can be predicted by differences in children's use of spatial language (Hermer-Vazquez et al., 2001; Pruden et al., 2011).

Block play is a kind of construction play that combines small blocks into larger objects in a certain way to represent the physical world (Yang et al., 2020). Peer interactions, goal-oriented construction behaviors and the related thematic context in block play can inspire children's spatial language (Casey et al., 2008; Ferrara et al., 2011). Many studies have focused on the family environment and children's spatial language, but few studies have analyzed the association between children's construction level and their use of spatial language in block play.

To support young children's spatial skills in kindergarten classrooms, it is necessary to investigate the frequency, type and level of young children's spatial language in the context of block play and their association with the level of block play.

Children's Spatial Language

Spatial language is the representation of spatial relations. Constructing and understanding the relationship between spatial cognition and the symbolic system is key to the development of spatial skills (Ferrara et al., 2011). Spatial language provides children with a representative system of spatial concepts to identify and code spatial clues (Miller et al., 2016) and understand spatial categories. Mastery of spatial language supports children's understanding of spatial concepts, provides children with classification experience (Bowerman and Choi, 2003, p. 387–428), and guides children to pay attention to the spatial environment (Ferrara et al., 2011). Moreover, children can recall relevant spatial information by describing the spatial properties of objects and events (Loewenstein and Gentner, 2005). Zhang et al. (2011) tested non-blind children, congenitally blind children, and acquired blind children. They found that visual loss blind children determined the features of organizing spatial concepts, and that language played an important role in this process. Spatial language can influence how people represent and reason about space (Hermer-Vazquez et al., 2001; Loewenstein and Gentner, 2005).

Many researchers classify spatial language according to its contents. The spatial language system in linguistics is divided into two sections. One is external spatial language, such as spatial relations (on the table), landmarks (come to me), and observers (in his left). The other is internal spatial language, in general, including spatial shapes (strip and bulk) and spatial metric terms (square meter and step), partially including the edge of space with objects at the center (corner) and parts of the human body (face, nose, and head) (Zhao, 2008, p. 82–90). An and Wu (2019) divided spatial language into two dimensions: spatial locations and spatial tendency words. Studies by Ferrara et al. (2011) and Levine et al. (2012) are more specific and detailed. Based on previous literature, this study classified children's spatial language into spatial locations (up and down), deictic terms (here and there), dimensions (long and tall), spatial features or properties (curvy and straight), shapes (rectangle and square), and spatial orientations or transformations ("turn it around," "the man is facing the block").

Chinese children show specific features in mastering spatial language due to the Chinese language system. For example, researchers found that Chinese children acquired spatial location words following the order of "inside, up, down, outside, back, front, middle, side, left, right" (Zhang, 1986; Kong and Wang, 2002). The use of spatial reference systems varies across different cultures and might stem from different spatial awareness. Some languages tend to involve self-centered (e.g., left and right) encoding positions, while other languages tend to involve concentric encoding positions (e.g., north and south) (Levinson, 2003). The concept of spatial orientation among the Han nationality in China is mainly based on the reference structure of "all things are one, and man and nature are one" (Zhu, 2017). Language and culture have crucial influences on the development of children's spatial concepts and spatial language in different societies. Currently, the relevant research is mainly focused on research on a particular type of spatial language (e.g., spatial locations and dimensions). It is necessary to analyze young children's use of different types of spatial language in the kindergarten context.

Recently, there has been increasing evidence that spatial language contributes to the development of spatial skills (Miller et al., 2016). Several studies have shown that the development of children's spatial skills is directly affected by the spatial language environment created by adults for children, such as adults' spatial words in free-play environments (Pruden et al., 2011), parent-child relationships (Levine et al., 2012) and family social and economic levels (Verdine et al., 2014). In addition to family environmental factors, the development of children is different depending on age and gender. The level of development of young children's ability to understand spatial representation language at the age of 3–5 is significantly higher than their ability to use spatial representation language (Pang et al., 2008). Otherwise, there were no sex differences in children's performance in the WPPSI-III Block Design subtest or the Spatial Analogies task. However, the cumulative spatial tokens of children showed a marginally significant difference in the amount of spatial language used by boys and girls (Pruden et al., 2011). The use of spatial language by children of different ages and genders in the kindergarten classroom environment needs to be studied further.

Relationship Between Block Play and Spatial Language

In recent years, there have been many studies on spatial language. Some studies have investigated children's representational ability to understand spatial language in the form of researchers' commanding children to put objects in certain places, asking them to also find and describe places. Loewenstein and Gentner (2005) provided clues about spatial language abilities in 4-year-old children. They found that spatial language clues could help them complete tasks more effectively. Children are better at producing spatial language (e.g., left/right, pass/side, or middle) related to tasks (Hermer-Vazquez et al., 2001; Ankowski et al., 2012; Miller et al., 2016). The current research mainly explores the relationship between providing spatial clues for children and their spatial language development in the task. However, in free play, other situations might also provide effective spatial clues for children, and the relationship between the situation and spatial language requires further study.

Blocks are basic materials used by children to construct and represent the world around them during play (Pan et al., 2016). Children need to think about the choice of the shape and size of blocks, the adjacent relationship of orientation, the stability of building works, all of these require children to have an ability to mobilize space comprehensively (Wu et al., 2019). During block building, children perceive and learn about the intrinsic features of objects, such as how objects vary with dimensions of size, pattern, symmetry, and shape (Casey and Bobb, 2003; Verdine et al., 2014; Suh et al., 2019). They can perceive space, geometry, and correctly grasp the concept of space (e.g., "Where am I?" "How far am I from it?" "Where is it?") (Clements et al., 1997; Hu, 2018). Zhang (2013) and Kang et al. (2020) measured the spatial skills and building ability of children who received pretest and posttest in building training, the same conclusion was that block play helped to improve children's spatial skills. Several studies have provided suggestive evidence that early block building can promote the development of children's spatial thinking (Verdine et al., 2014; Simoncini et al., 2020).

Blocks are also the media for children's original ideas and life experience, with an open versatility that means they can be and re-created. They provide children with a representation transformation mechanism to help them better explore the world (Hu, 2018). Block play provides opportunities for children's language learning and communication. Young children effectively use oral language and communicate with their peers (Cheng, 2017), express their construction goals and ideas, and naturally generate relevant spatial language. Ferrara et al. (2011) found that the frequency of children's spatial language in a common interactive group is lower than that in a block play group, which indicated that block play could stimulate children's conversation about spatial concepts, such as spatial orientation and matching the shape of blocks.

