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A developmental perspective on spatial reasoning: Dissociating object transformation from viewer transformation ability

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Abstract

Studies of adults provide evidence that spatial reasoning is non-unitary in nature, consisting of separate object transformation and viewer transformation abilities. This research examined the presence of this dissociation in children. Participants between 8 and 12 years of age, divided over three age groups (i.e., 65 children from 7.5 to 9 years old, 75 children from 9 to 10.5 years old, and 77 children from 10.5 to 12 years old) performed a battery of object and viewer transformation tasks. Analysis of variance showed that performance improved with age on the individual object and viewer transformation tasks, with the largest effects between 10.5 and 12 years of age. Multi-group confirmatory factor analyses to test the dissociation of object and viewer transformation ability over the different age groups revealed that in children under 10.5 years of age object and viewer transformation ability could not be differentiated. A dissociation between object and viewer transformation ability was shown between 10.5 and 12 years of age. This period of specialization of spatial abilities may be a particularly interesting time window for identifying spatial talents and providing spatial training and intervention.

Introduction

Spatial reasoning is an umbrella term covering many different abilities involving the mental representation and manipulation of spatial information, such as object rotation, mental folding, scaling, perspective taking, and navigating. There has been a long tradition of measuring and classifying these abilities. Several factor analytic studies tried to reveal the basic components of spatial thinking that these tests measure (e.g., Carroll, 1993; Hegarty & Waller, 2004). Unfortunately, these studies have only been performed in adults. The main goal of the current study was to identify the basic components of spatial thinking in elementary school children between 8 and 12 years old.

Enhanced understanding of the different components of spatial reasoning is necessary for different reasons. Theoretically, insight in the factorial structure of spatial reasoning may provide an empirical basis for a comprehensive developmental model, including developmental trajectories and psychological mechanisms contributing to individual differences. Practically, information on the fundamental components of spatial reasoning may support the identification of children with talent for science, technology, engineering, and mathematics (STEM) (e.g., Lubinski, 2010; Webb, Lubinski, & Benbow, 2007) and guide the design of spatial intervention and enrichment programs.

Factor Analytic Studies in Adults

In factor analytic studies the pattern of correlations among observed variables (e.g., scores on different tests) is examined, in an attempt to distil one or more latent factors. A factor represents an underlying ability or strategy, accounting for the variance in performance. Factor analytic studies in adults provided strong evidence that spatial ability is not a single, unitary construct (i.e., one factor), but that it consists of several correlated abilities. Theorists differ on the number and characterization of these factors. Lohman (1979), for example, distinguished three factors: spatial relations, spatial orientation, and visualization. Carroll (1993) differentiated the construct of visual perception into five factors: visualization, spatial relations, closure speed, closure flexibility, and perceptual speed. However, several other studies distinguished only two factors: object transformation ability and viewer (or perspective) transformation ability (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; McGee, 1979). The current study focuses on this well-established distinction between object transformations and viewer transformations.

During *object transformations* one imagines the movement and change of objects, for example when they rotate, change scale by expansion or shrinkage, are cut in half or folded. The observer maintains the same mental position, while the object 'moves or changes' in mind. Object transformations are often measured with mental rotation tasks, requiring participants to imagine the rotation of an object. For instance, in the Revised Vandenberg Mental Rotations Test (Peters et al., 1995), participants view an image of a three-dimensional target figure and four test figures; their task is to determine as quickly as possible which of the test figures are rotations, and not mirror versions, of the target figure. During *viewer transformations* the object does not move, but one imagines oneself (as the observer) moving around the object and taking new perspectives to it. Viewer transformations are usually measured with perspective-taking tasks, often variations of Piaget's Three-Mountain Task (Piaget & Inhelder, 1956). In this task participants view a table-top model of three mountains and a doll sitting at another position at the table; participants are asked to make judgments about how the scene looks to the doll.

Factor-analytic studies showed that object and viewer transformation tasks load on different factors. The study by Hegarty and Waller (2004) for example, comprising various mental rotation and perspective-taking tests, demonstrated that a one-factor model (assuming that the two types of tasks assess the same underlying processes) fitted the data less well compared to a two-factor model (assuming separability of both processes). It is argued that this dissociation reflects a difference in the spatial strategy that is dominantly used for these two types of tasks (e.g., Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001). Additional evidence for the dissociation of these two abilities in adults has been derived from behavioral and brain studies.

