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Spatial language and mental transformation in preschoolers: Does relational reasoning matter?

Eylül Turan[a,b], Mert Kobaş[a], Tilbe Göksun[a,*]

[a] Koç University, Turkey
[b] KU Leuven, Belgium

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ABSTRACT

There is a consensus that spatial language supports spatial reasoning. However, it remains a question of how specific spatial terms (e.g., prepositions) relate to distinct spatial skills that are critical for spatial cognition (e.g., mental transformation). We asked whether 1) preschoolers' spatial language skills, particularly knowledge of postpositions, were linked to their mental transformation abilities, and 2) other cognitive factors such as reasoning about relations were associated with this link. Turkish-speaking preschool-aged children (Mage = 53 months) completed spatial language (i.e., postposition comprehension and production), spatial reasoning (i.e., mental transformation), relational reasoning, cognitive inhibition, and general vocabulary knowledge tasks. Results showed that older children performed better on all tasks, except the relational reasoning one. Children's mental transformation performance was associated with their postposition knowledge and relational reasoning performance, beyond general vocabulary knowledge and cognitive inhibition. These findings present evidence on the link between spatial language and spatial reasoning from Turkish-learning preschool-aged children and emphasize the role of other cognitive factors such as relational reasoning on mental transformation.

1. Introduction

Spatial reasoning is central for achievement in STEM disciplines (Science, Technology, Engineering, and Mathematics) (e.g., Hawes, Moss, Caswell, Seo, & Ansari, 2019; Lauer & Lourenco, 2016; Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). As a critical feature of spatial reasoning, spatial language conveys information regarding the spatial features and dimensions of objects or their locative relations and actions (Chatterjee, 2008). Spatial language consists of a variety of terms such as shape (e.g., circle), dimension (e.g., big), feature (e.g., side), and locative terms (e.g., between) (e.g., Casasola, Wei, Suh, Donskoy, & Ransom, 2020; Miller, Andrews, & Simmering, 2020; Pruden, Levine, & Huttenlocher, 2011). Many studies reported that spatial language is closely associated with spatial thinking (e.g., Dessalegn & Landau, 2008; Loewenstein & Gentner, 2005; Miller, Patterson, & Simmering, 2016; Pruden et al., 2011; Pyers, Shusterman, Senghas, Spelke, & Emmorey, 2010). However, less is known about the role of specific spatial terms' contribution to spatial reasoning, particularly in different language environments than English. The present study investigates how Turkish-learning preschool-aged children's knowledge of locative postpositions (prepositions are postpositions in Turkish) relates to their mental transformation abilities. We also examine how relational reasoning abilities play a role in this association beyond children's overall language knowledge and cognitive inhibition.

* Corresponding author at: Department of Psychology, Koç University, Rumelifeneri Yolu, Sariyer, 34450, Istanbul, Turkey.
E-mail address: tgoksun@ku.edu.tr (T. Göksun).

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Language can change spatial cognition (Gentner, 2003), augment children's spatial thinking by making them attend to and maintain spatial information (e.g., Dessalegn & Landau, 2008; Pruden et al., 2011) or help them focus on task-relevant information (Miller & Simmering, 2018). Children who hear more spatial language from their caregivers during natural play (Pruden et al., 2011) or in museum-based interactions (Polinsky, Perez, Grehl, & McCrink, 2017) produce more of these terms and perform spatial tasks better. Spatial language provided by the experimenter during or before the task benefits children's spatial performance (e.g., Dessalegn & Landau, 2008; Loewenstein & Gentner, 2005; Miller et al., 2016.). The spatial language children hear and their knowledge and use of spatial terms can benefit their spatial reasoning (e.g., Miller et al., 2016; Pruden et al., 2011; Simms & Gentner, 2008). For example, children's production of spatial terms such as *left-right* (Hermer-Vazquez, Moffet, & Munkholm, 2001), *middle* (Simms & Gentner, 2019), or *by/next* (Miller et al., 2016) aids them in tasks involving those spatial relations. Additionally, children's spatial word production at 14 and 46 months of age is also predictive of their later performance at 54 months of age across various spatial tasks (Pruden et al., 2011). Last, Balcomb, Newcombe, and Ferrara (2011) reported that toddlers perform better in a place learning task (e.g., the correct search of a hidden object) when they have a larger spatial vocabulary for prepositions as obtained from parental reports. Hence, spatial thinking and spatial language are related, and the spatial language children hear can influence this link.

Despite the evidence pointing to the association between spatial language and spatial reasoning, it remains a question whether this link is specific to certain tasks. Studies have tested the relation between children's spatial language use and spatial reasoning using the children's mental transformation task (CMTT) (e.g., Levine, Huttenlocher, Taylor, & Langrock, 1999; Miller, Vlach, & Simmering, 2017; Pruden et al., 2011), the relational-matching-to-sample task (RMTS) (e.g., Christie & Gentner, 2014; Hespos, Anderson, & Gentner, 2020; Hoyos, Shao, & Gentner, 2016; Siddik, Lata, & Mahmud, 2019) or experimental spatial tasks such as object search tasks (e.g., Simms & Gentner, 2019). Among these spatial tasks, the CMTT seems to be a key measure for assessing spatial reasoning. According to Levine et al. (1999), spatial thinking is a "vital component of human intellectual competence" (p. 940), and they measure spatial thinking via the CMTT. Transformation abilities are essential for everyday activities such as navigating oneself in space and for more technical tasks such as interpretation of graphs and maps. The CMTT is an ideal test to measure such transformation abilities, as it requires children to integrate two separate parts of a shape mentally.