The Relationship Between Building Blocks, Language and Spatial Representation

Spatial representation describes the form of an object's position and spatial relation in individual psychology, and the internal process of individual thinking, reasoning, and the operation of spatial information (Zhao, 2006). The solution to spatial problems can be inextricably linked to the participation of spatial representation. As one of the crucial aspects of spatial cognition, an ability to understand and use spatial representation plays an important role in the process of exchanging and manipulating spatial information (Pang et al., 2008). Studies have shown that exposure to spatial language and that when diverse contexts promote children's spatial thinking. With stronger spatial representations, children may be able to dedicate more cognitive resources to spatial processing (Casasola et al., 2020). However, in the domain of spatial development, similar interactions among cognitive processes could underlie the spatial relations (Miller and Simmering, 2018). By analyzing the use of spatial language in building blocks, this study further develops understanding of children's spatial representation, exploring the links between the representation of building blocks and linguistic representation of verbal communication in children's cognitive spatial relations.

Building blocks are a representation of space. According to the study of Liu (2015, p. 568), when young children put blocks together, they can experience "proximity." Sequentially, arranging the blocks produces the "sequence." A certain space is composed of blocks to make the difference between "inside" and "outside." Blocks are inverted, converted, and built to form a certain model and generate various spatial structures. The formation of spatial concepts essentially lies in "being experienced" rather than "being informed." A building block is a highly practical spatial operational activity, providing rich opportunities for children to explore space, enabling them to directly and concretely perceive and experience abstract spatial relations. Moreover, building blocks provide children with a diversity and amount of spatial labels that may promote the representation of children's spatial information on a broader level than simply supporting labels for spatial information (Casasola et al., 2020). Further research has suggested that experience of spatial activities in block building may improve selective attention in children (Miller and Simmering, 2018). Specifically, children who play more spatial games tend to perform better in spatial performance, which indicates that they may learn how to focus on relevant information through spatial play (Jirout and Newcombe, 2015; Miller and Simmering, 2018).

Verbal communication during the process of building blocks facilitates the linguistic representation of space. Plumert and Hawkins (2001) have suggested that children aged 4–5 years old are able to understand the representational relationship between spatial language and spatial relationships in reality. For children, space is an abstract and difficult concept, while language is an effective tool to help children understand the concept of space. Multiple studies have proved that language plays a key role in spatial development through creating spatial labeling, changing spatial representations, and directing attention/encoding (Gentner, 2003, 2016; Dessalegn and Landau, 2008; Miller et al., 2016; Miller and Simmering, 2018). However, not all languages can promote the development of children's spatial skills. Children may not spontaneously recognize and produce spatial information about location before being prompted, and knowledge of language alone is insufficient to explain children's spatial performance (Farran and O' Leary, 2016; Miller and Simmering, 2018). At this time, verbal communication with peers can be employed as an external linguistic representation to prompt, express, transmit, and memorize spatial information and participate in the encoding and processing of children's spatial relations.

One possibility is that verbal communication can attract children's attention to relevant spatial information, improve children's selective attention, and stimulate children to produce language related to location information. As studies have suggested, "when children are provided with language cues by an adult, the language can direct their attention to improve their spatial performance (Miller and Simmering, 2018)." Similarly, children often produce location terms when prompted by peers in the contexts of block play. Verbal communication with peers makes it possible for children to focus attention on the labeled spatial information, improve the understanding of how children use particular spatial words differently based on the context and enhance their ability to use task-relevant adaptive language. Another possible explanation is that hearing and expressing the relational language in verbal communication promotes the development of children's representational structure, thus promoting children's spatial thinking process. As for the effects of acquiring and using spatial language within a language community, Loewenstein and Gentner (2005) suggested that "once relational terms have been acquired, hearing relational language might facilitate encoding relations in ways consistent with the semantics of the terms." Thus, "hearing the spatial language induces a conceptual representation of spatial relations." They also observe that, "relational labels invite the child to notice, represent, and retain structural patterns of elements (Gentner and Loewenstein, 2002, p. 103)." Relational language provides representational tools with which speakers can create construals that facilitate reasoning (Gentner and Loewenstein, 2002; Loewenstein and Gentner, 2005).

The gestures of parents during spatial conversations could predict children's spatial language, which may also be involved in children's future spatial cognition (Pruden et al., 2011). In the process of peer communication, children tend to use active representation to assist the expression of spatial information and spatial relations, and the overlapping of language representation and active representation occurs in the process of spatial representation.

Overall, building blocks and verbal communication are imperative forms for children to understand and use spatial representation. Children can determine the location of target objects according to the linguistic representation requirements of others and the need for building models, so as to understand the spatial relationship. Children use language, model operation, active, and other representational forms to convey spatial information to others. They extract and organize representational symbols to communicate and spread spatial information through verbal and action communication in peer interaction. Casasola et al. (2020) proved that providing spatial language as children manipulate blocks makes it possible for children to align their actions and attention to the labeled spatial information. The co-occurrence between building blocks and verbal communication may have created a synergy that is pitched to bolster the effect of spatial labels on children's spatial thinking. Therefore, exploring verbal communication with peers whilst using building blocks could help us to further understand the synergy between different forms of spatial representation and explore the relationship between language and spatial cognition.

The Present Study

Since block play embodies and promotes children's spatial skills and spatial language, it provides a context to study the development of children's spatial skills and spatial language. We examined the use of spatial language during block play in 228 children from the younger, middle, and older age groups, to examine the features and related factors of young children's spatial language. The questions we examined are described below.

First, what types of spatial language do young children use during block play? Previous empirical evidence shows that spatial skills are positively correlated with block building skill (Zhang, 2013; Kang et al., 2020). The spatial skills and spatial language of children might be inspired by peer interaction (Cheng, 2017). Therefore, the content and frequency of young children's spatial language use might vary in different contexts of block play. In contexts with more complex construction structures and more peer interactions, children might more frequently use spatial language in complex forms and contents.

Second, how does the use of spatial language during block play vary with age and gender? Previous studies have shown that children who were 3–5 years old could comprehend spatial language better than they could use it (Pang et al., 2008). There are also some differences in the spatial language used by children of different genders (Chan, 2007). Children of different ages and genders use different types of spatial language during block play.

MATERIALS AND METHODS

Participants

Considering the influence of daily experiences in play, four kindergartens were selected to provide medium-sized wooden blocks in the classroom and conduct free play every day. The four kindergartens had the same (Ji 级) and category (Lei 类), and these kindergartens were often called R1C1 kindergartens (this meant that kindergartens of the top rank and category were regarded as the best) (Pan et al., 2010). In the classroom, young children were randomly selected (n = 228, 114 boys and 114 girls) in a total of 57 groups: 19 groups in younger class (n = 76, mean age = 50.99 months, range: 41–59 months, SD = 4.17), 20 groups in the middle age class (n = 80, mean age = 60.98 months, range: 46–71 months, SD = 5.68), and 18 groups in older class (n = 72, mean age = 69.19 months, range: 62–76 months, SD = 3.80).