Additional Evidence for a Dissociation in Adults

Behavioral studies in adults provide further support for the claim that object and viewer transformations reflect two different abilities. Different speed and accuracy patterns have been observed for object and viewer transformation tasks, suggesting that they rely on different cognitive processes and strategies (e.g., Dalecki et al., 2012; Kozhevnikov et al., 2006; Wraga et al., 2000). For example, in a study investigating learning transfer of object rotations to viewer rotations, and vice versa, an object rotation task and a viewer rotation task were administered in counterbalanced order (Pellizzer, Ba, Zanello, & Merlo, 2009). Participants who first did the viewer rotation task committed, relative to the other group, fewer errors and had shorter response times in the object rotation task,

whereas subjects who first did the object rotation task had little if any advantage on the viewer rotation task. These results suggest that the viewer rotation task required additional cognitive operations compared to the object rotation task. Similar conclusions were obtained by Inagaki and colleagues (2002) and Devlin and Wilson (2010), who demonstrated age related differences in performance on object and viewer transformation tasks. Performance of adults declined more rapidly with age in the viewer rotation tasks than in the object rotation tasks. These differences may point at differences in task complexity: compared to the object rotation tasks, the viewer rotation tasks may have required more effortful cognitive strategies (Devlin & Wilson, 2010).

More evidence for the multi-faceted nature of spatial ability stems from functional magnetic resonance (fMRI) studies, which identified selective patterns of activation for object and viewer transformations: object transformations mainly involve the right temporo-parietal cortices and visuospatial cortical areas, whereas viewer transformations mainly rely on the left temporo-parietal cortices and motor areas (Wraga et al., 2005; Zacks et al., 2003). Thus, evidence from multiple research methods suggests that object and viewer transformation ability reflect two distinct, albeit correlated, abilities in adults.

Object and Viewer Transformations in Children

Research into children's spatial skills showed rapid development through the elementary school years. Children become more accurate and faster on both object and viewer transformation tasks; great individual differences are however observed (e.g., Frick, Hansen, et al., 2013; Frick et al., 2014; Jansen, Schmelter, Quaiser-Pohl, Neuburger, & Heil, 2013; Surtees & Apperly, 2012). Relatively little is known, however, about the dissociation of object and viewer transformation ability in children.

Piaget and Inhelder (1956; 1971) obtained the first evidence for a dissociation between object transformations and viewer transformations in children. Their experimental studies comprising different object rotation tasks (e.g. "draw the rod as it would look when 90° turned") and the Three Mountain Task indicated different developmental trajectories: rotation abilities on single objects emerged by 7 or 8 years of age, whereas viewer rotation abilities on scenes emerged later, by 9 or 10 years of age. Although showing promising results, the studies of Piaget and Inhelder are difficult to interpret in terms of comparing the object and viewer transformations, as these functions were measured with two completely different tasks.

To directly contrast these two types of abilities, Huttenlocher and Presson (1973) investigated mental rotation and perspective taking in children from third and fifth grade with comparable experimental materials. In line with Piaget and Inhelder (1956), they found that for all children the perspective-taking task was more difficult than the mental rotation task. On the object rotation tasks, the children committed as many egocentric errors as would be expected by chance, but on the perspective-taking tasks, the children committed more egocentric errors: they responded as if the appearance of an array would remain unchanged if viewed from a different position. Huttenlocher and Presson concluded that the two tasks required different mental operations, as the object rotation tasks were easier than the viewer rotation tasks and had a different pattern of errors. Similar results were obtained by Crescentini, Fabbro, and Urgesi (2014). They administered a letter transformation task (object transformation) and an "own body" transformation task (viewer transformation) to 7- to 11-year-olds. Performance on the two tasks followed different developmental trajectories: viewer transformations started to improve later than object transformations, namely from 8 to 9 years of age, instead of from 7 years of age.

In summary, in line with the evidence for a dissociation of spatial reasoning abilities in adults, studies in children provide initial evidence for the separability of object and viewer transformations: they may rely on different mental operations and have different developmental patterns. However, the evidence of a distinction between object and viewer transformation ability in children is not yet conclusive.