Research on CMTT suggests associations between children's spatial language use and their transformation abilities. For example, Pruden et al. (2011) examined the relationship between children's use of spatial "what" terms such as shapes of objects, dimensional adjectives during a natural play setting and their spatial transformation, analogy abilities, and block design performance. Children's use of these terms at 46 months correlated with their later performance on the CMTT when they were 54 months of age. In another study, Miller et al. (2016) tested 4-year-old children on the CMTT along with a spatial analogies task, a feature binding task, and a picture rotation test. Children were also tested on their spatial language production using a spatial scene description task. Children's use of size and location terms was coded separately from other types of spatial terms. Results indicated that children's use of task-relevant language (both spatial and non-spatial, i.e., adaptive use of language in this task) predicted their spatial performance, as calculated by a spatial task composite score that included all four spatial tasks. Although they used a spatial task composite score, the adaptation score predicted each task differently. For example, the CMTT scores were related to task-relevant language better than the picture rotation test.

Building on Miller et al.'s work, Miller and Simmering (2018) suggested that task-relevant language production and selective attention could be linked to children's spatial task performance, measured again by a spatial task composite score. In a very recent study, Miller, Andrews, & Simmering, 2020) asked children to explain their reasoning behind their choices on the CMTT and the spatial analogies task. As in prior studies, children's adaptive use of analogical (e.g., alike), dimensional (e.g., square), and movement (e.g., turn) terms in their speech and gestures predicted their performance in the CMTT. Moreover, Levine, Ratliff, Huttenlocher, and Cannon (2012) provided longitudinal evidence for the relation between transformation skills at 54 months of age and earlier experiences with puzzles that incorporated spatial language such as dimension, orientation, transformation, location, and direction terms. In line with the previous findings (e.g., Levine et al., 1999; Pruden et al., 2011), Levine and colleagues also reported significant sex differences in children's CMTT performance, where boys performed better than girls (see also Moore & Johnson, 2008; Quinn & Liben, 2008).

There is also causal evidence regarding the relation between spatial language and children's transformation skills. In their recent training study, Casasola, Wei, Suh, Donskoy, & Ransom, 2020 assessed 4-year-old children's improvements on the CMTT and the picture rotation test (PRT). Children were assigned to a spatial language or a play-only condition. Children in the spatial language condition heard various spatial information such as geometric shapes names, prepositions, and size terms. Several days after five play sessions, the spatial language group outperformed their peers on the posttest measure. Importantly, due to validity issues across the two CMTT measures (pretest and posttest CMTT), only the PRT was included in the analyses, leaving the question of whether spatial language causally relates to the CMTT open.

Taken together, these lines of evidence indicate that spatial language relates to spatial reasoning. These studies mostly investigated children's abilities to solve spatial tasks (e.g., Miller & Simmering, 2018; Miller et al., 2017) rather than understanding the factors contributing to specific spatial abilities such as mental transformation. Besides, most studies assessed a range of different terms and calculated a total score of using spatial language (e.g., an average number of spatial tokens, Levine et al., 2012; a cumulative number of spatial tokens, Pruden et al., 2011) or examined the use of a specific term for a particular spatial understanding (e.g., middle/between, Simms & Gentner, 2019). Are specific spatial terms more relevant to spatial skills based on task demands? Research suggests that producing specific spatial labels influences spatial understanding more than general spatial terms (Loewenstein & Gentner, 2005). Although many elements of speech could be considered spatial, not all of them are relevant to the spatial task that is being executed (Levine et al., 2012), and semantics of the spatial words are important for specific spatial tasks (Loewenstein & Gentner, 2005). A mental transformation task like CMTT would require knowledge of locative terms (i.e., prepositions) as a child should focus on the relative position of two pieces to solve how she puts them together (Levine, Goldin-Meadow, Carlson, & Hemani-Lopez, 2018). In this task, children are asked to move pieces perpendicularly or diagonally to the target shape's symmetry. These movements would require an understanding of location, such as moving one piece *above* the other or rotating pieces to the *left* or *right*. Therefore, we investigate whether prepositions, as a specific category of spatial language, relate to children's performance on the CMTT.

In addition to the CMTT, studies also assessed the RMTS to understand the associations between spatial language and spatial reasoning. The RMTS is a type of spatial analogies task that focuses mainly on children's relational understanding. Typically, spatial analogies tasks consist of a standard card depicting a certain relation and choice cards. Children are then asked which of the choice cards "goes best" with the standard. Compared to typical spatial analogies tasks, in which children are presented with four choice cards and competing similarity choices (Christie & Gentner, 2014), the RMTS presents children with only two choice options that do not compete with each other and requires them to extract the simplest relation, namely the relational identity relation. For example, given AA, children have to choose XX over YZ (Christie & Gentner, 2014). Two- and 3-year-olds fail in recognizing this relation, and even 4-year-olds choose the relational match only 65 % of the time. This suggests that young children do not show full competence, even in one of the simplest relations (Christie & Gentner, 2014). Importantly, language is a significant tool that facilitates children's performance on this task (Christie & Gentner, 2007, 2014). For example, 3-year-olds trained on the *same* and *different* meanings succeed in making relational matches (Christie & Gentner, 2014).

