HHS Public Access
Author manuscript
Child Dev. Author manuscript; available in PMC 2018 November 01.

Published in final edited form as:
Child Dev. 2017 November ; 88(6): 1966–1982. doi:10.1111/cdev.12664.

Producing spatial words is not enough: Understanding the relation between language and spatial cognition

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Abstract

Prior research has investigated the relation between children's language and spatial cognition by assessing the quantity of children's spatial word production, with limited attention to the context in which children use such words. This study tested whether 4-year-olds children's ($N = 41$, primarily white middle-class) adaptive use of task-relevant language across contexts predicted their spatial skills. Children were presented with a spatial scene description task, four spatial tasks, and vocabulary assessments. Children's adaptive use of task-relevant language was more predictive of their spatial skills than demographic and language factors (e.g., quantity of spatial words produced). These findings identify new links between language and spatial cognition and highlight the importance of understanding the quality, not just quantity, of children's language use.

Keywords

spatial cognition; language use; spatial vocabulary

Language supports children's learning across a variety of cognitive domains. Developing language skills are related to numerical representation (e.g., Miura, Kim, Chang, & Okamoto, 1988), categorization (e.g., Bowerman & Choi, 2003), and analogical reasoning (e.g., Gentner, 2003). In recent years, there has been increased interest in studying relations between language and spatial cognition (Evans & Chilton, 2010). Spatial skills predict achievement in math and science as well as entry into science, technology, engineering, and math (STEM) fields (Verdine et al., 2014; Wai, Lubinski, & Benbow, 2009). As a result, researchers have sought to determine whether there is a relation between children's early language and spatial abilities to understand the factors that contribute to the development of spatial skills.

Multiple studies have demonstrated links between spatial language and spatial cognition across a range of spatial tasks, using both correlational and experimental designs (e.g., Dessalegn & Landau, 2008, 2013; Hermer-Vazquez, Moffet, & Munkholm, 2001;

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Loewenstein & Gentner, 2005; Miller, Patterson, & Simmering, 2016; Pruden, Levine, & Huttenlocher, 2011; Pyers, Shusterman, Senghas, Spelke, & Emmorey, 2010; but see Nardini, Burgess, Breckenridge, & Atkinson, 2006; Ratliff & Newcombe, 2008 for exceptions). One proposed explanation for these findings is that spatial language supports children's encoding of spatial features and relations, thus facilitating their performance on spatial tasks (e.g., Hermer-Vazquez et al., 2001; Pruden et al., 2011). However, some results have shown that this facilitation effect is not specific to spatial words, but can be realized through non-spatial language if it is relevant to the task (Dessalegn & Landau, 2013; Shusterman, Lee, & Spelke, 2011). In the current study, we investigate the relation between spatial skills and language further by considering how children's use of both spatial and non-spatial language in the moment of a task relates to their spatial abilities.

Children's production of spatial words has been shown to be positively associated with their spatial skills (e.g., Hermer-Vazquez et al., 2001; Miller et al., 2016; Pruden et al., 2011; Simms & Gentner, 2008). For example, children's production of particular spatial words, such as “left” and “right” at 5 to 6 years of age (Hermer-Vazquez et al., 2001) or “middle” at 3 to 5 years of age (Simms & Gentner, 2008) is correlated with their performance on spatial tasks that depended on representing those relations. Additionally, the total number of spatial words that children produced in free-play sessions between 14 and 46 months of age predicted their performance on a diverse range of spatial tasks at 56 months of age (Pruden et al., 2011). This relation between children's spatial word production and their spatial skills is a robust effect, as it persisted even after controlling for other contributing factors such as spatial word comprehension (Hermer-Vazquez et al., 2001) or general receptive vocabulary (Pruden et al., 2011). Theorists have generally interpreted these findings as evidence that producing spatial words enables children to verbally encode relevant spatial information, and thus supports their spatial task performance (e.g., Hermer-Vazquez et al., 2001; Pruden et al., 2011).

Additional evidence for verbal encoding as a mechanism supporting spatial cognition comes from research manipulating the availability of verbal support for children's spatial task performance. In these studies, children between 3 and 5 years of age were exposed to verbal cues specifying relations among objects or features, either before or during the spatial tasks. Results showed that providing children with verbal cues containing relevant spatial language enhanced their spatial performance (Dessalegn & Landau, 2008, 2013; Loewenstein & Gentner, 2005; Miller et al., 2016; Shusterman et al., 2011). Moreover, studies have demonstrated similar effects with non-spatial but task-relevant language (Dessalegn & Landau, 2013; Shusterman et al., 2011).

For example, studies have shown that both spatial and non-spatial language can positively influence performance on the disorientation search task (Hermer-Vazquez et al., 2001; Pyers et al., 2010; Shusterman et al., 2011). The disorientation search task was designed to assess whether children integrate featural and geometric cues in the environment to reorient (Hermer & Spelke, 1994, 1996). On each trial, children would see an object hidden in one of the four corners of a small rectangular room, and then were disoriented by being spun around in circles by the experimenter before they searched for the hidden object. The conditions typically vary in the presence of a featural cue (distinct colored wall), such that on half the trials the four walls were the same color and on the other half of the trials one wall was a distinct color. Children's use of featural cues was tested by categorizing their responses as searches relative to the colored wall versus only the geometry of the room (i.e., searching in the geometrically equivalent corners regardless of the location of the colored wall). Two-year-old children's search performance did not differ with or without the featural cue present suggesting that young children may not be sensitive to featural cues in the environment when reorienting (even when room geometry was absent; Lew, Foster, & Bremner, 2006). Not until about 6 years of age did children reliably use featural cues to reorient in the original paradigm without language support (Hermer-Vazquez et al., 2001). Using correlational analyses, Hermer-Vazquez et al. (2001) argued that this developmental shift arose from children's ability to verbally encode the left/right position of the hidden object relative to the colored wall, as children's production of "left" and "right" in another task correlated with their use of features to reorient in the disorientation search task.

However, subsequent research has demonstrated that the words "left" and "right" were not the only language cues that could support children's performance in the task. Shusterman et al. (2011) showed that providing 4-year-olds with task-relevant language, whether spatial ("I'm hiding the sticker at the red/white wall") or non-spatial ("the red wall can help you find the sticker") increased their likelihood of using featural cues in the task space to reorient. This effect was specific to task-relevant language, as not all types of language improved children's performance. For example, saying "look at the pretty wall" without indicating the utility of the red wall did not significantly improve children's performance. Thus, although the correlational results suggested that language facilitated performance through the verbal encoding of specific spatial words, such as "left" and "right" (Hermer-Vazquez et al., 2001), studies manipulating the availability of verbal cues indicated that non-spatial language can facilitate younger children's performance through drawing attention to task-relevant information (see Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, & Huttenlocher, 2001; Nardini, Atkinson, & Burgess, 2008, for further evidence that young children can use features to reorient prior to the acquisition of "left"/"right" and without language support).