The Current Study

The main aim of the current study was to examine, taking a factor-analytic approach, whether the dissociation of object transformation ability and viewer transformation ability is evident in children between 8 and 12 years old. This time window might render the observation of developmental milestones in spatial reasoning, since this period is characterized by a remarkable development of both types of spatial ability and its (possible) underlying processes, such as working memory and executive functions (e.g., Best, Miller, & Jones, 2009; Davidson, Amso, Anderson, & Diamond, 2006; Epley, Morewedge, et al., 2004; Kaufman, 2007; Miyake et al., 2001; Qureshi et al., 2010). The decision to limit the youngest age group to eight-year-olds was based on the consideration that the present task battery was probably too difficult for children younger than this age (e.g., Hoyek et al., 2012).

To date, different assessment methods to investigate object transformation ability in children are available. Unfortunately, assessment methods to investigate viewer

transformation ability are scarce (Newcombe & Shipley, 2012). Therefore, we first developed and validated two viewer transformation tasks, requiring a transformation of perspective to a collection of objects. Based on findings that perspective taking involves a hypothesized rotation of the own body (e.g., Kessler & Thomson, 2010), which is probably best elicited by three-dimensional experimental layouts with real objects (Kozhevnikov et al., 2006), we developed tasks with explicit mental position changes with respect to a layout of tangible objects. The *Eye Spy task* required children to construct a layout of objects from a 180° rotated perspective. In the *City Walk task* children had to walk routes through a layout of blocks from 180° and 90° rotated perspectives.

In addition, we administered three well-known and validated object transformation tasks: the Revised Vandenberg & Kuse Mental Rotations Test (Peters et al., 1995), the Paper Folding Test (Ekstrom et al., 1976), and the WISC-III Block Design subtest (Wechsler, 2003). Using multi-group confirmatory factor analyses, we investigated whether object transformation ability could be distinguished from viewer transformation ability in different age groups (i.e., 8-year-olds, 9-10-year olds, and 11-year-olds). More specifically, we first fitted a two-factor model for each age group (i.e., assuming separability at all ages). Subsequently, we fixed per age group the correlation between the two factors (i.e. assuming that all tasks load on one spatial reasoning factor) in order to examine the age at which a possible dissociation would emerge. Based on developmental studies showing that viewer transformation ability emerges at a later point in development than object transformation ability (i.e., between age 8 and 9 vs. at age 7), requiring additional and (or) more effortful cognitive strategies (Crescentini et al., 2014; Huttenlocher & Presson, 1973; Piaget & Inhelder, 1956), it was hypothesized that a second latent factor, reflecting the accomplishment of this new ability, would emerge in children around ten years of age.

Methods

Participants

The sample consisted of 217 children (112 girls) between 8 and 12 years old (*M* age = 9.88 years, *SD* = 1.09). We divided the children in three age groups of about equal size and age range: (1) *8-year-olds* (*n* = 65 [37 girls], *M* age = 8.60 years, *SD* = 0.30, range = 7.75-9.00); (2) *9-10-year-olds* (*n* = 75 [34 girls], *M* = 9.71, *SD* = 0.36, range = 9.08-10.50); and (3) *11-year-olds* (*n* = 77 [41 girls], *M* = 11.13, *SD* = 0.37, range = 10.58-11.92).

The sex distribution did not differ across age groups, $\chi^2(2) = 2.00$, $p = .37$. The children were recruited from seven regular elementary schools in the Netherlands. Parents gave written informed consent. All participants had normal or corrected-to-normal vision. The children received no compensation for their participation. The Ethical Committee of the Faculty of Behavioral and Movement Sciences of Vrije Universiteit Amsterdam approved the research protocol.

Materials

Object transformation tasks. We administered the following three existing object transformation tasks:

Revised Vandenberg & Kuse Mental Rotations Test (Peters et al., 1995). The child received a booklet with 24 problems with cube figures. Each problem consisted of a target object on the left and four objects on the right. The participant was required to determine which two (out of four) stimuli were rotations of the target figure. When providing instructions, we used a physical example item to show that all figures of a problem had the same constellation of cubes, but were rotated around the vertical axis. There were two sections with twelve problems each, with a time limit of four minutes per section. One point was given if the child identified *both* correct answers, with a maximum score of 24. The variable of interest was the total number of correct answers.