The children in the study came from the same racial backgrounds, and they could communicate well with their peers and express their ideas using Mandarin. All the kindergarten classrooms were based on developmentally appropriate early childhood practices (Casey et al., 2008), with a variety of activity centers in the rooms (including a block area), and choice time for the children to play in these areas (e.g., constructive play, role play, and exhibition play). The researchers made sure that there were a sufficient number of blocks of different sizes and shapes provided in each of the classrooms.

Material

Material, Size, Shape, and Quantity of Blocks

Medium-sized wooden blocks were chosen. The size of the unit blocks was 3.5 cm × 7 cm × 14 cm, including 18 types of shapes (e.g., cuboid, cylinder, slope, triangle, and Y-shape) formed based on the size of the unit block. As the number of blocks was reduced, it had a significant impact on the level of children's construction (Yang et al., 2020). Under the condition that the number of pairs of blocks (such as isosceles right triangle blocks or slope blocks) was even, according to the number and use of different shapes of blocks by the children, we ensured that the number of blocks the children has access to was greater than 200.

Design

Play Partners and Zone Area

In the classroom, a large meeting room, or a music classroom, we created the building block play area. The number of young children entering the block area, as specified by most classrooms in kindergarten practice, did not exceed six. In most cases there were four children (Pan et al., 2016), and a space density of 1.47 square meters was an ideal activity site (Zhang and Fang, 2018). As mentioned, the number of young children in the same play group was limited to four, and the per capita activity area was 1.5 square meters.

Play Duration

Young children were allowed to enter the block area for free play. The duration was from the time when the children began constructing to the time when they stopped constructing, proceeded to other types of activities for a long time, and did not return to playing blocks. The average time for block play in this experimental study was 25 min.

Procedure

Each play consisted of two boys and two girls randomly selected by kindergarten teachers from the same classroom. With no other children on-site, the young children entered the block area for free play. Before the children entered the area, the researchers informed them of the basic rules of behavior, such as not throwing blocks and not constructing directly beside the block cabinet. The researchers did not intervene unless the children's behavior may have threatened their physical safety. Children were allowed to introduce their building work when the play was over. The researchers videotaped the entire process and took pictures of the young children's construction structure during the building process. In this study, 57 videos and several pictures of children's block play were collected.

Coding

Coding Spatial Language of Young Children

Based on studies by Ferrara et al. (2011) and Levine et al. (2012), the present study divided young children's spatial language into (1) spatial locations (up and down), (2) deictic terms (here and there), (3) dimensions (long and tall), (4) spatial features or properties (curvy and straight), (5) shapes (rectangle and square), and (6) spatial orientations or transformations ("turn it around," "the man is facing the block"). We transcribed all language during the free block play, coded the spatial locations, deictic terms, dimensions, shapes, spatial features or properties, spatial orientations and transformations of each child during play, and counted their frequency. Words with metaphorical meaning (e.g., "he sits on the ground," "block this up") were temporarily not considered. In the same sentence, spatial language expressed with the same meaning was counted once. Considering the differences between the English and Chinese languages, we listed English-speaking and Chinese-speaking coding tables, as shown in **Table 1**.

Coding Construction Structure of Young Children

Researchers evaluated children's building skills when constructing a structure and the spatial structure of blocks (Hanline et al., 2001; Casey et al., 2008; Ramani et al., 2014). As Borriello and Liben (2017) said, "complexity was judged by the number of blocks, the number of horizontal levels and vertical planes, and the extent to which all blocks were visible." We assessed the construction structure completed by each child. Based on the complexity of the works (Casey et al., 2008; Pan et al., 2016), children's construction structures were divided into seven levels: (1) random block placement, (2) tile/pile structure, e.g., one-dimensional structure (row of single blocks, or stack of single blocks), or two-dimensional structure (no internal space), structure with no width (a wall), no height (a floor), or no length (a two block-wide tower), (3) simple overhead structure, e.g., two-dimensional structure vertical internal space (arches), (4) crowd around structure, e.g., two-dimensional with horizontal internal space (enclosure), (5) complex overhead structure, e.g., three-dimensional structure vertical internal space (house), three blocks high and above, the structure of each layer are different, (6) simple combination structure, e.g., two-dimensional vertical or horizontal internal space plus depth to make a three-dimensional structure (arch + 1 or more blocks placed in front or behind, or two walls), (7) complex combination structure, complex overhead structure + horizontal internal space plus depth (or crowd around structure etc.) to make a three-dimensional structure. Each construction structure completed by the children during block play was coded and scored (0–6 points in sequence).

Coding Building Form of Young Children

According to the level of children's social interaction behavior (Ma et al., 2013; Hu, 2018), the children were free to choose whether to cooperate with their peers during play. Block building forms were divided into independent construction and cooperative construction.

RESULTS

Descriptive Statistics

Generally, young children used spatial locations, deictic terms, and dimensions more frequently in block play, accounting for 76.38% of usage. Young children used spatial locations most frequently (more than 30%). Next, the proportion of spatial deictic terms (22.56%) and dimensions (22.19%) was quite similar. Then, shapes account for 11.62%, while spatial orientations or transformations (6.81%) and spatial features or properties (5.20%) occur relatively less frequently, with a total of only 12.01% (see **Table 2**).

The first result of the present study relates to the spatial position words used by children, which were more diversified. According to different directions and areas, spatial locations were divided into vertical direction (e.g., up and down), horizontal direction (e.g., left, right, nearby, side, front, and behind), specific region (e.g., corner, edge, and spatial common sense), relative distance (e.g., side), and dynamic position (e.g., cross, leave, around, and enter), and then classified statistics were conducted (Bracken and Crawford, 2010; Zhu, 2017). Young children were more inclined to use spatial language in the vertical direction (34.50%) and dynamic position (31.99%), while the horizontal direction (16.00%), specific region (11.35%), and relative distance (6.17%) were used less frequently (see **Table 3**).

TABLE 1 | Categories of spatial language in English-speaking and Chinese-speaking.