Studies conducted using a different spatial task, the feature binding task, provide another example of how both spatial and non-spatial language can positively influence children's spatial task performance (Dessalegn & Landau, 2008, 2013). The feature binding task was designed to examine how children remember the visual feature configurations of color and location (i.e., the relative location of two colors within an object) over a short delay. In the task, 4-year-old children were presented with a picture of a square with half the square of one color (e.g., red) and the other half of a different color (e.g., green). Across trials, the square was divided in half vertically, horizontally, or diagonally. After a 1-second delay, children chose which one of three squares exactly matched the original square. Children performed better on this task both when provided with language specifying relevant spatial relations ("the red is on the top") and when provided with non-spatial language that highlighted the asymmetric relation between the two features ("the red one is prettier") (Dessalegn & Landau, 2008, 2013). Similar to Shusterman et al. (2011)'s findings, not all language facilitated children's performance. For example, telling the child that "the red one is touching the green" did not facilitate performance; the authors argued this was likely because the cue did not highlight the asymmetric relation between the locations of the two colors (Dessalegn & Landau, 2008). Taken together with the results from the disorientation search task (Shusterman et al., 2011), these findings demonstrate that the relation between language and spatial cognition is not limited to spatial words, but can arise through non-spatial language when it conveys the relevance of the cues to the task.

Results showing a benefit from non-spatial, but task-relevant, language suggest that the relation between children's language and spatial cognition might not solely be about children's acquisition and frequency in producing spatial words. This suggests that abilities to produce task-relevant language may be more indicative of spatial skills than abilities to produce spatial words because language in general can cue one into important cues or features of spatial tasks. Most preschool-aged children's productive vocabularies include the non-spatial task-relevant cues used in these studies to promote their spatial task performance (e.g., "prettier"). It may be that, even though children know and can use these words, children are not spontaneously using this type of language to support their performance during spatial tasks. Little is currently known about whether individual differences in children's production of task-relevant language, both spatial and non-spatial, predict their spatial skills. Previous research has primarily evaluated children's production of either specific words (Hermer-Vazquez et al., 2001; Simms & Gentner, 2008) or the total number of spatial words (Pruden et al., 2011), but not whether children spontaneously produced these words in task-relevant ways (but see Miller et al., 2016). Thus an important factor yet to be considered in the relation between language and spatial cognition is children's abilities to produce language relevant to the task at hand.

Research suggests that there may be developmental changes in children's production of task-relevant information during early childhood (Craton, Elicker, Plumert, & Pick, 1990; Plumert & Hawkins, 2001; Plumert & Nichols-Whitehead, 2007). For example, Plumert and Nichols-Whitehead (2007) found that preschool-aged children's preferences for using color, size, and location cues to disambiguate object locations varied with age, as younger children often struggled to produce the most relevant cues and instead tended to produce cues that were irrelevant for describing the object's location (e.g., providing a color cue that did not differentiate location). If young children have difficulty producing task-relevant cues, as these studies suggest, it is possible that they may fail to use language adaptively to support their spatial performance even once the relevant words are within their productive vocabularies. That is, children's abilities to *produce* spatial words may not be enough to enable them to encode relevant spatial information to support their spatial performance. Rather, the enabling factor may be children's *adaptive use of language* in response to task demands.

Current Study

The current study tested whether children's abilities to use task-relevant language adaptively was more predictive of their spatial task performance than was their general ability to produce spatial words. Correlations between children's spatial word production and their spatial task performance have been interpreted as evidence that spatial word production supports encoding in spatial tasks (e.g., Pruden et al., 2011). However, it is possible that the relevance of children's language production underlies this relation. Indeed, these studies were not designed to evaluate the contexts in which children produced particular words, leaving open the possibility of a more complex relation between language and spatial skills. Furthermore, results from studies experimentally manipulating whether the relevant language provided to children was spatial or not (e.g., Dessalegn & Landau, 2008; Shusterman et al., 2011), combined with developmental changes in children's communication of spatial information (e.g., Plumert & Nichols-Whitehead, 2007), indicate that relations between language and spatial skills are not limited to production of spatial words. Rather, these findings suggest that the use of language more generally, to either draw attention to or describe task-relevant information, could be a key contributing factor to the relation between language and spatial cognition.

We hypothesized that children's performance in adaptively using task-relevant language would predict their spatial task performance above and beyond their spatial language production and other factors that have been shown to contribute to their spatial skills and language use (e.g., Levine, Huttenlocher, Taylor, & Langrock, 1999; Pruden et al., 2011; Voyer, Voyer, & Bryden, 1995). Specifically, we predicted that children's adaptive use of language would predict their spatial skills above and beyond demographics (age, gender), vocabulary (general receptive vocabulary, productive spatial vocabulary), and task-related language production (quantity of spatial and non-spatial terms used during the production task). Alternatively, in line with other studies (e.g., Pruden et al., 2011), it is possible that the relation between language and spatial cognition arises from children's abilities to produce spatial words, irrespective of the context in which words are produced. If this were the case, then children's adaptive use of language would not be more predictive than the quantity of spatial words produced.

Four-year-old children were selected to participate in this study because children at this age have been producing spatial words for a few years (Fenson et al., 1994), yet they still perform poorly on spatial tasks. Additionally, multiple studies have shown relations between spatial skills and language at 4 years of age (Dessalegn & Landau, 2008, 2013; Loewenstein & Gentner, 2005; Miller et al., 2016; Pruden et al., 2011; Shusterman et al., 2011; Simms & Gentner, 2008). We obtained a general measure of spatial skills by having children complete the following four spatial tasks: Children's Mental Transformation Task (Levine et al., 1999), Spatial Analogies Task (Huttenlocher & Levine, 1990), Feature Binding Task (Dessalegn & Landau, 2008, 2013), and Picture Rotation Test (Quaiser-Pohl, Rohe, & Amberger, 2010; Quaiser-Pohl, Rohe, & Marke, 2010). We chose these tasks because they vary in the extent to which one can use specific spatial words, but have been shown to relate to language (Cassasola, Wei, & Suh, 2015; Dessalegn & Landau, 2008, 2013; Pruden et al., 2011). The Spatial Analogies Task and the Feature Binding Task are easier to verbalize and the Mental Transformation Task and the Picture Rotation Test are more difficult. Additionally, these tasks span a range of spatial skills and are commonly used with 4-year-olds. Together, these tasks provide a comprehensive measure of children's spatial abilities. From these tasks, we created a spatial composite score to measure children's general spatial skills and also examined the tasks individually to investigate whether language use related differently based on the type of spatial skill.

We also included multiple language measures to assess children's general language, spatial language, and task-relevant language skills. As a proxy for children's general language skill, we administered the Peabody Picture Vocabulary Test-IV (Dunn & Dunn, 2007), which is a standardized assessment of general receptive vocabulary. To measure spatial language skills, we gave caregivers a productive spatial vocabulary checklist. Additionally, we designed a spatial scene description task to evaluate children's production of both spatial and non-spatial language in task-relevant ways. In this task, children described the location of a target object in a simple scene containing three referent objects. Across trials, the color and size of the referents varied such that they were not always relevant for describing the target object's location. From this task, we measured not only the task-related words children produced, but also considered the trial context in which words were produced to evaluate the relevance of the cues. We quantified children's adaptive use of language by subtracting the number of irrelevant cues produced from the number of relevant cues produced; this provided an index of children's sensitivity to the relevance of cues across trials.