Paper Folding test (Ekstrom et al., 1976). The Paper Folding Test (PFT) required the participant to predict from two, three or four pictures how a square piece of paper would look after it had been folded, a hole has been punched in it, and it has been unfolded again. We used a model item for the instructions. The test consisted of ten problems, with a time limit of three minutes. The child got one point for each correct answer, with a maximum of 10. The variable of interest was the total amount of correct answers.
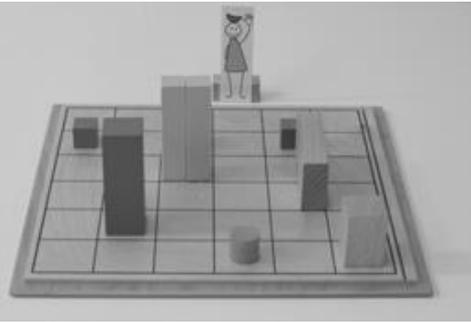
WISC Block Design test (Wechsler, 2003). The test consisted of small cubes (some sides all red, some all white, and some half-red and half-white on the diagonal). The child had to turn and put together the sides of the cubes, such that the top surfaces of the blocks matched the pattern in the picture. The test consists of twelve patterns with increasing difficulty. Testing was terminated when the child failed two items in a row. We followed the standard scoring procedure of the WISC (Wechsler, 2003). That is, for item 1 to 3 no bonus points are awarded. For item 4 to 12, one to three bonus points are awarded for fast reactions, on top of the four points given for correctly completing a pattern within time. The variable of interest was the total amount of points with a maximum score of 69.

Viewer transformation tasks. We developed two viewer transformation tasks; one requiring the rebuilding of a layout after a change of perspective, the other requiring the navigation of a route through a layout after a change of perspective.

I Spy With My Little Eye. Participants were required to build layouts with small wooden figures in different colors (e.g., animals, buildings). These layouts were depicted on example cards (see Figure 2.1). The 0° condition (four item pairs) required the children to build the layout on the pictures from their own perspective (no spatial transformation required); the 180° condition (four item pairs) required building the same layouts from the perspective of the experimenter who sat across the child (i.e., a 180° mental rotation was required). The instruction and example item consisted of two figures, standing next to each other. The number of figures increased from three on the first item pair to six on the fourth item pair. In these items, figures were not only positioned next to each other, but also in front or behind each other (see Figure 2.1). In the 180° condition, children were not allowed to rotate the instruction cards, as this would show them the view of the scene from the other perspective. They were encouraged to pretend sitting on the chair of the researcher and to complete the item through his/her eyes. Maximum solution time per item was 120 s. Total duration of the test was between five and ten minutes. We recorded accuracy (correct/incorrect) and response time. Adapted from the WISC Block Design scoring procedure (Wechsler, 2003), the total score was a composite of accuracy (item correct within time, 1 point) and speed (1, 2, or 3 bonus points for fast responses), with a maximum score of 4 per item. The bonus points for speed were computed afterwards and based on quartile scores. These quartiles were calculated for each item pair, for the total group of children. The 4th quartile represented the 25% slowest times and delivered no bonus point, the 3rd quartile one bonus point, the 2nd quartile two bonus points, and the 1st quartile with the 25% fastest times delivered three bonus points. The maximum score per condition was 32. The variable of interest was the percentage of acquired points of this maximum score in the 180° condition.
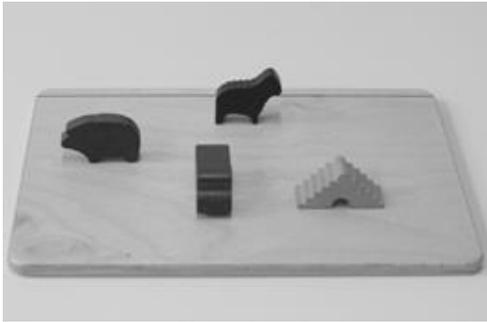
Figure 2.1. The Eye Spy task.   Figure 2.2 The City Walk task.