Although not with the RMTS specifically, studies reported correlations between children's performance on the CMTT and their performance on other spatial analogies tasks that included four choices than only relational identity choices (e.g., Miller et al., 2017; Pruden et al., 2011). Importantly, the RMTS reflects children's relational understanding, which is key to higher-order human cognition (Christie & Gentner, 2007). Relational reasoning lies at the core of various cognitive processes, including analogical reasoning (Gentner, 1983, 2003; Kokinov & French, 2003), categorization (Ramscar & Pain, 1996), inductive inferencing (Holland, Holyoak, Nisbett, & Thagard, 1986), and numerical reasoning (Hurst & Cordes, 2018). Having a fundamental role in different cognitive processes, relational understanding measured by the RMTS could be an important factor in the association between spatial language and spatial performance. The RMTS necessitates children to understand that two objects have a certain relationship with each other (e.g., a card with two yellow squares depicts an identity relation), and the CMTT requires them to combine two objects (i.e., two halves of a shape) to create a whole. To do so, during the CMTT, children must focus on the relationship these two halves have with each other. Given that relational abilities are relevant to different cognitive processes, relational performance, as reflected by the RMTS, forms a general framework of understanding commonalities and associations between stimuli. Transformation abilities may require spatial operations along with such general relational representations. Therefore, performance on the RMTS might relate to children's performance on the CMTT.

Apart from relational reasoning, other variables could also play a role between spatial language and spatial reasoning. For example, given that developmental changes in executive functions relate to spatial performance (Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014), inhibition skills could be related to children's spatial performance. Additionally, children's overall vocabulary knowledge should be considered while assessing the link between spatial language and spatial reasoning, as general vocabulary correlates with spatial language knowledge (Pruden et al., 2011). Hence, children's spatial performance can be linked to a combination of different factors (Miller, Andrews, & Simmering, 2020). Even though spatial language seems to be a key factor explaining the variance in spatial reasoning performance, it is important to consider other relevant variables to understand children's spatial performance.

Up to date, most of our theories and experimental evidence on spatial development comes from studies testing Western languages such as English (e.g., Casasola, Wei, Suh, Donskoy, & Ransom, 2020; Levine et al., 1999; Miller et al., 2016; Pruden et al., 2011; but see Haun, Rapold, Janzen, & Levinson, 2011). Is the relation between spatial language and spatial reasoning being realized similarly in languages that differ in encoding spatial relations? As suggested by the relational relativity hypothesis (Gentner, 1982), prepositions "exist in linguistically defined systems and are therefore more variable cross-linguistically than those of concrete nouns" (Gentner & Boroditsky, 2001, p. 218). For example, the Turkish language uses a postpositional system instead of a prepositional one. In the most commonly used word order, the object name is presented first, followed by the locative term. Turkish also uses a flexible word order that may assist Turkish-learning children's attention to object relations. Turkish-learning children seem to learn postpositions (e.g., *in, on, under, beside, between, back*) more quickly and at earlier ages than their English peers (Johnston & Slobin, 1979). Given the role of selective attention in spatial performance (Miller & Simmering, 2018), in postpositional languages hearing the object name first could drive attention to the target object and help eliminate other irrelevant information, which could, in turn, ease the processing of the spatial information. That is, the order of hearing a spatial term may influence children's attention to specific spatial relations (Newcombe, Uttal, & Sauter, 2013). Apart from linguistic differences, we need to consider cross-cultural differences in attending to relations suggested by Christie, Gao, and Ma (2020)) for analogical reasoning.

In sum, spatial language supports different aspects of spatial reasoning, including children's mental transformation abilities. However, the transformation seems to be a challenging task for young children, as they obtain relatively low scores from the CMTT until the age of 5 (Levine et al., 1999). Less is known about how and which aspects of spatial language are more relevant for mental transformation skills and whether more general reasoning abilities (e.g., relational understanding), children's inhibition skills, and overall vocabulary contribute to the link between spatial language and spatial performance. Among these, relational understanding seems to be particularly important, given its role in different higher-order cognitive processes and detecting associations between stimuli. The CMTT also requires children to detect relations between two parts of the stimuli; thus, relational reasoning may contribute to transformation abilities. Earlier studies mostly focused on languages that use prepositions to describe relations between objects. Turkish-speaking children acquire these terms (i.e., postpositions) earlier than their peers learning prepositional languages such as English (Johnston & Slobin, 1979). Turkish-learning children's performances in the CMTT task and the role of their spatial postposition knowledge on their performance can help generalize previous findings on the link between spatial language and spatial reasoning.

The present study asks whether 3- to 5-year-old children's knowledge of postpositions associates with their performance on the CMTT and whether relational reasoning, as well as cognitive inhibition and expressive vocabulary knowledge, can be related to this link. We use the CMTT as a specific spatial reasoning task and the RMTS as a general relational reasoning task. We assess spatial language by testing children's postposition comprehension and production on a newly developed experimental set-up. Given the relation between executive function and spatial performance (Verdine et al., 2014), we also assess children's cognitive inhibition ability. Last, we control children's overall vocabulary knowledge, particularly their expressive vocabulary, due to the relation between general vocabulary and spatial language (Pruden et al., 2011). We hypothesize that children's performance on the CMTT will be associated with their spatial language abilities. Additionally, RMTS scores (as a general relational reasoning task), cognitive inhibition, and overall language scores can also explain the variance on this link. We further predict that the RMTS will play a key role in children's CMTT performance, together with spatial language scores, that will go beyond children's cognitive inhibition and general vocabulary knowledge.