Method

Participants

Forty-one 4-year-old children (M = 4.56 years, SD = 0.40 years, 23 females) participated in the study. An additional eight children participated but were excluded for incomplete data (two), non-compliance (four), experimenter error (one), or insufficient vocabulary (one; described further below). Additionally, scores from the Spatial Analogies Task were excluded from two participants' data due to experimenter error. Participants were recruited through a database compiled by a university affiliated research center in the Midwest in 2014. Participants were primarily from white middle-class backgrounds.

Design and Procedures

Children participated in a warm-up task, a spatial scene description task, four spatial tasks, and the PPVT-IV as well as two other production tasks not reported. The tasks were administered in a quasi-randomized order with these constraints: each spatial task followed a production task; the warm-up task came after the first spatial task, which preceded the first production task; and the PPVT-IV was last. Caregivers completed a productive spatial vocabulary checklist. Additionally, children participated in two other production tasks not reported. These tasks involved manipulation of the spatial relation between the target and referents, and proved to be too difficult for 4-year-olds to perform reliably. Because children lacked variability in performance and performed near floor, we have excluded these tasks from our current investigation. Sessions were video- and audio-recorded. Children received small prizes and were offered breaks between tasks. Each session lasted approximately 45 to 60 minutes.

Production tasks—A warm-up task was used to promote children's understanding of the spatial scene description task and to increase children's comfort in talking aloud. Children viewed 10 PowerPoint slides showing one familiar object (e.g., apple) on each slide and described what they saw to a stuffed animal named Bucky who was not looking at the screen. Children were asked on every trial to "tell Bucky what you see." The stuffed animal was used to help children understand that they needed to describe the target object's location to someone who was not looking at the same scene as them, and thus to encourage children to give complete descriptions. To discourage pointing, the experimenter instructed children to sit on their hands throughout both production tasks.

The spatial scene description task tested children's skills at describing a target object's location relative to referent objects within different scenes. We used this task both to obtain a measure of children's task-related language production (non-spatial and spatial) and to obtain a measure of their adaptive use of task-relevant language. This allowed us to assess the frequency of children's spatial word production in naturalistic speech, similar to past research (Pruden et al., 2011), and to examine children's sensitivity to task-relevant cues. The task was administered on a computer using PowerPoint. Each trial included three referent objects (e.g., three tables) distributed diagonally across the screen (Figure 1); the diagonal orientation (top-left to bottom-right versus top-right to bottom-left) varied randomly across trials. The target object (i.e., mouse) was always located in a support relation to one of the referent objects. On each trial, the experimenter asked the child to describe the location of a target object to a stuffed animal who was not looking at the screen, as in the warm-up task (i.e., "tell Bucky where the mouse is"). Across four trial types, the number of relevant cues varied such that children could use any of three cues (color, size, and location; Figure 1A), two cues (color and location, size and location; Figures 1B and 1C), or one cue (location; Figure 1D) to differentiate the target object's location.

The spatial scene description task included 24 trials presented in one of four randomized orders. For each cue trial type, there were 6 trials, 2 trials for each possible target object's location (front, middle, or back referent; see Figure 1). We chose a diagonal alignment of the referent objects to allow children to use a variety of spatial words to describe the locations. These words included: front, middle, back, first, second, third, last, left, right, top, bottom, up, down, and corner. The position of each color and size cue was randomized across trials (i.e., position was not confounded with particular featural cues). Children received stickers and viewed short attention-getter videos after every three trials to help maintain motivation.

Spatial tasks—Children participated in four spatial tasks (Figure 2): Children's Mental Transformation Task (Levine et al., 1999; Pruden et al., 2011), Spatial Analogies Task (Huttenlocher & Levine, 1990; Pruden et al., 2011), Feature Binding Task (Dessalegn & Landau, 2008, 2013), and Picture Rotation Test (Quaiser-Pohl, Rohe, & Amberger, 2010; Quaiser-Pohl, Rohe, & Marke, 2010). We used a short form of the Children's Mental Transformation Task and Spatial Analogies Task adapted from Pruden et al. (2011). In the Mental Transformation Task (10 trials; Figure 2A), children saw two pieces of a shape and selected which of four shapes the two pieces would make if combined. In the Spatial Analogies Task (13 trials; Figure 2B), children viewed a picture depicting two objects in a spatial relation and chose which of four other pictures shared that relation. In the Feature Binding Task (24 trials; Figure 2C), children saw a square with two different colors on opposite sides and chose a matching figure out of three options following a 1 second delay. In the Picture Rotation Test (16 trials; Figure 2D), children viewed a picture of an object rotated up to 180° and mentally rotated the object to identify its match out of three options.

Vocabulary assessments—The PPVT-IV measured children's general receptive vocabulary and required children to point to one of four pictures depicting a target word. The spatial vocabulary checklist measured children's productive spatial vocabulary and included 80 words taken from both the MCDI: Words and Sentences (Fenson et al., 1994) and from a spatial word coding manual (Cannon, Levine, & Huttenlocher, 2007). Caregivers indicated words they have heard their child produce from the following spatial categories: location, position, feature, shape, size, and quantity (see Appendix S1). Caregivers were asked to only check off the word if they have heard their child use the word spatially. The caregivers were given examples of spatial and non-spatial usages of words (e.g., "the apple is *on* the table" vs. "turn *on* the TV").

Coding and Measurement

Spatial scene description task—Research assistants blind to the hypotheses of the study transcribed and coded the spatial scene description task. Two research assistants transcribed each session, obtaining an inter-rater reliability of 89% agreement across trials. Disagreements were resolved by a third research assistant blind to the first two transcripts, who transcribed only the trials on which the first two transcribers disagreed.

A second set of research assistants coded the children's responses from the transcripts. Coders scored the number of times children mentioned the color of the referent object or used spatial terms and whether they used these terms correctly on each trial. Within the category of spatial terms, we separately categorized both <u>size</u> and <u>location</u> terms from the other types of spatial terms mentioned to assess task-relevant adaptation. Size terms were defined as terms referring to the relative magnitude of the referent object (e.g., *small/smallest*, *medium*, *big/biggest*). Location terms were defined as words referring to the referent object's location in the scene (e.g., "the *top* chair"), not the relation between the target and the referent (e.g., "*on top* of the chair"). We differentiated these uses of spatial words in order for location terms to provide an analogous level of description to the color and size words children could use to differentiate the referent objects (cf. Figure 1). However, we included other spatial words in our total production count to be comparable to prior studies assessing children's spatial vocabulary and production. Inter-rater reliability was high for all measures (*r*s > .91) and disagreements were resolved by the first author.