Category	Example
Spatial locations	Up (上/上面/向上), down (下/下面/向下), outside (外面/外边/外头), inside (里面/里头/里边), middle (中间), behind (后边 后面/后部), right (右边), left (左边), front (前面), both sides (两边), broadside (侧边), corner (角落), side (旁边), "it is too far away" (太远了), nearest block (最近的积木), nearby (附近), "from here to there" (从这儿到那儿), "it covered the ground" (铺满一地)
Deictic terms	Here/this space/this place (这儿/这是/这里/在这里/这块), there/over there/that space/that place (那儿/那边/那块)
Dimensions	Long/longest/such a long/"it's too long" (长的/最长的/长段/这么长的/太长了), tall/too high/"how tall it is" (高的/ 高高的/太高了/够高了/好高呀/特别高), thin/a little bit thin/"it's too thin" (细的/薄的/更瘦一点的/太细了/瘦的), a little shorter (更矮一点的), a bit high (有点高), big/largest (大的/最大的/特别大), fat (胖的), small (少的/小的), thick (厚的/厚厚的/粗的), short (矮的/短的/短短的), just right (size) (刚刚好), super small (超小的), conglobate (圆圆的)
Shapes	Rectangle (长方形/长板/长条/柱子/夹板/薄板/平木/大长棍/薄片), square (正方形/方的/方块/小方块/小方方/小 木块/小柱子), Y-shape (Y形), cylinder (圆柱/圆木), triangle (三角/大三角/小三角), bending (弯弯), up and down slope (上下坡)
Spatial orientations or transformations	"Turn it around"/"twist over" (翻转过来/翻跟斗/翻过去), "the man is facing the block" (那个人正对着积木/冲着/对着), "in the direction of block" (顺着积木的方向), "turn on both sides" (往两边拐), "turn round" (掉头), "lean that way" (往那边倾斜), "go sideways" (横着走), "circle around" (围起来), "turn the blocks around" (把积木拐弯), "the road diverges" (分叉), "loop the loop" (翻跟斗), "put blocks sideways and upside down" (横着倒着放积木), "master the balance of the blocks" (掌握平衡), "spread out the blocks" (把积木分散放)
Spatial features or properties	Curvy (弯的), straight (直的), close (封闭起来了), solid (坚固的/结实的/稳当的), supporting (支撑的), oblate (扁扁的/平的), lacunal (有孔的), the symmetrical/corresponding structure (一样的/对称的/相称的/相应的), balanced (平衡的), oblique (斜的), "S-shape curve" (S曲线), "it is too stiff" (太死板了/太生硬了), "the block is too crooked" (太歪了), "this space is too empty" (太空了)

The second finding was that young children tended to use deictic terms with strong functionality and directionality. Usually, words such as "here" (这儿/这是/这里/在这里) and "there" (那儿/那边/那里) were used to represent the space area where the object was located, words such as "where" (哪里) were used to ask for the spatial location of the object, and words such as "this space/this place" (这块/这片), "that space/that place" (那块/那片) were used to delimit the spatial scope. Moreover, young children often used spatial locations along with gesture language. They tended to use gestures to divide the space and point to the region represented.

TABLE 2 | Descriptive statistics of spatial language.

	MAX	*M*	SD	Proportion (%)	Total
Spatial locations	47	4.91	6.16	31.63	1119
Deictic terms	21	3.50	4.15	22.56	798
Dimensions	25	3.44	3.80	22.19	785
Shapes	13	1.80	2.38	11.62	411
Spatial orientations or transformations	7	1.06	1.63	6.81	241
Spatial features or properties	8	0.81	1.29	5.20	184
Spatial language	94	15.52	15.60	100.01	3538

For the rounding-off method, the sum is 100.01%. For the minimum value is "0," it does not show up in the table.

TABLE 3 | Descriptive statistics of spatial direction locations.

	MAX	*M*	SD	Proportion (%)	Total
Vertical direction	31	1.69	3.16	34.50	386
Dynamic position	17	1.57	2.26	31.99	358
Horizontal direction	6	0.79	1.28	16.00	179
Specific region	10	0.56	1.32	11.35	127
Relative distance	4	0.30	0.71	6.17	69
Spatial locations	47	4.91	6.16	100.01	1119

For the rounding-off method, the sum is 100.01%. For the minimum value is "0," it does not show up in the table.

The third finding was that, among the shapes, tetragon words accounted for the highest proportion (34.30%). Specifically, young children could use relatively standard shape words, including "triangle" (三角形), "ellipse" (圆形), "semicircle" (半圆形), "rectangle" (长方形), and "square" (正方形), which to represent the shape of objects (accounting for 58.87%). Among them, the frequencies of "large and small triangle" words (29.68%) were the highest, "ellipse and semicircle" words (19.22%) were the second most frequent, and "rectangle" words (5.35%) and "square" words (4.62%) were the lowest. However, when young children used shape words, they often replaced shape words with object's names (accounting for 41.12%). Furthermore, the children used similar things they experienced in daily life to represent all kinds of blocks with different shapes. Most of them used "column" (圆柱) (13.38%) to represent cylinder blocks, "long strip (长条), long block (长木), long board (长板), flat plate (平板), thin sheet (薄片)" (13.38%) to represent cuboid blocks, "boxes, small boxes" (方块/木块/小木块/小方方/小方块) (10.95%) to represent square blocks, "trapezoid, up and down slope" (梯形/上下坡) to represent oblique triangle blocks, and "Y-shaped, curved" (Y 形/拐弯) to represent irregular-type blocks (3.41%) (see **Table 4**).

The fourth result was that spatial orientations or transformations (6.81%) and spatial features or properties (5.20%) were used less frequently. In the process of building, young children mainly used spatial language such as "turn" (转过来), "go straight"(直走), "on end"(竖起来), "turn around"(翻转/掉头) "circle around"(围起来), and "turn the

TABLE 4 | Descriptive statistics of shapes.

Shapes	Representation words	Count	Proportion (%)
Triangle	Big triangle, small triangle	122	29.68
Cylinder	Ellipse, semicircle	79	19.22
	Column	55	13.38
Tetragon	Long strip, long block, long board, flat plate, thin sheet, etc.	55	13.38
	Boxes, small boxes, etc.	45	10.95
	Rectangle	22	5.35
	Square	19	4.62
Others	Trapezoid, up and down slope, Y-shaped, curve, etc.	14	3.41

For the rounding-off method, the sum is 99.99%.

blocks around" (拐弯) to represent the change of the blocks and the movement direction of the building. They attempted to use spatial language such as "facing" (正对/面向) and "lean that way" (往那边倾斜) to describe the spatial position relationship and represent spatial positioning information.