City Walk. This task consisted of twelve items requiring the child to "walk" routes with a token, through a layout of wooden blocks ("the city") by using a map with gridlines (see Figure 2.2). The route had a start and a finish, both located on the map. The child was required to begin at "start" and to step section by section to the finish. The task was comprised of three conditions, each consisting of two item pairs. In the first item pair the city consisted of six buildings and the child had to take twelve steps to reach the finish, in the second item pair there were twelve buildings and twenty steps to take. The 0° condition required children to walk the route from their own perspective, the two rotated conditions required a 180° and 90° rotation of their own perspective. In the rotated conditions, children were told that the person who drew the map had made a mistake: he drew the city upside down (180°) or rotated a quarter turn (90°). The array of blocks and the map stayed in the same position during testing, which means that the children had to mentally rotate their position half a turn or a quarter turn (see Figure 2.3). For each trial there was a demonstration and a practice trial. Maximum solution time per item was 180 s; total test duration was about fifteen minutes. Similar to the Eye Spy task, scoring reflected a composite of accuracy (route completely correct within time, 1 point) and speed (1, 2 or 3 bonus points for fast responses, based on quartile scores). The maximum score per condition was 16. The variable of interest was the percentage acquired points in the 180° and 90° condition.
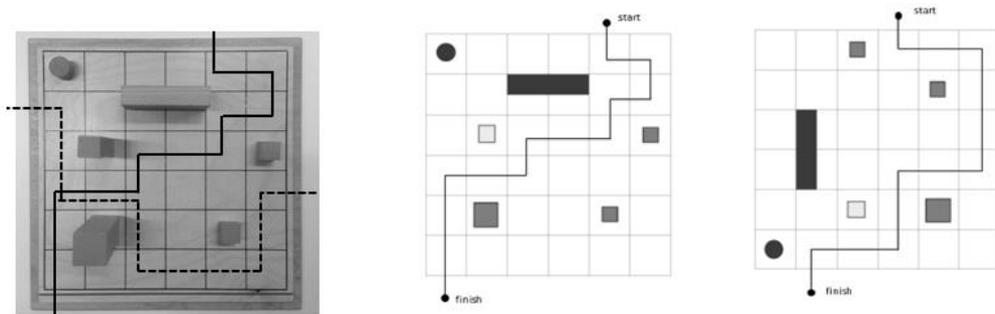
Figure 2.3. Example of two items of the City Walk task. The figure in the middle is a route from the 0° condition: in this case the map corresponds to the array of blocks (left figure) and no mental position change is required. The right figure is from the 90° condition: the map has been rotated 90° with regard to the array of blocks, requiring a mental position change. The correct routes are depicted in the left figure, with a black line for the 0° condition and a dashed line for the 90° condition.

Procedure

Testing consisted of three sessions. The administration of the tasks was standardized, and all children received the same instructions and uniform testing conditions. The first session was a group session and took about 45 minutes. Each child sat at their own desk in the classroom and worked alone. After a short oral introduction about the background and procedure of the study, the children completed the Mental Rotation Test (Peters et al., 1995) and Paper Folding Test (Ekstrom et al., 1976). During the same week, the children received two individual sessions, taking place on two different days. These sessions took place in a quiet room in the school. In the first session (10 minutes), the WISC Block Design (Wechsler, 2003) was administered. In the second session (30 minutes), the children were administered the two viewer transformation tasks, presented in random order. Children were instructed to work as fast and accurately as possible.

Data Analytic Strategy

We performed the analyses in two steps[1]. The first step included preliminary analyses to investigate performance on the individual object and viewer transformation tasks. We performed a Multivariate Analysis of Variance (MANOVA) to examine differences between the three age groups (i.e., 8-year-olds, 9-10-year-olds, and 11-year-

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[1] Validity and reliability analyses of the two new object transformation tasks are included in Appendix A.

olds) on the object transformation tasks. Since the viewer transformation tasks consisted of multiple conditions, we performed a repeated measures ANOVA on the scores of each task, with condition as within-subjects factor and age group as between-subjects factor. In addition, we computed correlations between the tasks for each age group.