For the regression analyses, we calculated three different measures from the coding. For the task-related language production (Step 3), we created two measures, one for the quantity of non-spatial terms used and the other for the quantity of spatial terms used. The measure for the quantity of non-spatial terms used was created by averaging the number of color terms each child produced per trial during the spatial scene description task, and the measure of quantity of spatial terms used was created by averaging the total number of spatial terms each child used per trial (including but not limited to size and location terms) during the task.

For the adaptation score (Step 4), we considered how often each child produced relevant versus irrelevant cues during the spatial scene description task. On each trial, a child's responses was scored for the three cue types (color, size, and location) as a 0 or 1 depending on whether they produced any description of those cues. Multiple descriptions of the same cue type were only counted as one (i.e., “front corner” and “front” would both count as 1 for location cues on that trial). To account for the relevance of the cues, color and size terms were coded as negative if produced on trials when they could not differentiate the referents. Specifically, color was coded as negative on 2 cue (size and location) and 1 cue trials (Figure 1C and 1D), and size was coded as negative on 2 cue (color and location) and 1 cue trials (Figure 1B and 1D). On all other trials color and size cues were coded as positive, and location cues were always coded as positive because location was relevant on all trial types. Thus, an individual’s adaptation score could potentially range from −2 to 3. Positive adaptation scores reflected children providing more relevant than irrelevant cues and negative adaptation scores reflected children providing more irrelevant than relevant cues. Scores closer to 0 reflected performance that did not differ by trial type; for example, if a child mentioned only color terms on every trial, they would receive a score of 0. Scores farther from 0 reflected both the number of cues mentioned and the cue relevance. Specifically, a child who mentioned color only on trials when color was a relevant cue (Figure 1A and 1B) would receive a score of 1; a child who mentioned color and size on trials when each was a relevant cue (Figure 1A = color and size, Figure 1B = color, Figure 1C = size), but not when they were irrelevant (Figure 1D) would receive a score of 2; and a child who also mentioned location, which was always relevant, would receive a score of 3. Thus, the adaptation score was sensitive to the context in which children provided different types of cues.

To ensure that children had sufficient language knowledge to perform the task, we made two types of trial exclusions. First, we excluded trials if the child’s caregiver indicated on the productive spatial vocabulary checklist that their child did not produce any of the relevant location words for a given trial (e.g., excluding trials in which the target was on the middle object if the checklist indicated the child did not produce *middle* or *center*) and the child did not produce these words during the task. This resulted in the exclusion of 4% of the total number of trials from two participants (with one participant being entirely excluded, as described above). Second, we excluded trials of participants from the spatial scene description task if the participant used an incorrect color, size, or location term (e.g., saying “top”, when the object was on the bottom). This resulted in exclusion of 7% of the total number of trials (across 19 participants; the remaining 22 participants used all terms correctly).

Spatial tasks—The experimenter marked children’s spatial task responses on a session sheet during participation. Eighty percent of the responses were checked by a second research assistant from the video-recordings (reliability agreements > 97%). Disagreements were resolved by a third researcher. Proportion of correct responses was calculated for each spatial task. To adjust for different chance levels across tasks (due to different numbers of alternatives; .25 on Mental Transformation and Spatial Analogies Tasks, .33 on Feature Binding Task and Picture Rotation Test), we normalized scores by taking each child’s score minus chance, then dividing by one minus chance, resulting in scores with 0 as chance performance and 1 as perfect performance. A composite spatial performance score was calculated for each child by averaging their adjusted scores across the four spatial tasks.

Vocabulary tasks—The experimenter marked children's responses while administering the PPVT-IV and terminated testing when the child responded incorrectly on eight or more trials within a 12-trial block (following the standard instructions). Research assistants calculated children's standardized scores offline using established norms (Dunn & Dunn, 2007). Productive spatial vocabulary was calculated as the proportion of words caregivers checked.

Results

This study investigated the relation between children's use of task-relevant language and their spatial skills. We hypothesized that individual differences in 4-year-olds' adaptive use of task-relevant language during the spatial scene description task would predict their spatial composite score above and beyond demographics (age, gender), vocabulary (PPVT-IV, and productive spatial vocabulary), and task-related language production (quantity of non-spatial and spatial terms used). Tables 1 and 2 present descriptive and correlational statistics on these measures.

To quantify variability in children's use of task-relevant language, we grouped participants based on the types of cues they produced during the spatial scene description task. Children were categorized based on whether they mentioned color, size, and/or location cues, in isolation or in combination, on any trial. As shown in Table 3, children were variable in their use of these cues during the spatial scene description task. For example, more than half the sample (61%) never used location cues to describe the referent object (e.g., *front* chair), despite the relevance of such terms and the fact that caregivers indicated children could produce these terms. Additionally, about a third of the sample never used color, size, or location cues (5 participants; e.g., "the mouse is on a table") or only provided one type of cue throughout the entire task (9 participants). Only 24% of the sample used all the possible types of relevant terms across trials. This suggests that there was high variability in children's use of task-relevant language in this task.

To evaluate our hypothesis that individual differences in children's adaptive production of task-relevant cues would predict their spatial performance, we conducted a set of regression analyses (Table 4). Children's spatial composite score was regressed on demographics (age, gender), vocabulary (PPVT-IV score and productive spatial vocabulary), task-related language production (quantity of non-spatial and quantity of spatial terms used during the spatial scene description task), and adaptation score, adding these four factors to the model in separate steps. Step 1 (demographics) showed that age was a significant predictor of children's spatial composite score, $t(39) = 2.75$, $p = .009$, $\Delta R^2 = .031$, but not gender ($p = .225$). Step 2 (vocabulary) showed that neither the PPVT-IV score nor the spatial vocabulary factor significantly predicted children's spatial composite score above and beyond the demographic factors ($p = .159$ and $p = 0.225$, respectively). Step 3 (quantity of task-related language production) showed that the quantity of spatial words produced significantly predicted children's spatial composite score, $t(34)= 2.45$, $p = .020$, $\Delta R^2 = .101$, replicating previous results (Pruden et al., 2011). However the quantity of non-spatial terms used did not predict performance ($p = .342$). As hypothesized, Step 4 (Adaptation) showed that children's adaptation score significantly predicted their spatial composite score above and beyond all other factors, $t(33) = 2.64$, $p = .013$, $\Delta R^2 = .099$, see Figure 3. When adding the adaptation score into the model, the total number of spatial words used became non-significant ($p = .315$). These results suggest that the relation between language and spatial cognition is not fully explained by abilities to produce spatial words, but reflects children's adaptive use of this knowledge to select task-relevant cues in the moment of a task.