2. Method

2.1. Participants

Based on previous studies (Miller & Simmering, 2018; Miller et al., 2017), we collected data from 58 Turkish-reared children between 37 and 70 months of age (M_{age}= 52.7, SD_{age}=7.63). There were 37 boys (M_{age}= 51.5, SD_{age}=7.36) and 21 girls (M_{age}= 54.7, SD_{age}=7.88). Two children were excluded from data analysis due not to obtain the exact age information or to be very young for this study. Data was collected from a kindergarten in İstanbul, Turkey. Koç University's Institutional Review Board approved the study.

2.2. Materials and procedure

2.2.1. Relational matching to sample task (RMTS)

We used the same RMTS task created by Christie and Gentner (2014). The RMTS consisted of 8 triads, each including three cards with pictures. Each picture card included two geometric shapes. The main card consisted of two identical shapes (e.g., two circles). The other cards were choice cards: one of them was a *relational match* card that included identical shapes (e.g., two rectangular shapes), and the other was a *non-relational match* card that included different shapes (e.g., a circle and a square) (see Fig. 1a for a sample trial). The experimenter placed the main card in front of the child, saying, "I am going to show you a card with some shapes on it. Look at this one." and then the two choice cards below it and asked, "Can you show me which one of these two cards resembles the card at the top more?" We calculated the RMTS score by summing all the correct answers of children in 8 triads.

2.2.2. Children's mental transformation task (CMTT)

We used the short version of the CMTT task of Levine et al. (1999). This version consisted of 10 trials. In each trial, children were first presented with a shape divided into half. They were also presented with a 2 × 2 array of four choice shapes (see Fig. 1b for a sample trial). On the first trial, the experimenter gestured to the target pieces and then to the array of four shapes saying, "Look at these pieces. Look at these pictures. If you put the pieces together, they will make one of the pictures. Point to the picture the pieces make." In the subsequent trials, the experimenter said, "Point to the picture the pieces make." No feedback was given on any trials. Children's performance was calculated as the sum of correct answers in 10 trials.

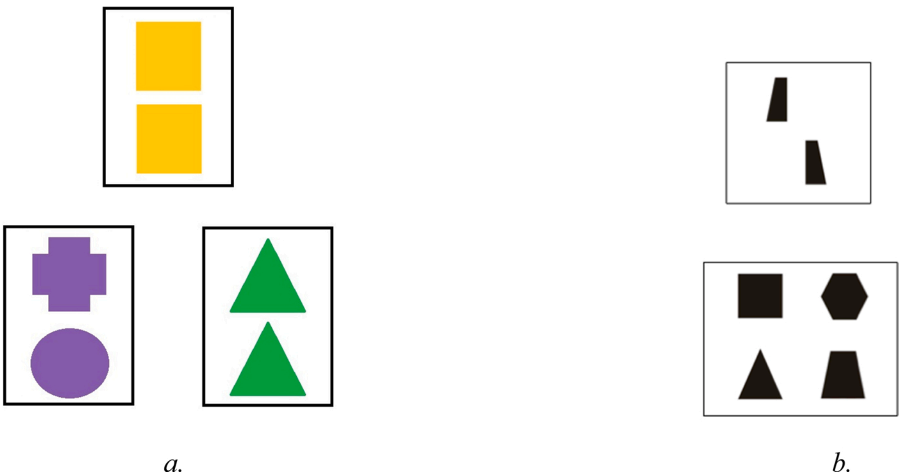

Fig. 1. Fig. 1a presents a sample trial of the RMTS: above is the standard, and the two choice cards are below it (the card on the left as a non-relational, and the card on the right as a relational match). Fig. 1b presents an example of the CMTT task. These figures were adapted from Christie and Gentner (2014) and Levine et al. (1999), respectively.

2.2.3. Day-night task

The Day-Night task we used was a combination of the original Day-Night (Diamond, Kirkham, & Amso, 2002) and the Grass-Snow (Carlson & Moses, 2001) tasks. The Day-Night task asks children to respond verbally upon seeing a card shown by the experimenter, whereas in the Grass-Snow task, children give their responses by pointing to the target picture. According to Carlson (2005), the Grass-Snow task is less demanding compared to the Day-Night task. As we tested relatively younger children, we asked children to point to the target shape instead of making a verbal response. The game involved a day card with a yellow sun and a night card with a moon (Diamond et al., 2002). Children were shown the two cards, and the experimenter said, "This is the day card, look there is a sun, and the sky is blue. This is the night card, look there is a moon, and the sky is dark. Now, we will play an interesting game, and we will switch the day and night. So when I say *day*, you will point to the night card, and when I say *night*, you will point to the day card." While instructing the child, the experimenter pointed to the relevant cards. The task involved two practice trials and ten experimental trials. The number of correct items indicated the performance score.