The second step included the main analysis. That is, we performed confirmatory factor analyses to assess changes in the factor structure of spatial reasoning ability with age. The main question was at what age the distinction between object and viewer transformation ability started to emerge. We fitted a multi-group model (three age groups: 8-year-olds, 9-10-year-olds, 11-year-olds) with two latent factors: an object transformation factor (MRT, PFT, WISC Block Design) and a viewer transformation factor (Eye Spy 180°, City Walk 180° and 90°), see Figure 2.4. We tested four different nested models:

- *Model 1*, in which the factor correlation was freely estimated in all three age groups (i.e., a two-factor model in all age groups).
- *Model 2*, in which the factor correlation was set at one in the 8-year-olds and freely estimated in the 9-10-year-olds and 11-year-olds (i.e., a one-factor model for the 8-year-olds, and a two-factor model in the 9-10-year-olds and the 11-year-olds).
- *Model 3*, in which the factor correlation was set at one for the 8-year-olds and 9-10-year-olds and freely estimated in the 11-year-olds (i.e., a one-factor model in the 8-year-olds and 9-10-year-olds, and a two-factor model in the 11-year-olds).
- *Model 4*, in which for all three age groups the factor correlation was set at one (i.e., at all ages there is no distinction between the two factors, all tasks load on one factor).

First, to assess the absolute goodness-of-fit of each separate model, we considered fit indices from multiple fit categories (Brown, 2006). The χ^2/df ratio, the Root Mean Square Error of Approximation (RMSEA) and the Comparative Fit Index (CFI) were used as indicators of the goodness-of-fit. A χ^2/df ratio lower than 2.0 represents acceptable fit (Tabacknick & Fidell, 2007). For the RMSEA, values lower than .08 are indicative of reasonable fit and values lower than .05 indicate good fit (Kline, 2005). CFI values greater than .90 indicate reasonable fit, and values greater than .95 indicate good fit (Kline, 2005).

Second, to select the model with the best fit to the data (i.e., relative goodness-of-fit), we compared the models with chi-square (χ^2) difference tests. If the χ^2 difference was

significant, the null hypothesis of equal fit for both models was rejected, and the more complex model (i.e., the model with less df) was preferred. If the χ^2 difference was not significant, there was no difference in model fit, and the more parsimonious model (i.e., the model with more df) was preferred (Schermelleh-Engel, Moosbrugger, & Müller, 2003).
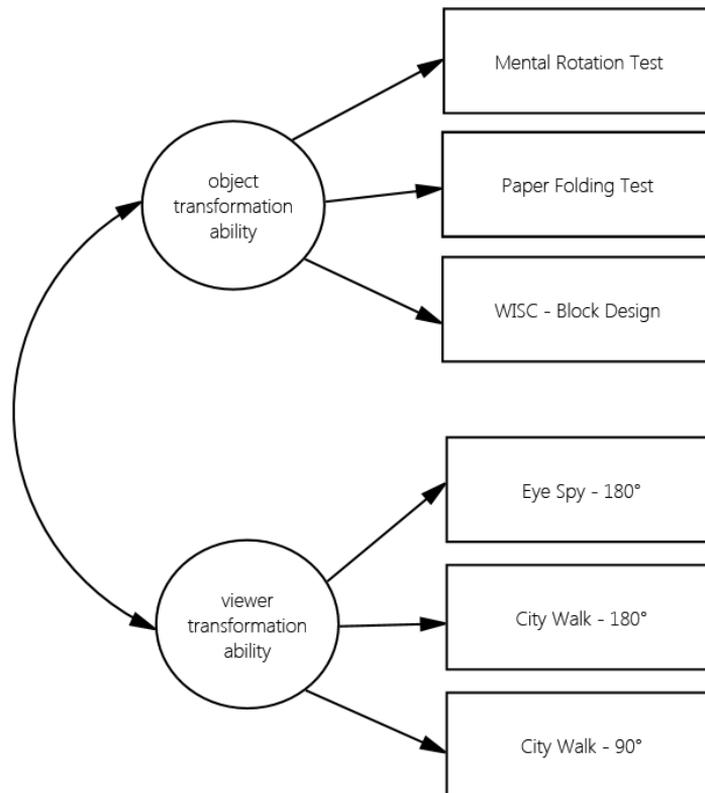
Figure 2.4. Two-factor model of spatial reasoning: distinction between object and viewer transformation ability. The circles represent the two spatial functions (latent variables); the rectangles represent the individual tasks that were administered to assess these specific functions, as indicated by the straight, single-headed arrows. The curved double-headed arrow represents the correlation among the latent variables.