In addition to the spatial composite score, we ran a set of exploratory regression analyses separately for each spatial task (Tables 5–8). Although our study was not specifically designed to differentiate among tasks, the relative strength of the relationship between children's language skills and each task may indicate promising avenues for further study. The regression models showed that the adaptation score significantly predicted children's performance on the Mental Transformation Task, $t(33) = 2.77$, $p = .009$, $\Delta R^2 = .096$, marginally predicted performance on the Spatial Analogies Task, $t(31) = 2.01$, $p = .053$, $\Delta R^2 = .081$, and Feature Binding Task, $t(33) = 1.95$, $p = .060$, $\Delta R^2 = .088$, and did not significantly predict performance on the Picture Rotation Test ($p = .209$), while controlling for demographics, vocabulary, and task-related production.

Discussion

This study examined whether children's adaptive use of task-relevant language was more predictive of their performance on the spatial tasks than their spatial word production. We hypothesized that 4-year-olds' adaptive use of task-relevant language would predict their spatial composite score above and beyond demographics (age, gender), vocabulary (PPVT-IV score, productive spatial vocabulary), and task-related production (quantity of non-spatial and spatial terms used). Before adding the adaptation score into the model, the results showed that the number of spatial words that children produced during the spatial scene description task predicted their spatial composite score, while controlling for demographics, vocabulary, and the production of non-spatial task-related terms. This finding replicates previous results showing that the quantity of children's spatial language production predicted their spatial performance (e.g., Pruden et al., 2011).

However, when the adaptation score was added to the regression model, results showed that children's skills in adaptively producing task-relevant language predicted their spatial composite score above and beyond all other factors, including the number of spatial words produced. In fact, the spatial term use variable became non-significant when adding the adaptation score into the model. The unique contribution of this work is that it demonstrates that the quality and adaptability of how children use spatial language is more predictive of their spatial skills than the quantity of their spatial word production. Indeed, the current research suggests that children's abilities to produce task-related language is not the strongest predictor of their spatial performance. Children need to be adaptive in their use of task-relevant language, considering the relevance of various cues across task contexts. The implications of these findings will be discussed in the sections below.

Individual Spatial Tasks

In addition to investigating how children's adaptive use of language related to their spatial skills generally, we also examined how children's adaptive use of language related to performance on each spatial task separately. It is important to note that the goal of the study was to investigate spatial skills generally, which is why we included a variety of spatial tasks. However, to include a variety of spatial tasks and still keep the study at a reasonable length for young children, we limited the total number of trials per task. Without more extensive testing of each particular spatial task, we cannot draw strong conclusions about how individual tasks relate to the production measures we collected. These exploratory results showed that the adaptation score significantly predicted performance on the Mental Transformation Task, marginally predicted performance on the Spatial Analogies and Feature Binding Tasks, and did not predict performance on the Picture Rotation Test, while controlling for the demographics, vocabulary, and quantity of potentially task-relevant production factors.

It is possible that children's adaptive use of language predicted performance more strongly on the Mental Transformation, Spatial Analogies, and Feature Binding Tasks than on the Picture Rotation Test because these tasks may depend more heavily on children adapting their attention to different types of cues throughout the task. In contrast, the Picture Rotation Test may depend more on attending to the same kinds of cues across trials. For example, the Mental Transformation task has shape pieces in various orientations and depends on children either mentally translating or rotating the pieces in different ways across trials to imagine how they would form a shape. The Spatial Analogies task requires children to identify and match different spatial relations across trials (e.g., whether pieces are touching relations, which way they are oriented, how they are aligned). Similarly, the Feature Binding task depends on children attending to different dimensions of relations across trials (e.g., left/right, above/below). Unlike these tasks that require attention to different types of information across trials, the Picture Rotation Test requires children to mentally rotate the target object of various degrees to find its match, but the manner of the transformation is constant across trials (i.e., circular rotation). Further research will be needed to determine why children's adaptive use of language is more predictive of performance in certain types of tasks more than in others.

This study employed a novel methodology for examining how children adaptively use language in the moment of the task. It showed that children's spatial word production was partially separable from how they adaptively use language to describe spatial scenes and, in fact, their adaptive use of language is the better predictor of their spatial skills. In extending this work, it will be important to examine a broader range of spatial tasks and language measures. For example, it would be useful to investigate whether children's adaptive use of language is predictive of performance in navigation and orientation tasks, which require children to attend to various landmark and distal cues. These types of comparisons could shed additional light on the processes that are common between children's adaptive use of language and performance on different types of spatial tasks. Also, it would be valuable to complement the present use of parental report as a comprehensive measure of productive spatial vocabulary with behavioral measures of productive vocabulary. By including these behavioral measures, we can compare children's use of particular spatial words in contexts that encourage the use of these words with minimal distracting cues (e.g., productive vocabulary task) versus in contexts that require children to select these words as relevant in the presence of other potentially irrelevant cues (e.g., spatial scene description task). This type of analysis will increase understanding of how children use particular spatial words differently based on context.

Implications for Theories of Language and Spatial Cognition

How do the current findings relate to theories of language and spatial cognition? One theoretical account considers language as a tool that can facilitate spatial encoding (e.g., Hermer-Vazquez et al., 2001; Loewenstein & Gentner, 2005; Pruden et al., 2011). Spatial language is proposed to affect spatial cognition by changing children's spatial behavior (e.g., Hermer-Vazquez et al., 2001) or by promoting their attention to spatial information (e.g., Pruden et al., 2011). This type of approach views spatial language as leading children to better encode spatial cues, thus facilitating their spatial performance. A second account is that the relation arises from children's use of language to draw their attention to task-relevant information (both spatial and non-spatial). The current findings provide stronger support for the latter theory; the relation between language and spatial cognition may not be specific to spatial language or to having words for verbal encoding, but arises from children's general ability in using language adaptively. It is important to note that the current findings and this latter explanation do not preclude the use of verbal encoding as a mechanism supporting spatial cognition. Children need to be able to produce words to use them in relevant contexts and potentially are using language during spatial tasks to encode relevant spatial information. The central difference between the two theoretical accounts is that the latter view suggests that other mechanisms besides abilities to produce relevant words, such as adapting to task contexts, are important and underlie the relation between language and spatial cognition.

An open question in the study of children's language and spatial cognition is the nature of the causal pathway between these two cognitive domains. The results of the current study are consistent with multiple potential causal pathways between children's adaptive use of language and their spatial skills. For instance, previous research suggests that language can promote spatial cognition through helping children verbally encode task-relevant spatial information, emphasizing language as the causal factor (e.g., Loewenstein & Gentner, 2005; Shusterman et al., 2011). It is possible that children who are more adaptive in using language are better at verbally encoding task-relevant cues during spatial tasks. However, there is mixed evidence as to whether verbal encoding is a mechanism that adults or children reliably use during spatial tasks (Hermer-Vazquez, Spelke, & Katsnelson, 1999; Nardini et al., 2006; Ratliff & Newcombe, 2008).

Alternatively, it is possible that spatial skills play the causal role, influencing children's abilities to use language adaptively. Children with spatial abilities could have an easier time learning spatial words, which could explain the current and prior findings that children's production of spatial words correlated with their spatial skills. Furthermore, the type of spatial experiences children have (e.g., puzzles, Legos, blocks) could promote adapting to task demands and learning to attend to task-relevant cues. In turn, these children would become more proficient at adaptively producing task-relevant language. The causal pathway between adaptation in language use and spatial skills may also be bi-directional. Producing task-relevant cues through language may help children perform better on spatial tasks, but experience with spatial tasks may increase children's sensitivity to featural and relational properties, which in turn propels children to use language more adaptively.