Finally, we also found that the children mainly used spatial language (e.g., big, small, long, and high) to perceive the spatial dimension, and used the words "curvy" (弯曲的/弯的), "straight" (直的), "empty" (空的), "stable" (稳固的), "oblique" (斜的) to describe the spatial features or properties of the building. Similarly, young children had an emotional tendency in using words for the dimensions and spatial features or properties, showing their tone of praise, wonder or complaint. For instance, the words such as "it is too high" (太高了/够高了/特别高), "it is too stiff" (太死板了). In addition, young children used comparative and superlative words such as "biggest" (最大的), "a little shorter" (更短的). Interestingly, the use of dimension words was also characterized by personification, and children would use words describing people (thin, fat, short, etc.) to represent the size of objects. Furthermore, young children were able to use more complex characterizations of spatial features or properties, such as "symmetrical/corresponding" (一样的/匀称的/对称的), "balanced" (平衡的), and lacunal (有孔的).

Block Building Context

The block building context mainly included construction structures and forms made by the children. Firstly, to analyze the frequency of children's spatial language for different construction structures and based on the spatial dimensionality and hierarchical integration of the children's construction structure, we split them into three levels. The lower construction structure included random block placement and tile/pile structure. The middle construction structure included a simple overhead structure and crowd around the structure. The higher construction structure included a complex overhead structure, simple combination structure, and complex combination structure. Next, according to the children's choice as to whether they would cooperate with peers during building block play, the block building form was divided into independent construction and cooperative construction. Independent construction included the spatial language generated by young children's self-talk.

The descriptive statistics in **Table 5** show that the more complex the construction structure, the more spatial language children would use. The frequency of young children's spatial language in cooperative construction was higher than during independent construction. Subsequently, we conducted a series of 3 (construction structure: lower, middle, and higher) $\times$ 2 (construction form: independent vs. cooperative) analysis of variance (ANOVA) tests to examine the differences between structure and form in spatial language. In these ANOVAs, construction structure and form were the between-subject variables, the frequency of spatial language and different types (dimensions, shapes, spatial features or properties, deictic terms, spatial locations, spatial orientations or transformations) were dependent variables. The results of the 3 $\times$ 2 ANOVAs indicated that the main effect of construction structure in spatial language was significant, $F(2,225) = 7.65$, $p < 0.05$, $\eta^2 = 0.064$. The *post hoc* test proved that children who built higher construction structures used significantly more spatial language than those who built middle and lower construction structures ($p < 0.05$). The main effect of construction form in spatial language was also significant, $F(2,225) = 18.88$, $p < 0.001$, $\eta^2 = 0.078$,

TABLE 5 | Descriptive statistics of construction structure and form.

	Construction structure						Construction form			
	Lower (A) (*N* = 54)		Middle (B) (*N* = 98)		Higher (C) (*N* = 76)		Independent (*N* = 107)		Cooperative (*N* = 121)	
	M	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD
Dimensions	2.93	2.92	2.97	3.82	4.42	4.14	2.23	2.74	4.51	4.26
Shapes	0.80	1.17	2.07	2.92	2.17	2.04	0.93	1.68	2.58	2.63
Spatial features or properties	0.61	1.12	0.47	0.92	1.38	1.59	0.48	0.92	1.10	1.49
Deictic terms	2.50	3.03	2.60	3.53	5.37	4.92	2.30	3.01	4.56	4.70
Spatial locations	2.98	3.07	3.76	4.72	7.76	8.16	3.31	3.94	6.32	7.33
Spatial orientations or transformations	0.85	1.64	0.83	1.45	4.42	4.14	0.64	1.12	1.43	1.90
Spatial language	10.67	9.87	12.69	13.97	2.17	2.04	9.88	10.05	20.50	17.82

"A" stands for lower construction structure, "B" for middle construction structure, and "C" for higher construction structure.

with more spatial language in cooperative construction than independent construction.

In practical terms, the main effect of construction structure in shapes was significant, $F(2,225) = 5.51$, $p < 0.01$, $\eta^2 = 0.047$. The main effect of construction structure in spatial features or properties was significant, $F(2,225) = 7.81$, $p < 0.01$, $\eta^2 = 0.066$, The main effect of construction structure in deictic terms was significant, $F(2,225) = 7.42$, $p < 0.01$, $\eta^2 = 0.063$. The main effect of construction structure in spatial locations was significant, $F(2,225) = 8.28$, $p < 0.001$, $\eta^2 = 0.069$. The *post hoc* test proved that the children who built higher construction structure used spatial features or properties, deictic terms and spatial locations were significantly more than those built middle and lower construction structure ($p < 0.05$). Shapes occurred significantly more often among children who built higher and middle construction structure than those built lower construction structure ($p < 0.05$). Moreover, the main effect of construction form in dimensions was significant, $F(2,225) = 16.09$, $p < 0.001$, $\eta^2 = 0.068$. The main effect of construction form in shapes was significant, $F(2,225) = 22.66$, $p < 0.001$, $\eta^2 = 0.093$. The main effect of construction form in spatial features or properties was significant, $F(2,225) = 7.34$, $p < 0.01$, $\eta^2 = 0.032$. The main effect of construction form in deictic terms was significant, $F(2,225) = 10.86$, $p < 0.01$, $\eta^2 = 0.047$. The main effect of construction form in spatial locations was significant, $F(2,225) = 7.70$, $p < 0.01$, $\eta^2 = 0.035$. The main effect of construction form in spatial orientations or transformations was significant, $F(2,225) = 9.51$, $p < 0.01$, $\eta^2 = 0.041$. Children who adopted cooperative construction had a higher frequency of each type of spatial language than those with independent construction. No significant interaction effect was observed between construction structure and form ($p > 0.05$) (see **Table 6**).

Age and Gender Difference

The descriptive statistics in **Table 7** showed that the frequency of children's spatial language increases with the growth of age. In the study, we conducted a series of 3 (age class: younger class, middle class, and older class) × 2 (gender: boy vs. girl) ANOVA tests to examine age class and sex differences in spatial language. In these ANOVAs, age class and gender were the between-subjects variables, the frequency of spatial language and different types (dimensions, shapes, spatial features or properties, deictic terms, spatial locations, spatial orientations or transformations) were the dependent variables. Results of the 3 × 2 ANOVAs showed that the main effect of age class in spatial language was significant, $F(2,225) = 6.84^{**}$, $p < 0.01$, $\eta^2 = 0.058$. The *post hoc* test proved the spatial language of children in the older class was significantly higher than that in the younger class ($p < 0.05$). Concretely, the age class main effect of in spatial features or properties was significant, $F(2,225) = 5.51^{**}$, $p < 0.01$, $\eta^2 = 0.047$. The age class main effect of in deictic terms was significant, $F(2,225) = 13.37$, $p < 0.001$, $\eta^2 = 0.107$. The age class main effect of in spatial locations was significant, $F(2,225) = 6.00$, $p < 0.01$, $\eta^2 = 0.051$. The age class main effect of in spatial orientations or transformations was significant, $F(2,225) = 3.78$, $p < 0.05$, $\eta^2 = 0.033$). The *post hoc* test proved the spatial features or properties, spatial locations and spatial orientations or transformations of children in the older class was significantly