2.2.4. Postposition production and comprehension tasks

Children were assigned to one of the two conditions for the spatial language task. In both conditions, the target postpositions for the production and comprehension tasks were identical; however, the order they were asked were different. We used two identical playhouses for the production part of the language task, with identical objects in them. Both houses had four rooms, and each room contained specific landmarks (i.e., a bed, a table, a chair, two armchairs, a dog, and a basket) (see Fig. 2 for the playhouses). We also used two identical dolls, each doll belonging to one of the houses. For the comprehension part, we used only one house and one doll.

For the production task, children were seated on the floor, and the experimenter sat next to them. After introducing the child to the confederate, the experimenter said, “Look, this is our house, and look at *X*’s (the confederate’s name) house. It is the same as ours. Look, this is our bed." Then the confederate showed his own bed, saying, "Look, I also have a bed, and it is the same as yours." This landmark introduction was done for each object, and it was emphasized that the two houses and the objects in the houses were exactly the same. Then, the experimenter put a black screen between the two houses by saying, “I am going to make this game a bit more interesting. Look, I am placing this screen between two houses so that *X* does not see our house, and we do not see his house. Throughout the game, we aim to make our houses look exactly the same to each other.” Following this, the child received two practice trials, in which the experimenter placed the doll first *in front of* the house and then *next to* the house. For each trial, the experimenter asked the child, “Can you tell *X* where to put her doll so that our houses look exactly the same?” If the child had not responded, the experimenter would have said, "Okay, let’s tell *X* to put the doll *in front of* the house?” If there had still been no response from the child, the experimenter would have told the confederate where to put the doll and then would have said, "Let’s lift the screen and see if our houses look the same. Yes! Look, our houses look the same, great!” After this, the screen would be placed again between the two houses, and the second practice trial would be given. These practice trials were followed by nine experimental trials in which the experimenter put the doll in various places inside the house.

We used *in, in front of, above, next to, below, between, behind, left,* and *right* as target prepositions. For each trial, after putting the doll in each location, the experimenter asked the child, "Can you tell *X* where to put his doll so that our houses look exactly the same?" After the child’s response, the experimenter lifted the screen and said, "Look, our houses look the same!" If the child had not responded, the experimenter would have given prompts (e.g., *X* wants his house to be like ours, but he cannot see our house, let’s tell him where he should put his doll). If the child had given responses such as "Put it there," in which no postposition was used, the confederate prompted the child saying, "But I cannot see where it is," and if needed, the experimenter would have given a second prompt (i.e., "I cannot see it, you have to tell me where I should put it"). The confederate always followed the child’s instructions throughout the trials, although she still kept track of the list’s target postpositions. The only feedback the child received was whether the two houses looked the same or not.

Fig. 2. Two houses were used in the spatial language task. The experimenter and the child used the house on the right side, and the confederate used the one on the left. For the comprehension part of the task, only one house was used.

After the production task, the children completed the comprehension task. The experimenter said, "Now, we will play a game together, and, in this game, we do not need the other house. You will put the doll to the places I will tell you to." No practice trial was given. The same postpositions that were used in the production task were asked in a randomized order. After the child placed the doll for each trial, the experimenter took it and asked the next target location, such as "Okay, now I want you to put the baby *next to* the dog," and passed the doll to the child. If the child did not respond, the experimenter gave two prompts such as "Where is the dog?" and then "Which one is the dog?"

The correct responses in the production task included any response that involved the correct postposition. Even if the child had not produced the noun that was used in the introduction phase of the experiment, by producing the target postposition, children would have received the full point. We also coded the errors children made. None of them produced an incorrect noun, although some children produced different but similar nouns to the original one (e.g., using the word *sofa* instead of an *armchair*). Each correct response was worth 1 point. We summed the correct responses and calculated each child's performance score in percentages. The same coding was done for the comprehension task, in which 1 point was given to each correctly comprehended postposition, and 0 was given when the child put the toy animal to the wrong location of the object.

TIFALDI-E. We administered the Turkish Expressive and Receptive Language Test-Expressive subtest (TIFALDI-E) to assess children's expressive language skills (Berument & Güven, 2010). The test includes 80 items, each having a picture that depicts the target word. The child's task is to say the name of the objects in the picture.

Children were tested individually in a quiet room in the kindergarten by the same two experimenters. The tasks were administered in the same order to all children: RMTS, CMTT, Day-Night, postposition production, postposition comprehension, and TIFALDI-E. Each session took approximately 40 min.

3. Results

3.1. Preliminary analyses

We first present descriptive statistics for the tasks, assessing whether children's performances were above chance level for the CMTT and RMTS tasks (see Table 1 for the descriptive statistics, and Table 2 for the correlation matrix). We also analyzed whether there were sex differences in children's performances in any task.

Children performed above chance level (25 %) for the CMTT task ($M = 4.21$, $SD = 2.13$), $t(57) = 7.91$, $p < .001$. For the RMTS task, the performance was at chance level (50 %) ($M = 4.40$, $SD = 1.93$), $t(57) = 1.57$, $p = 0.123$. No sex differences were found on children's performance in any of the tasks, $ts < 1.89$, and $ps > .07$. As shown in Table 2, children's age correlated with scores from all tasks except the RMTS score. Fig. 3 shows the relationship between age and CMTT. We included age as a continuous variable (in months) in our further analyses.