Finally, another possibility is that the adaptation measure in the current research may reflect a third factor influencing both language and spatial cognition. That is, a domain-general learning ability may underlie the relation between children's language production and spatial skills. For instance, basic processes such as abilities to direct attention or to abstract relevant information could be supporting language and spatial skills simultaneously. Indeed, these abilities could support children's production of relevant words and selection of relevant spatial dimensions. Because there are several potential causal pathways between children's adaptive use of language and their spatial abilities, future research should examine how domain general abilities, and domain-specific language and spatial abilities, operate in conjunction to drive cognitive development.

In conclusion, the current research suggests that having words to verbally encode task-relevant spatial information is an incomplete explanation for the relation between language and spatial cognition. Rather, children's adaptive use of their language knowledge to select task-relevant cues is a stronger predictor of their spatial skills. This research highlights the importance of understanding both children's knowledge of language and how they use language in the moment of a task when examining the mechanisms underlying the relation between language and spatial cognition.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

Thanks to the families who participated in this research, as well as the research assistants who aided in data collection and coding. Funding for this research was provided by: a) the University of Wisconsin-Madison Office of the Vice Chancellor for Research and Graduate Education through Wisconsin Alumni Research Foundation awards to VRS and HAV; b) the Eunice Kennedy Shriver National Institute of Child Health & Human Development of the National Institutes of Health (R03-HD067481) to VRS; and c) the Waisman Intellectual and Developmental Disabilities Research Center grant (P30HD03352). The content is solely the responsibility of the authors and does not represent the official views of the National Institutes of Health. Subsets of the data included here were presented at the 44th Annual Meeting of the Jean Piaget Society, 36th Annual Conference of the Cognitive Science Society, the 71st Biennial Meeting of the Society for Research in Child Development, and the 9th Biennial Meeting of the Cognitive Development Society.

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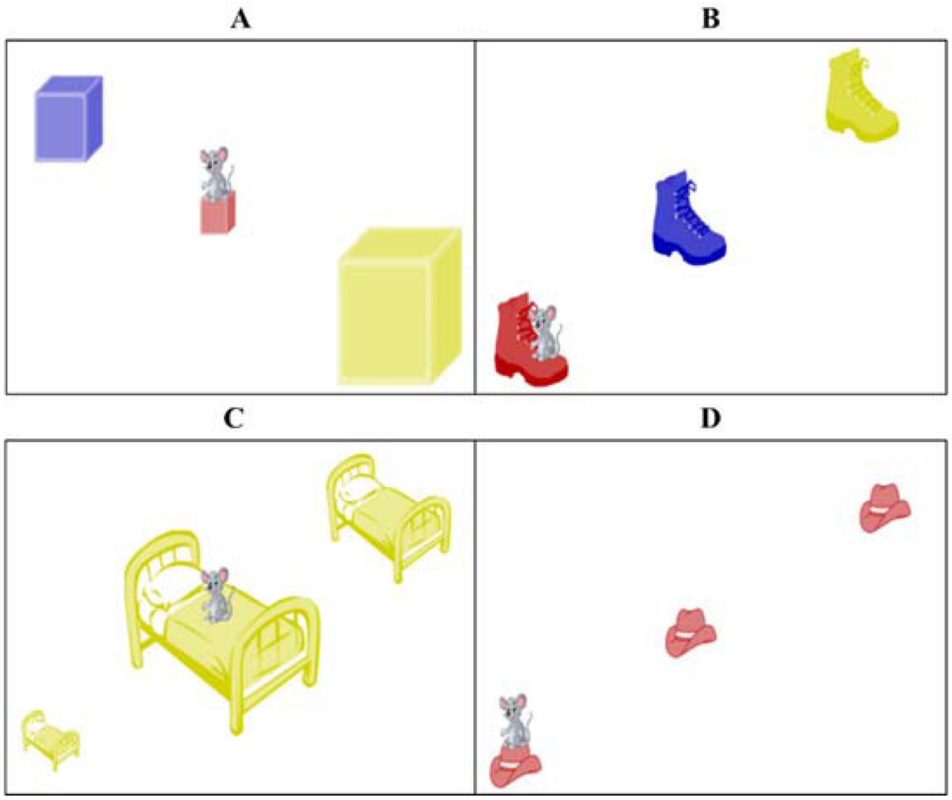

Figure 1.

Examples of the four trial types in the spatial scene description task: A) a three cue trial with color, size, and location cues; B) a two cue trial with color and location cues; C) a two cue trial with size and location cues; and D) a one cue trial with only location cues.

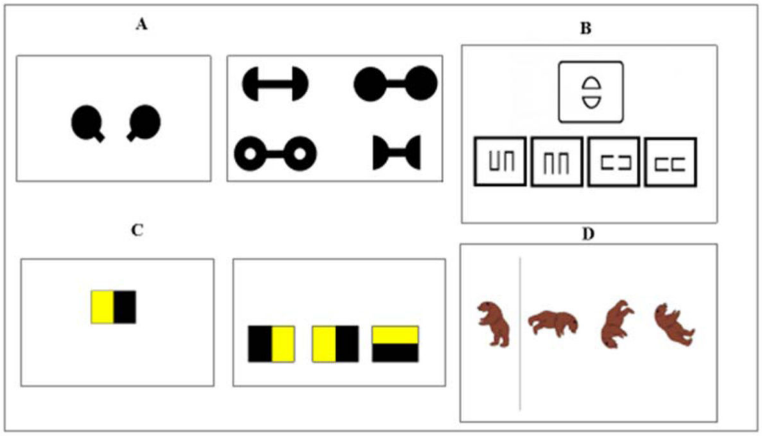

Figure 2.
Sample trials of spatial tasks. A) In the Children's Mental Transformation Task, children were asked to "select the shape that the pieces make." B) In the Spatial Analogies Task, children were asked to "select the picture that goes best with that picture (target picture)." C) In the Feature Binding Task, children saw the target square and were asked after a 1s delay, to "select the square that is the same as the one you just saw." D) In the Picture Rotation Test, children were asked "which one of these bears (picture) is the same as the first bear?"