Results

Preliminary Analyses on Individual Tasks

As a first step, we performed analyses of variance to examine differences between the three age groups on the spatial reasoning tasks (Table 2.1). Additional analyses on the separate accuracy and speed scores of the viewer transformation tasks can be found in Appendix 2B.

Age differences on object transformation tasks. A MANOVA with age (three levels) as between-subjects factor indicated a multivariate effect of age: $F(6, 424) = 6.98$, $p < .001$, $\eta_p^2 = .09$ (medium effect), showing that performance on the object transformation tasks increased with age. On the Mental Rotation Test, $F(2, 217) = 10.69$, $p < .001$, $\eta_p^2 = .09$ (medium effect), post hoc Bonferroni tests showed that the 9-10-year-olds outperformed the 8-year-olds ($p = .003$). There were no differences between the 9-10-year-olds and 11-year-olds ($p = .79$). On the Paper Folding Test, $F(2, 217) = 11.87$, $p < .001$, $\eta_p^2 = .10$ (medium effect), there were no differences between the 8-year-olds and 9-10-year-olds ($p = .27$), but the 11-year-olds outperformed the 9-10-year-olds ($p = .005$). Also on the WISC Block-Design test, $F(2, 217) = 11.50$, $p < .001$, $\eta_p^2 = .10$ (medium effect), there were no differences between the 8-year-olds and the 9-10-year-olds ($p = .80$), and the 11-year-olds had higher scores than the 9-10-year-olds ($p = .001$).

Age differences on viewer transformation tasks. For the Eye Spy task, the repeated measures ANOVA showed large main effects of condition (two levels: 0° and 180°), $F(1, 214) = 640.79$, $p < .001$, $\eta_p^2 = .75$, and age, $F(2, 214) = 20.65$, $p < .001$, $\eta_p^2 = .16$. Children scored higher in the 0° condition than in the 180° condition. Overall, children's performance increased with age. Post hoc Bonferroni tests revealed no difference between the 8-year-olds and 9-10-year-olds ($p = 1.00$). The 11-year-olds outperformed the 9-10-year-olds ($p < .001$). The interaction effect of condition and age failed to reach significance: $F(2, 214) = 2.04$, $p = .13$.

For the City Walk task, the repeated measures ANOVA showed large main effects of condition (three levels: 0°, 180° and 90°), $F(2, 428) = 153.13$, $p < .001$, $\eta_p^2 = .42$, and age, $F(2, 214) = 22.82$, $p < .001$, $\eta_p^2 = .18$. Post-hoc tests revealed that children had the highest scores in the 0° condition, and performed better in the 180° condition than in the 90° condition (all ps < .001). Overall, there were no differences between the 8-year-olds and 9-10-year-olds ($p = .14$), but the 11-year-olds outperformed the 9-10-year-olds ($p < .001$). The interaction effect of condition and age failed to reach significance: $F(4, 428) = 0.99$, $p = .42$.

In summary, performance on both the object and viewer transformation tasks increased with age, and the largest effects were observed between 10.5 and 12 years of age. Except for the Mental Rotation Test, no developmental differences were observed between the 8-year-olds and 9-10-year-olds. On the viewer transformation tasks, we observed better performance in the unrotated conditions compared to the rotated conditions.

Table 2.1. Descriptive Statistics of Scores on the Object and Viewer Transformation Tasks Including Maximum Possible Score (Max), Range, and Observed Mean Scores (Standard Deviations Between Brackets), Separately for the Three Age Groups

	max	range	8-yo. (*n*=65)	9-10-yo. (*n*=75)	11-yo. (*n*=77)
MRT	24	0-22	5.45 (3.50)	8.05 (4.93)	8.88 (4.94)
PFT	10	0-9	2.75 (1.58)	3.25 (1.65)	4.14 (1.92)
Block Design	67	12-64	34.82 (9.18)	36.77 (10.89)	42.75 (10.89)
Eye Spy 0°	100	6.25-100	52.08 (23.60)	51.23 (22.71)	67.90 (24.04)
Eye Spy 180°	100	0-75	4.23 (9.05)	7.04 (13.91)	14.57 (19.45)
City Walk 0°	100	0-100	46.63 (24.00)	50.83 (24.75)	72.89 (22.78)
City Walk 180°	100	0-100	20.10 (25.11)	28.25 (29.96)	44.07 (36.88)
City Walk 90°	100	0-100	9.62 (22.59)	19.42 (30.05)	31.41 (34.55)