For the spatial language tasks, children performed better in the comprehension task (M=6.24, $SD = 1.91$) than in the production task ($M = 5.10$, $SD = 2.93$), $F(1,57) = 20.49$, $p < .001$, $\eta_p^2 = 0.26$. Table 3 presents children's performance in each postposition (production and comprehension). The majority of children produced the postposition *under* correctly and comprehended the postposition *above* correctly. In comparison, the postpositions *left* and *right* were the least to be produced and comprehended correctly. However, postposition production and postposition comprehension scores positively correlated with each other ($r = .77$, $p < .01$), after controlling for age (see Table 2). We used a composite postposition language score for the following regression analyses (see Supplementary Tables 1 and 2 for separate regression models of production and comprehension scores).

We used hierarchical linear regression analysis to examine the relationship between postposition language abilities and CMTT performance. We took CMTT scores as the outcome variable in the model. In the first step, age was introduced as a continuous variable, and sex was introduced as a dummy variable. The second step included TIFALDI-E, Day-Night, and RMTS scores. In the third step, the postposition score was entered. The final step included the interaction between age and postposition language scores.

The model was significant ($R^2 = .52$, $F(7,50) = 7.61$, $p < .001$) and accounted for 52 % of the variance in CMTT scores. In the first step, age was significantly correlated with mental transformation scores ($\beta = .12$, $p < .001$). In the second step, RMTS ($\beta = .27$, $p = .035$) and TIFALDI-E ($\beta = .06$, $p = .007$) were significant and in the third step, both the RMTS ($\beta = .33$, $p = .010$) and the postposition scores ($\beta = .38$, $p = .024$) were significant variables. In the last step, when we included the interaction of postposition score with age, the RMTS ($\beta = .29$, $p = .019$), the postposition scores ($\beta = .47$, $p = .006$), and the interaction score ($\beta = .03$, $p = .045$) remained significant (see Table 4).

Table 1
Descriptive statistics obtained in each test.

	Mean	SD	Min	Max
RMTS	4.40	1.93	1	8
CMTT	4.21	2.13	0	8
Day-Night	6.33	4.12	0	10
Postposition production	5.10	2.93	0	9
Postposition comprehension	6.24	1.91	2	9
TIFALDI-E	49.59	11.66	17	68

Note: All values indicate raw scores.

Table 2
Correlations between different measures.

	Age	CMTT	RMTS	Day-Night	Postposition production	Postposition comprehension	TIFALDI-E
Age	1						
CMTT	0.460***	1					
RMTS	0.183	0.245	1				
Day-Night	0.303*	0.399**	0.041	1			
Postposition production	0.442***	0.557***	−0.116	0.569***	1		
Postposition comprehension	0.334*	0.518***	−0.117	0.435***	0.765***	1	
TIFALDI-E	0.447***	0.500***	0.023	0.388**	0.711***	0.641***	1

$^*p < .05$, $^{**}p < .01$, $^{***}p < .001$.

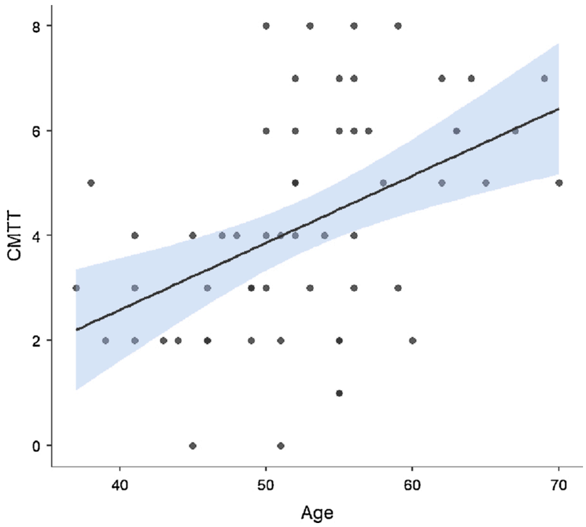

Fig. 3. Scatterplot for the relation between mental transformation scores and age (in months).

4. Discussion

Spatial reasoning is critical for STEM abilities (e.g., Hawes et al., 2019), and spatial language supports spatial thinking (e.g., Miller et al., 2016). Little has been known about the relationship between specific spatial language and particular aspects of spatial reasoning. This study investigated 3- to 5-year-old children's mental transformation skills and how this spatial reasoning ability was related to their knowledge of postpositions. We also examined whether general relational understanding, cognitive inhibition, and general vocabulary played roles in this association, beyond children's age.

Confirming previous findings (e.g., Scott & Sera, 2018; Washington, 1974), we found that children's comprehension of postpositions was better than their production abilities. The majority of children had difficulty understanding and producing the postpositions *right* and *left*, respectively. This is in line with previous studies indicating that *right* and *left* are among the postpositions that children around this age group struggle the most with (e.g., Scott & Sera, 2018). Children's comprehension and production abilities positively correlated with each other and their performance on the CMTT. Children's age was related to their performance on all tasks, except the RMTS. Older children performed better than younger ones on the CMTT, postposition, expressive vocabulary, and cognitive inhibition tasks. The regression analyses demonstrated a relation between children's postposition knowledge beyond age as measured by a composite score of their production and comprehension performance and their CMTT performance. As expected, children's relational understanding and vocabulary knowledge were related to their CMTT performance. Yet, relational understanding, postposition knowledge, and an interaction between age and postposition knowledge remained the only significant variables at the last step, contributing to children's CMTT performance.