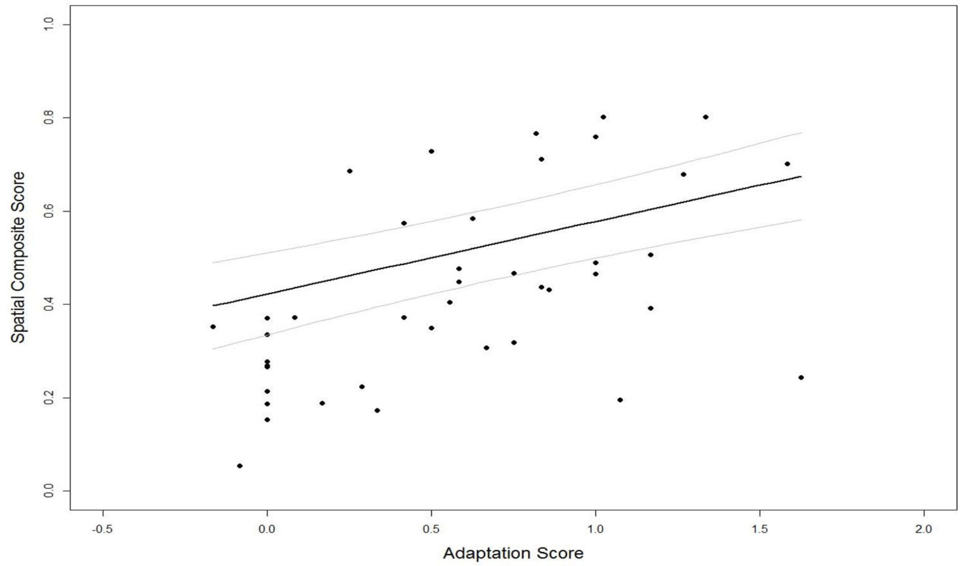

Figure 3.
The relation between children’s adaptation score and their spatial composite score. The prediction line represents the effect of adaptation on spatial task average, while controlling for age, gender, Peabody Picture Vocabulary Test (PPVT-IV) score, spatial vocabulary, and number of spatial words and non-spatial words used during the spatial scene description task. The error bars represent ± 1 standard error for point estimates from the regression model.

Table 1

Measures	*Mean*	*SD*	95% *CI*	*Observed Range*
Spatial Composite	0.43	0.20	0.37 – 0.49	0.05 – 0.80
Mental Transformation	0.61	0.20	0.55 – 0.67	0.10 – 0.90
Spatial Analogies	0.49	0.21	0.42 – 0.56	0.15 – 0.92
Feature Binding	0.70	0.16	0.65 – 0.75	0.46 – 1.00
Picture Rotation	0.59	0.24	0.52 – 0.66	0.19 – 0.94
Age	4.57	0.40	4.45 – 4.69	3.92 – 5.11
Gender	_______	_______	_______	_______
PPVT-IV	124.10	12.93	120.15 – 128.06	101.00 – 151.00
Spatial Vocabulary	0.69	0.19	0.63 – 0.75	0.11 – 0.98
Quantity Non-Spatial	0.45	0.37	0.34 – 0.56	0.00 – 1.25
Quantity Spatial	1.52	0.67	1.31 – 1.73	0.13 – 3.00
Adaptation Score	0.58	0.49	0.43 – 0.73	−0.17 – 1.63

Note. SD = standard deviation of the mean. CI = confidence interval of the mean. PPVT-IV= Peabody Picture Vocabulary Test-IV. Spatial Composite score was normalized for differing levels of chance across tasks (see text for details), resulting in a chance level of 0. Mental Transformation (chance = 0.25), Spatial Analogies (chance = 0.25), Feature Binding (chance = 0.33), and Picture Rotation (change = 0.33) are proportion scores. The PPVT-IV scores were standardized, ranging from 20 to 160. Spatial Vocabulary was calculated as the proportion of terms caregivers checked (out of 80). The Quantity of Non-Spatial Terms was calculated by averaging the total number of color terms mentioned, and the Quantity of Spatial Term was calculated by averaging the total number of spatial terms mentioned during the spatial scene description task across all trial types. The adaptation score could range from −2 to 3 (see text for description).

Table 2

Measures	1	2	3	4	5	6	7	8	9	10	11
1. Spatial Composite											
2. Mental Transformation	0.75***										
3. Spatial Analogies	0.64***	0.39*									
4. Feature Binding	0.61***	0.32*	0.09								
5. Picture Rotation	0.82***	0.44**	0.34*	0.40**							
6. Age	0.51***	0.38*	0.29	0.20	0.51***						
7. Gender	−0.30	−0.30	−0.22	−0.19	−0.16	−0.15					
8. PPVT-IV	0.33*	0.36*	0.35*	0.11	0.13	0.16	−0.13				
9. Spatial Vocabulary	0.26	0.43**	0.27	0.03	0.04	0.02	−0.21	0.31*			
10. Quantity Non-Spatial	−0.05	−0.23	0.03	0.07	−0.02	0.03	−0.05	−0.22	0.05		
11. Quantity Spatial	0.35*	0.20	0.30	0.23	0.26	−0.07	0.13	0.15	0.24	0.21	
12. Adaptation Score	0.65***	0.49**	0.49**	0.45**	0.43**	0.06	−0.01	0.34*	0.22	0.06	0.49**

Note.

* $p < .05$

** $p < .01$

*** $p < .001$.

Gender was contrast coded (−.5 = female, .5 = male). PPVT-IV= Peabody Picture Vocabulary Test-IV

Table 3

Grouping of Participants by Types of Cues Produced during Disambiguation Task

Cue Type	#Participants	Spatial Composite Score
None[a]	5	0.26
Color Only	5	0.32
Size Only	0	______
Location Only	4	0.62
Color & Location	1	0.43
Color & Size	15	0.43
Size & Location	1	0.41
All Cues	10	0.48
No Location Cues	25	0.37
Location Cues	16	0.51

Note. PPVT-IV= Peabody Picture Vocabulary Test-IV. Spatial Composite Score was calculated by normalizing the proportion of correct scores from each spatial task for different levels of chance. The No Location Cues include participants (*N* = 25) that were grouped as None, Color Only, Size Only, and Color & Size. The Location Cues include participants (*N* =16) that were grouped as Location Only, Color & Location, Size & Location, and All Cues.

[a]An example of "none" would be providing no color, size, or location cues (e.g., "the mouse is on the table").

Table 4

Hierarchical Regression Analysis Predicting Spatial Composite Score

	b	SE_b	β	R^2	ΔR^2	ΔF	*p*
Predictors							
Step 1: Demographics				0.22	0.22	5.38**	.009
Age	0.20	0.07	0.40**				
Gender	−0.07	0.06	−0.18				
Step 2: Vocabulary				0.33	0.11	2.80	.074
Age	0.20	0.07	0.39**				
Gender	−0.05	0.06	−0.13				
PPVT-IV	0.00	0.00	0.21				
Spatial Vocabulary	0.20	0.16	0.18				
Step 3: Potential Task Relevant Production				0.43	0.10	3.07	.059
Age	0.20	0.07	0.41**				
Gender	−0.07	0.06	−0.18				
PPVT-IV	0.00	0.00	0.16				
Spatial Vocabulary	0.14	0.16	0.13				
Quantity Non-Spatial Terms	−0.07	0.08	−0.13				
Quantity Spatial Terms	0.10	0.04	0.34*				
Step 4: Adaptation				0.53	0.10	6.94*	.012
Age	0.18	0.06	0.36**				
Gender	−0.06	0.05	−0.15				
PPVT-IV	0.00	0.00	0.11				
Spatial Vocabulary	0.16	0.15	0.15				
Quantity Non-Spatial Terms	−0.06	0.07	−0.11				
Quantity Spatial Terms	0.05	0.04	0.15				
Adaptation	0.16	0.06	0.37*				

Note.