TABLE 6 | Comparison of differences among children of different construction structure and form (*N* = 228).

		df	MS	*F*	*p*	η^2	*Post hoc*
Dimensions	Structure	2	29.35	2.25	0.108	0.020	n.s.
	Form	1	209.74	16.09***	0.000	0.068	
	Structure × form	2	14.05	1.08	0.342	0.010	
Shapes	Structure	2	26.45	5.51**	0.005	0.047	B > A, C > A
	Form	1	108.84	22.66***	0.000	0.093	
	Structure × form	2	6.57	1.37	0.257	0.012	
Spatial features or properties	Structure	2	11.46	7.81**	0.001	0.066	C > A, C > B
	Form	1	10.77	7.34**	0.007	0.032	
	Structure × form	2	0.90	0.61	0.543	0.005	
Deictic terms	Structure	2	111.32	7.42**	0.001	0.063	C > A, C > B
	Form	1	162.99	10.86**	0.001	0.047	
	Structure × form	2	7.58	0.51	0.604	0.005	
Spatial locations	Structure	2	273.81	8.28***	0.000	0.069	C > A, C > B
	Form	1	263.50	7.70**	0.005	0.035	
	Structure × form	2	31.79	0.51	0.604	0.005	
Spatial orientations or transformations	Structure	2	4.52	1.82	0.164	0.016	n.s.
	Form	1	23.58	9.51**	0.002	0.041	
	Structure × form	2	0.97	0.39	0.677	0.004	
Spatial language	Structure	2	1559.63	7.65**	0.001	0.064	C > A, C > B
	Form	1	3850.45	18.88***	0.000	0.078	
	Structure × form	2	17.76	0.09	0.917	0.001	

*n.s. p > 0.05, *p < 0.05, **p < 0.01, ***p < 0.001.*
"A" stands for lower construction structure, "B" for middle construction structure, and "C" for higher construction structure.

TABLE 7 | Descriptive statistics of age class and gender.

	Age class						Gender			
	Younger (Y) (*N* = 76)		Middle (M) (*N* = 80)		Older (O) (*N* = 72)		Boy (*N* = 114)		Girl (*N* = 114)	
	M	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD
Dimensions	3.32	3.68	3.41	4.28	3.61	3.35	3.23	3.77	3.66	3.81
Shapes	1.33	2.31	1.95	2.64	2.14	2.08	1.52	2.06	2.09	2.64
Spatial features or properties	0.55	1.04	0.69	1.12	1.21	1.59	0.89	1.44	0.72	1.13
Deictic terms	1.84	2.70	3.55	3.90	5.19	4.96	3.41	4.16	3.59	4.16
Spatial locations	3.30	4.77	4.79	5.58	6.74	7.50	4.76	6.36	5.05	5.97
Spatial orientations or transformations	0.66	1.09	1.16	1.86	1.36	1.76	1.01	1.66	1.11	1.60
Spatial language	11.00	12.86	15.55	15.19	20.25	17.37	14.82	15.84	16.21	15.39

"Y" stands for younger class, "M" for middle class, and "O" for older class.

higher than that in the younger class ($p < 0.05$), deictic terms of children in the older and middle class was significantly higher than that in the younger class ($p < 0.05$). Results showed no gender differences in the spatial language of children, but there was a marginally significant difference in the number of shapes used by boys and girls ($p = 0.067$). No significant interaction effect was observed between age class and gender (p > 0.05) (see **Table 8**).

Correlations

We performed two-tailed Pearson and Spearman correlation of variables to determine the relationship among variables. As shown in **Table 9**, young children who built construction structures were significantly related to spatial language ($r = 0.321$, $p < 0.01$). Building a complex structure mobilized young children to use more spatial language. Specifically, there were significant positive correlations among the frequency of dimensions, shapes, spatial features or properties, deictic terms, spatial locations, spatial orientations or transformations, and construction structures built by young children ($r = 0.171$, $p < 0.01$; $r = 0.292$, $p < 0.01$; $r = 0.302$, $p < 0.01$; $r = 0.286$, $p < 0.01$; $r = 0.288$, $p < 0.01$; $r = 0.239$, $p < 0.01$). Next, there was a significant positive correlation between children's choice of the building form in block play and their spatial language ($r = 0.341$, $p < 0.01$). The young children who adopted cooperative construction had significantly higher spatial language in shapes ($r = 0.348$, $p < 0.01$), dimensions ($r = 0.301$, $p < 0.01$), spatial positions ($r = 0.245$, $p < 0.01$), deictic terms ($r = 0.273$, $p < 0.01$), spatial orientations or transformations ($r = 0.244$, $p < 0.01$), spatial features or properties ($r = 0.241$, $p < 0.01$) than those who adopted independent construction. Therefore, young children who adopt the cooperative building form used more spatial language. Otherwise, there were a significant positive relation between young children's age and spatial language ($r = 0.289$, $p < 0.01$). There was a significant positive correlation among the frequency of deictic terms, spatial locations, shapes, spatial features or properties, spatial orientations or transformations, and the age class of young children ($r = 0.349$, $p < 0.01$; $r = 0.275$, $p < 0.01$; $r = 0.247$, $p < 0.01$; $r = 0.224$, $p < 0.01$; $r = 0.169$, $p < 0.05$).

DISCUSSION AND CONCLUSION

The purpose of this study was to explore the frequency, type, and level of spatial language in the context of block play and the differences that vary by age and gender in young Chinese children. Overall, spatial locations, deictic terms, dimensions, and shapes were used more frequently by young children, and spatial features or properties and spatial orientations or transformations were used less frequently. Specifically, the following conclusions were drawn: (a) spatial locations were used most frequently, and young children tended to use vertical locations to represent the corresponding location; (b) most young children used gesture in conjunction with spatial deictic terms; (c) tetragon words were more frequently used in the shape words, and the representation of shapes showed alternatives, collective tendencies, and gender differences; (d) the frequency of spatial language in children was related to their construction structure and form; and (e) the age class of young children was also associated with the frequency of spatial language.