Research has shown that mental transformation develops as early as preschool age (Frick, Hansen, & Newcombe, 2013; Krüger, Kaiser, Mahler, Bartels, & Krist, 2014) and undergoes significant changes during development. For example, Levine et al. (1999) reported a significant increase in children's CMTT performance between 4 and 6. Similarly, Hawes, LeFevre, Xu, and Bruce (2015) found positive links between age and CMTT scores in a sample of 4- to 8-year-old children. We indicate that, as in studies testing English-learning children, the Turkish-learning children showed better performance on this task with increasing age. Most studies on CMTT reported sex differences (e.g., Ehrlich, Levine, & Goldin-Meadow, 2006; Levine et al., 1999, 2012; Pruden et al., 2011; but see also Miller et al., 2017, who did not report sex differences on the CMTT task in a Western sample); however, in our Turkish-learning sample, we did not observe sex differences in any of the tasks (see also Newcombe, 2020 for a review).

Table 3
Percentage of children who correctly identified each postposition.

Postposition	% of children
*Postposition Production Task**	
under	82.8
behind	74.1
in	67.2
next to	63.8
in front of	58.6
between	56.9
above	51.7
right	29.3
left	25.9
*Postposition Comprehension Task**	
above	98.3
next to	91.4
behind	89.7
under	86.2
in front of	72.4
between	53.4
in	48.3
left	43.1
right	41.4

*Children were assigned to one of the two conditions for the spatial language task. Both conditions included the production and the comprehension task; however, the order in which the postpositions were asked differed. The same postpositions were used in both conditions. Turkish equivalents of the prepositions (in Turkish postpositions) are in parantheses: under (*altında*), behind (*arkasında*), in (*içinde*), next to (*yanında*), in front of (*önünde*), between (*ortasında*), above (*üzerinde*), right (*sağ*), left (*sol*). under (altın

Table 4
Regression analysis: the CMTT score as the outcome variable.

Step	Variables	Outcome: CMTT ΔR^2	F-change	β	t	p
1		0.220	7.74			
	Age			0.12	3.63	<0.001***
	Sex			0.41	0.77	0.443
2		0.200	5.95			
	Age			0.05	1.29	0.202
	Sex			0.84	1.69	0.096
	Day-Night			0.10	1.60	0.116
	TIFALDI-E			0.06	2.80	0.007**
	RMTS			0.27	2.17	0.035*
3		0.056	5.44			
	Age			0.04	1.13	0.264
	Sex			0.56	1.13	0.262
	Day-Night			0.04	0.55	0.587
	TIFALDI-E			0.02	0.70	0.487
	RMTS			0.33	2.67	0.010*
	Postposition			0.38	2.33	0.024*
4		0.041	4.22			
	Age			0.04	0.98	0.264
	Sex			0.38	0.78	0.442
	Day-Night			0.04	0.58	0.563
	TIFALDI-E			0.01	0.51	0.610
	RMTS			0.29	2.42	0.019*
	Postposition			0.47	2.88	0.006**
	Age*Postposition			0.03	2.05	0.045*

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

Our findings add to studies on preschoolers' spatial reasoning skills and how these relate to their spatial language abilities. Prior research has shown that children's knowledge of specific terms such as *by/next to* (Miller et al., 2016) and *middle* (Simms & Gentner, 2019) was associated with their performance on tasks involving these particular spatial relations. Unlike these studies, we measured children's performance on several postpositions that develop during this age period (see Farran & Atkinson, 2016). Testing both children's production and comprehension of these different terms allowed us to have a more comprehensive spatial language measure. Our findings showed that children's knowledge of different spatial postpositions relates to their performance in the CMTT, a spatial task that does not directly assess these spatial relations. One would argue that postposition production could be a better predictor than postposition comprehension, as producing postpositions may have a facilitative role in verbally encoding the relations between two objects. Our results, however, showed a strong correlation between production and comprehension performances that restricted us from testing its unique effects on CMTT.

Children's production of different spatial terms is related to their performance on several spatial tasks and the CMTT (Pruden et al., 2011) and their composite spatial performance, including the CMTT (Miller et al., 2017). A recent training study (Casasola, Wei, Suh, Donskoy, & Ransom, 2020) even reported a causal link between spatial language and spatial performance, such that being exposed to spatial language led to significant gains in children's mental rotation skills. Although Casasola, Wei, Suh, Donskoy, & Ransom, 2020 intended to test the CMTT, they failed to do so due to validity issues making the causality argument only possible for the rotation task used. Studies using CMTT either included more than one spatial category (e.g., Pruden et al., 2011) or measured children's general spatial skills as reflected by a composite score (e.g., Miller et al., 2017). Some spatial terms might be more relevant to the spatial task at hand (Levine et al., 2012). Unlike these studies, we were interested in the association between a specific spatial skill (i.e., mental transformation) and a specific spatial language category that we hypothesized to be relevant for executing the spatial task (i.e., postpositions).