* $p < .05$

** $p < .01$.

Gender was contrast coded (−.5 = female, .5 = male). PPVT-IV= Peabody Picture Vocabulary Test-IV.

Table 5

Hierarchical Regression Analysis Predicting Mental Transformation Task Score

	b	SE_b	β	R^2	ΔR^2	ΔF	p
Predictors							
Step 1: Demographics				0.23	0.23	5.66**	.007
Age	0.18	0.07	0.36*				
Gender	−0.10	0.06	−0.26				
Step 2: Vocabulary							
Age	0.18	0.07	0.36*	0.39	0.16	4.87*	.013
Gender	−0.07	0.05	−0.18				
PPVT-IV	0.00	0.00	0.17				
Spatial Vocabulary	0.35	0.15	0.32*				
Step 3: Potential Task Relevant Production				0.49	0.10	3.27*	.050
Age	0.19	0.06	0.38**				
Gender	−0.09	0.05	−0.23				
PPVT-IV	0.00	0.00	0.08				
Spatial Vocabulary	0.34	0.15	0.31*				
Quantity Non-Spatial Terms	−0.15	0.07	−0.28*				
Quantity Spatial Terms	0.07	0.04	0.24				
Step 4: Adaptation				0.50	0.10	7.64**	.009
Age	0.17	0.06	0.34**				
Gender	−0.08	0.05	−0.20				
PPVT-IV	0.00	0.00	0.03				
Spatial Vocabulary	0.36	0.14	0.33*				
Quantity Non-Spatial Terms	−0.14	0.06	−0.26*				
Quantity Spatial Terms	0.02	0.04	0.05				
Adaptation	0.15	0.05	0.37**				

Note.

* $p < .05$

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** $p < .01$.

Gender was contrast coded (−.5 = female, .5 = male). PPVT-IV= Peabody Picture Vocabulary Test-IV.

Table 6

Hierarchical Regression Analysis Predicting Spatial Analogies Task Score

	b	SE_b	β	R^2	ΔR^2	ΔF	*p*
Predictors							
Step 1: Demographics				0.12	0.12	2.37	.108
Age	0.14	0.08	0.26				
Gender	−0.08	0.06	−0.18				
Step 2: Vocabulary				0.22	0.11	2.36	.109
Age	0.12	0.08	0.23				
Gender	−0.05	0.06	−0.12				
PPVT-IV	0.00	0.00	0.25				
Spatial Vocabulary	0.19	0.18	0.17				
Step 3: Potential Task Relevant Production				0.30	0.08	1.72	.195
Age	0.13	0.08	0.25				
Gender	−0.07	0.06	−0.18				
PPVT-IV	0.00	0.00	0.21				
Spatial Vocabulary	0.11	0.18	0.10				
Quantity Non-Spatial Terms	0.00	0.09	0.00				
Quantity Spatial Terms	0.09	0.05	0.29				
Step 4: Adaptation				0.38	0.08	4.04	.053
Age	0.12	0.08	0.23				
Gender	−0.07	0.06	−0.17				
PPVT-IV	0.00	0.00	0.13				
Spatial Vocabulary	0.10	0.17	0.09				
Quantity Non-Spatial Terms	0.00	0.08	−0.01				
Quantity Spatial Terms	0.04	0.05	0.13				
Adaptation	0.15	0.08	0.35				

Note. Gender was contrast coded (−.5 = female, .5 = male). PPVT-IV= Peabody Picture Vocabulary Test-IV.

Table 7

Hierarchical Regression Analysis Predicting Feature Binding Task Score

Predictors	b	SE_b	β	R^2	ΔR^2	ΔF	p
Step 1: Demographics				0.07	0.07	1.44	.250
Age	0.07	0.06	0.18				
Gender	−0.05	0.05	−0.17				
Step 2: Vocabulary							
Age	0.07	0.07	0.17	0.08	0.01	0.14	.872
Gender	−0.05	0.05	−0.16				
PPVT-IV	0.00	0.00	0.09				
Spatial Vocabulary	−0.02	0.15	−0.02				
Step 3: Potential Task Relevant Production				0.15	0.07	1.40	.261
Age	0.07	0.06	0.17				
Gender	−0.06	0.05	−0.20				
PPVT-IV	0.00	0.00	0.08				
Spatial Vocabulary	−0.07	0.15	−0.08				
Quantity Non-Spatial Terms	0.01	0.07	0.03				
Quantity Spatial Terms	0.06	0.04	0.27				
Step 4: Adaptation							
Age	0.05	0.06	0.12	0.24	0.09	3.78	.060
Gender	−0.05	0.05	−0.17				
PPVT-IV	0.00	0.00	0.03				
Spatial Vocabulary	−0.05	0.15	−0.06				
Quantity Non-Spatial Terms	0.02	0.07	0.04				
Quantity Spatial Terms	0.02	0.04	0.09				
Adaptation	0.11	0.06	0.35				

Note. Gender was contrast coded (−.5 = female, .5 = male). PPVT-IV= Peabody Picture Vocabulary Test-IV.

Table 8

Hierarchical Regression Analysis Predicting Picture Rotation Test Score

	b	SE_b	β	R^2	ΔR^2	ΔF	*p*
Predictors							
Step 1: Demographics				0.19	0.19	4.55*	.016
Age	0.26	0.09	0.43**				
Gender	−0.02	0.07	−0.04				
Step 2: Vocabulary							
Age	0.25	0.09	0.43**	0.20	0.01	0.18	.873
Gender	−0.01	0.07	−0.02				
PPVT-IV	0.00	0.00	0.08				
Spatial Vocabulary	0.04	0.21	0.03				
Step 3: Potential Task Relevant Production							
Age	0.26	0.09	0.44**	0.27	0.07	1.62	.213
Gender	−0.03	0.07	−0.07				
PPVT-IV	0.00	0.00	0.03				
Spatial Vocabulary	−0.02	0.21	−0.02				
Quantity Non-Spatial Terms	−0.07	0.10	−0.10				
Quantity Spatial Terms	0.10	0.06	0.28				
Step 4: Adaptation							
Age	0.24	0.09	0.41*	0.30	0.03	1.47	.234
Gender	−0.02	0.07	−0.05				
PPVT-IV	0.00	0.00	0.00				
Spatial Vocabulary	−0.01	0.21	−0.01				
Quantity Non-Spatial Terms	−0.06	0.10	−0.09				
Quantity Spatial Terms	0.06	0.06	0.17				
Adaptation	0.10	0.08	0.21				

Note.

* $p < .05$

** $p < .01$.

Gender was contrast coded (−.5 = female, .5 = male). PPVT-IV= Peabody Picture Vocabulary Test-IV.