One important finding from the present research was that the most frequent use of spatial language during young Chinese children's block play involved spatial locations, which accounted for nearly a third of spatial language. These results agree with prior findings that English-speaking children acquired many spatial relational terms in preschool years, and they use the most spatial position words in free block play (Ferrara et al., 2011). Three-year-old children have shown high levels of comprehension for these basic spatial terms such as "on, in, and under and top, middle, and bottom" (Meints et al., 2002; Loewenstein and Gentner, 2005). Moreover, young Chinese children's spatial locations appeared in the order of vertical direction, dynamic position, horizontal direction, a specific region, and relative position from high to low. They preferred to use spatial language in the vertical direction (e.g., "up," "down"). The general order of spatial locations was the same as previous results. Preschool is a period when young children most rapidly master spatial locations. From the age of three years old, Chinese-speaking children identify spatial orientation according to the development order of "up/down-front/back-left/right" (Huang, 2007, p. 209–211). One possible reason involved the spatial properties of blocks. Blocks occupied a certain space in

TABLE 8 | Comparison of differences among children of different age class and gender (*N* = 228).

		df	MS	*F*	*p*	η^2	*Post hoc*
Dimensions	Age class	2	1.67	0.12	0.892	0.001	n.s.
	Gender	1	10.67	0.73	0.392	0.003	
	Age class × gender	2	10.06	0.69	0.502	0.006	
Shapes	Age class	2	13.47	2.45	0.088	0.022	n.s.
	Gender	1	18.64	3.39	0.067	0.015	
	Age class × gender	2	9.76	1.78	0.172	0.016	
Spatial features or properties	Age class	2	8.83	5.51**	0.005	0.047	O > Y
	Gender	1	1.71	1.07	0.303	0.005	
	Age class × gender	2	1.20	0.75	0.475	0.007	
Deictic terms	Age class	2	207.91	13.37***	0.000	0.107	M > Y, O > Y
	Gender	1	2.32	0.15	0.7	0.001	
	Age class × gender	2	18.19	1.17	0.312	0.01	
Spatial locations	Age class	2	218.83	6.00**	0.003	0.051	O > Y
	Gender	1	4.95	0.14	0.713	0.001	
	Age class × gender	2	33.68	0.92	0.399	0.008	
Spatial orientations or transformations	Age class	2	9.83	3.78*	0.024	0.033	O > Y
	Gender	1	0.60	0.23	0.632	0.001	
	Age class × gender	2	1.24	0.48	0.622	0.004	
Spatial language	Age class	2	1581.82	6.84**	0.001	0.058	O > Y
	Gender	1	116.62	0.50	0.478	0.002	
	Age class × gender	2	308.48	1.33	0.265	0.012	

*n.s. p > 0.05, *p < 0.05, **p < 0.01, ***p < 0.001.*
"Y" stands for younger class, "M" for middle class, and "O" for older class.

TABLE 9 | Correlations among the variables (*N* = 228).

	1	2	3	4	5	6	7	8	9	10	11
1. Dimensions	–										
2. Shapes	0.615**	–									
3. Spatial features or properties	0.526**	0.345**	–								
4. Deictic terms	0.527**	0.391**	0.493**	–							
5. Spatial locations	0.588**	0.576**	0.602**	0.655**	–						
6. Spatial orientations or transformations	0.474**	0.314**	0.516**	0.526**	0.548**	–					
7. Spatial language	0.802**	0.695**	0.686**	0.808**	0.907**	0.666**	–				
8. Construction structure	0.171**	0.292**	0.302**	0.286**	0.288**	0.239**	0.321**	–			
9. Building form	0.301**	0.348**	0.241**	0.273**	0.245**	0.244**	0.341**	0.132*	–		
10. Age class	0.066	0.247**	0.224**	0.349**	0.275**	0.169*	0.289**	0.447**	0.209**	–	
11. Gender	0.057	0.120	−0.068	0.021	0.024	0.030	0.045	−0.105	0.132*	0.000	–

Gender, age class, and building form are the dummy variable: girl = 1, boy = 0; younger class = 1, middle class = 2, older class = 3; cooperative form = 1, independent form = 0.
**p < 0.05, **p < 0.01.*

both vertical and horizontal directions. The size of the space occupied by a block in the vertical or horizontal direction depends on the way it is placed. Blocks could make a building higher when they are stacked together, head-to-tail connection could make the building longer, and continuous tiling could make the area occupied by objects continue to expand (Liu, 2015, p. 565–571). Young children use blocks to construct all kinds of buildings to represent the world. Through the analysis of young children's construction structure in free block play, we found that the themes of structures were mainly houses, bridges, and roads (Yang et al., 2020). Most structures adopted a vertical construction to form a simple combination, complex overhead, and complex combination structure. Therefore, the frequency of use of vertical direction words was higher. In addition, young Chinese children used a variety of dynamic location words to represent changes in spatial positions. Words such as "let us go through here" (从这儿钻过去), "enter into" (进入), and "get out" (离开) reflected the interaction between them and the spatial structure of buildings, words such as "step over" (踩过去/跨过去), "walk around" (绕过去), and "pass through" (穿过) indicated the way they used limited space, and words such as "move past" (从这里过去) and "put back"

(回来) showed their perception of the spatial distance between themselves and blocks.

We also found that young Chinese children used spatial deictic terms with strong functionality and directionality, aiming to express precise spatial locations through language. The use of deictic terms indicated that young children could understand the building space occupied by blocks, structure, and spatial relationships. Spatial deictic terms were often used to represent the spatial location of blocks and different spaces. They could be used to help young children better plan spatial scope, by developing consciousness of spatial matching, clarifying the space occupied by the building [such as using "this space" (这片/这块) or "that space" (那片/那块) to delimit the spatial area], and coordinate a continuation of the same space. Of course, the division of space also reflected children's competition for limited space. Whether this involved negotiation or competition about space, it consistently reflected their spatial awareness in the process. Children had a certain understanding of the spatial structure, the spatial location of a structure, and the space occupied by humans. The use of spatial language showed the differentiation of "the relationship of object and I." Young children began to distinguish and think about the spatial location of the "object" and "I," which could also help children "decentrate" to some extent and promote their social development. However, when young children expressed spatial properties, the effect of their expression was not satisfactory due to their limited spatial vocabulary. Therefore, when young children used spatial deictic terms, they made full use of gesture language and other actions to assist in representing the space area and scope, pointing or delineating the space. The role of gesture language was emphasized in both Chinese and English children's spatial language. Gesture language with spatial information could not only help children and their peers understand linguistic information and improve the quality of communication but also promote the encoding of spatial information (Alibali, 2005; Cartmill et al., 2010; Li and Kang, 2019). One study showed that the amount of young children's spatial language was positively correlated with the number of adult's gesture and spatial language, and gesture language was an important predictor of young children's spatial language when controlling adults' spatial language (Young et al., 2014). Li and Kang (2019) proposed that gesture language conveyed spatial concepts to young children in a vivid way, and spatial concepts would be understood, transmitted, and shared by peers. Therefore, young children could be encouraged to express spatial language in two ways: gesture language and oral language. When adults help young children input and output spatial language, they should try their best to use oral language and gesture language.