Our study also differed from previous studies as we assessed possible factors that can contribute to children's CMTT performance. We measured children's vocabulary knowledge, cognitive inhibition, and relational reasoning in addition to the spatial language. Although previous studies showed relations between analogy and transformation skills, we used a different test for analogical reasoning (RMTS), which has been argued to be more appealing for younger age groups and involves relational reasoning (Christie & Gentner, 2014). Relational reasoning covers many different aspects of cognition, including analogical thinking (e.g., Kokinov & French, 2003). We indicated that overall, children did not perform well in this task. However, together with children's spatial language, relational understanding explained the variance in mental transformation performance beyond cognitive inhibition and vocabulary knowledge. This finding suggests a central role for relational reasoning on children's spatial reasoning performance. As reflected by the RMTS in our study, relational performance can present children's understanding of commonalities and associations between stimuli (i.e., the ways in which objects relate to one another). We suggest that mental transformation abilities may require spatial operations along with such general relational representations. That is, to succeed in a transformation task it is likely that children must focus on the relation between each separate part, which reflects a more general relational understanding.

We also observed an interaction between children's age and their spatial language related to their mental transformation performance. With increasing age, children got better in the CMTT, but being competent in the spatial language (i.e., producing and comprehending these terms correctly) was also related to this link. Thus, age and spatial language knowledge's interactive effect moves beyond the linear increase in mental transformation performance by age. Spatial language helps organize and access spatial information faster, even in nonverbal tasks (Scott & Sera, 2018). Therefore, with increasing age, children might get better at using spatial language and other cognitive processes relevant for spatial tasks (e.g., executive functioning, Verdine et al., 2014; selective attention, Miller & Simmering, 2018). This, in turn, might provide opportunities for the development of spatial abilities.

Our findings also contribute to broader spatial development research, testing an under-researched sample and language (see Sümer & Özyürek, 2020). Although some studies investigated spatial cognition in children from other language environments (e.g., Haun et al., 2011; Rüsseler, Scholz, Jordan, & Quaiser-Pohl, 2005; Sümer & Özyürek, 2020), the majority of research on spatial development assessed English-speaking children. This restricts our knowledge of spatial language and spatial reasoning to Western groups. However, previous research suggests language- and culture-related differences in spatial cognition. For example, elementary school speakers of Dutch and Namibian –two languages that differ in how they express spatial relations- show differences in their cognitive strategies to process spatial relations (Haun et al., 2011). We demonstrated similar performance for our spatial task as of English-speaking children (e.g., Levine et al., 1999; Pruden et al., 2011). We investigated spatial reasoning development in Turkish that uses postpositions to deliver information about spatial relations, with flexible word order. Unlike a prepositional system, in Turkish, object names are presented first, followed by locative labels, which may influence children's attention. Prior cross-linguistic research indicated that Turkish-speaking children learn these spatial terms more quickly and at earlier ages than their English-speaking peers (Johnston & Slobin, 1979). Our sample performed well on both postposition tasks, and similar to English-learning children (Scott & Sera, 2018), Turkish-learning children found the postpositions *left* and *right* the most challenging. These findings also suggest earlier reported spatial language-spatial task performance relation in a postpositional language.

The present study has some limitations. First, we did not include other categories of spatial language; thus, the observed relation between postpositions and the mental transformation can be associated with a general spatial language effect. Research has shown that children do not use each spatial category to the same extent. For example, in unguided play activity, Pruden et al. (2011) observed that spatial feature terms (e.g., side) were produced the least, whereas all children used dimension terms (e.g., big). Similarly, Miller and Simmering (2018) found that children mostly provided color and size terms and rarely used location terms in a spatial scene description task. Therefore, children can have different levels of competence in each spatial category. Future studies should investigate whether different spatial terms exhibit similar effects to spatial performance or whether certain spatial terms are more relevant for specific types of spatial abilities. Second, our results showed that relational reasoning, a more general reasoning skill, relates to mental transformation performance. However, we do not know the exact nature of this link. More research investigating the causal mechanisms among relational reasoning, spatial language, and spatial performance is needed.

Third, it is possible that in a postpositional language like Turkish, children would have better performance on CMTT at an earlier age than children learning a prepositional system, due to possible earlier acquisition of spatial terms (Johnston & Slobin, 1979). To uncover the relations between spatial language and mental transformation based on developmental change, we need a cross-sectional study with a larger sample size that includes different age groups. Additionally, this study's spatial language task did not allow us to explore how linguistic characteristics of the Turkish language (i.e., using postpositions to depict spatial relations) influence children's acquisition of these words. With a more precise spatial language task that includes many spatial terms, we can test both the effects of the Turkish language and other spatial terms on mental rotation performance. Moreover, to examine the specific role of learning a prepositional system on the link between spatial language and mental rotation, we should conduct a cross-linguistic study, comparing Turkish-learning children with children learning a prepositional system. Finally, prior studies reported sex differences in spatial task performances (particularly in the CMTT). However, sex differences are less examined on the spatial language domain (see Pruden & Levine, 2017). Future research should investigate sex differences in different spatial language tasks and its relation to spatial task performance (see Newcombe, 2020 for a review).

In conclusion, this study furthered our understanding of the link between spatial language and spatial reasoning, demonstrating that knowledge of postpositions and relational reasoning supports young children's spatial performance, particularly their mental transformation performance. Importantly, our study contributed to research on spatial development by providing evidence from a culturally and linguistically different sample than those typically reported in the literature. This study also presents the association between relational reasoning and preschool-aged children's mental transformation skills and highlights the associations between spatial language and spatial cognition in a different language environment.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cogdev.2020.100980.

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