Our findings showed that the representation of tetragon words accounted for the highest proportion, among the shapes words. In the previous literature, young Chinese children showed a preference for tetragon blocks (Sun, 2015), they tended to use rectangular blocks to represent the main part of a building (Yang et al., 2020). Normally, young children used more tetragon words to represent the shapes of blocks. In the study, young children could distinguish squares, triangles, and other shapes and use standard shape words to represent the shape of blocks, which also conformed to previous studies indicating that young children older than 4 years old could completely recognize Euclidean figures (e.g., triangle, square, rectangle) (Zhao, 2007). Otherwise, young children used the names of similar objects and the use of objects to represent the shape of blocks. For example, the words "strip (长条), long board (长板)" and other similar objects were used to represent rectangular blocks, the word "column" (圆柱/圆木) was used to represent cylindrical blocks, irregular blocks used for turning were named "bending" (弯弯), and oblique triangular blocks were named according to the purpose of "up and down slope" (上下坡). Therefore, the representation of young children's shapes showed an alternative. Based on their own life experience and building needs, young children creatively used shapes related to the theme and content of building blocks and used various symbols to represent the shapes of blocks, such as "small square" (小方块) and "slice" (薄片). These symbols could be spread among children in the same group, which promoted the transformation of the representation from "personal" to "collective" and ultimately reached a consensus (Liu, 2015, p. 567–581). Thus, the representation of young children's shapes had the meaning of "communication," showing the tendency toward collectivization within small groups.

We had two major findings relating to the block building context. The first is that young Chinese children who built higher construction structures used significantly more spatial language than those who built middle and lower construction structures. Many studies have proved that there was a positive correlation between children's building ability and children's spatial skills (Zhang, 2013; Kang et al., 2020). It might be that building a higher construction structure required children to engage in more discussion and communication, which naturally increased the frequency of their spatial language. Therefore, adults can make a certain assessment of the building skills of young children, make a reasonable sectionalization according to the ability of block building, control the number of young children entering the building block area, ensure the optimal configuration of the block building skills of young children, make full use of the role of the community, and improve the relative probability of spatial language and peer influence among young children in the same group. Adults should also create rich building situations for young children, use goal-directed block play as a means of introducing and acting out spatial concepts and relationships (Ferrara et al., 2011), guide children's building themes and skills, and encourage children to complete higher construction structure. Furthermore, adults should guide young children to perceive and describe changes in spatial graphics and structures, pay attention to the spatial environment, and strengthen their spatial concept and experience.

Another finding was those young Chinese children who made cooperative forms used spatial language more frequently. A possible reason was that cooperative construction could lead to more peer interaction and prompt young children to share and negotiate building structure and solution strategies, such as how to obtain building blocks of various shapes, how to maintain the balance and symmetry of buildings, how to represent things in real life and other issues, all of which involve interactions of spatial language.

A cooperative and pleasant play atmosphere could encourage young children to use more spatial language for communication, stimulate spatial language among peers. Building together provided young children with opportunities to communicate, listen and discuss with each other. The children began to accept group rules, divide work and cooperate. Even if there were differences, they would try to solve them through consultation. Naturally, young children learned to share, respect others, and develop altruistic behavior. This provided an excellent context to cultivate their concentration and help them experience division and cooperation (Hu, 2018). Peers who are experienced in social interaction can also develop the construction and communication skills of children (Sluss and Stremmel, 2004). Therefore, adults should pay attention to the role of peers, encourage cooperation among peers, teach young children the expressive skills of spatial language, and support the discussion of spatial language among children.

In the present research, the spatial language used by young Chinese children had a relationship with age and class. Spatial features or properties, deictic terms, spatial locations, and spatial orientations or transformations of children in the younger class were significantly lower than those in the older class. This indicates that attention should be paid to the development of spatial language among younger and middle-class children. Previous studies had shown that biological maturity played an important role in the development of young children's spatial concepts in early childhood (Zhao, 2007), such as the self-centered spatial coding ability at 3–5 years of young Chinese children increased significantly with age and made a significant leap from 4 to 5 years (Wang, 2009). Those aged 4–5 years old also had a rapid development period in the ability to recognize low level of spatial shapes (Li et al., 1997). Moreover, multiple studies had shown the relationships between spatial skills and spatial language at 4 years of age (Dessalegn and Landau, 2008, 2013). Studies have demonstrated that 4–5 years is a sensitive period for young children's spatial ability development (Li et al., 1997; Wu et al., 2019), and a critical period for young children's spatial language development. For a long time, collective teaching was an important form of educational organization in Chinese kindergartens (Qi, 2009; Zhu, 2011, p. 54). Accordingly, adults should pay attention to the class environment in younger age and middle-class settings, and the performance and features of the spatial language of young children's block play. Meanwhile, adults should attach importance to children's learning according to the children's age, experience level, interests and needs (Yang, 2020), to create an appropriately spatial environment.

The present study found that the representation of shapes showed marginally significant differences in children in terms of gender. Young children's perception of the different shapes of blocks was the embodiment of their application value and regularity in real life, and young children had different ways of using and representing blocks of different shapes. For instance, children of different genders used different symbols to represent blocks of the same shape: girls used "V"-shaped blocks to represent "flowers and grass," and boys used them to represent "Mazda" (a car symbol). The potential reason was that the accumulation of gender differential spatial experience for male and female subjects (Chan, 2007). This might be related to young children's gender roles and daily life experiences. The different requirements of social gender roles affected young children's interests in different things (Hu, 2018) and their different representations of the same shape.

LIMITATIONS AND FUTURE RESEARCH

This study conducted cross-sectional research of young children's spatial language in block play. In the future, a longitudinal study of young children's spatial language should be conducted to examine the impact of the abilities and forms of block building on spatial language and analyze the relationship between peer communication and the production and development of spatial language. Moreover, future research should expand the selection range to sample sizes of different construction structures and forms of block building and increase the number of participants so that the research results are more representative. Although the participants were all from the same type of kindergarten, their family educational environment, parenting style, and family economic level differed. Therefore, the variables of the family educational environment, parenting patterns, temperament types, and family economic level should also be examined. Future studies should analyze other variables synthetically to make the experimental results more rigorous.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Office of Scientific Research, Faculty of Education at Beijing Normal University and Kindergartens involved of China.

AUTHOR CONTRIBUTIONS

XY and YP designed the research and collected data for analysis. XY analyzed the data. YP provided crucial guidance. All authors were involved in interpretation and provided critical feedback and helped shape the research, analysis, and manuscript. All authors drafted the work and approved the published version.

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