Correlations between object and viewer transformation tasks. We computed Pearson-correlations within and between the object and viewer transformation tasks, separately for each age group (Table 2.2). Within the object transformation tasks, there were weak to moderate correlations in the youngest age group (*r*s between .17 and .41), but clearly stronger correlations in the oldest age groups (*r*s between .45 and .56). The same held for the viewer transformation tasks (8-year-olds: *r*s between .15 and .28; 11-year-olds: *r*s between .26 and .55). Relations between object and viewer transformation tasks varied at all ages, ranging from slightly negative to strongly positive (*r*s between -.13 to .60). However the vast majority of correlations between object and viewer transformation tasks were weak or moderate (only two correlations were strong), suggesting that the two types of tests measured unique abilities, sometimes sharing common processes.

Confirmatory Factor Analysis

We investigated the effect of age on the factorial structure of spatial reasoning via confirmatory factor analysis. We fitted a multi-group (8-yo., 9-10-yo., 11-yo.) model with two latent factors: object transformation ability (MRT, PFT, Block Design), and viewer transformation ability (Eye Spy 180° and City Walk 180° and 90°). For both the object and viewer transformation tasks, we used the percentages of acquired points of the maximum score as the indicator variables (i.e., all variables ranged from 0 to 100).

Table 2.2. Correlations Between Tasks, Separately for the Three Age Groups (8-yo./9-10-yo./11-yo.)

	1	2	3	4	5	6
1. MRT (OT)	-					
2. PFT (OT)	.17/.27/.50	-				
3. BD (OT)	.41/.63/.45	.24/.33/.56	-			
4. ES 180 (VT)	.30/.19/.25	-.13/.04/.06	.30/.30/.16	-		
5. CW 180 (VT)	.23/.44/.40	.32/.36/.39	.39/.60/.46	.15/.28/.31	-	
6. CW 90 (VT)	.24/.31/.50	.01/-.04/.32	.23/.36/.39	.25/.34/.26	.28/.34/.55	-

Note. OT = Object Transformation, VT = Viewer Transformation. Correlations in bold are significant at a $p < .05$ level. Effect sizes: $r < .30$ = small, r between .30 and .50 = moderate, $r > .50$ = large.

The fit indices of the different models are presented in Table 2.3. Looking at the absolute fit, all four models provided an acceptable fit to the data (i.e., $\chi^2/df < 2$, CFI > .90 and RMSEA < .08). Comparison of the models with χ^2 difference tests revealed that Model 2 (i.e., constraining the factor correlation to 1 for the 8-yo.) was preferred over Model 1 (i.e., all factor correlations free). Adding this constraint made the model more parsimonious, but did not result in a decrease of model fit. Model 3 (i.e., factor correlation constrained to 1 for the 8-yo. and 9-10-yo.) was preferred over Model 2 (i.e., more parsimonious, no decrease in model fit). However, Model 4 (i.e., factor correlation constrained to 1 in all age groups) led to a significant decrease in model fit compared to Model 3: $\Delta\chi^2$ (1) = 8.08, $p = .004$. Thus, Model 3 provided the best fit to the data. This indicates that there was no distinction between object and viewer transformation ability in the 8-year-olds and 9-10-year-olds, while in the 11-year-olds object and viewer transformation ability could be distinguished. The two latent factors were however strongly related to each other: $r = .75$. The standardized factor loadings for the different age groups are presented in Table 2.4.

In summary, the results from the confirmatory factor analyses showed an increasing distinction between object and viewer transformation ability with age. In children until 10.5 years of age, these two abilities could not be differentiated from each other. From 10.5 years of age, object and viewer transformation ability developed into two distinct, albeit highly correlated, spatial abilities.

Table 2.3. Results of the Multi-Group Confirmatory Factor Analyses: Absolute Goodness-of-Fit and χ^2 Difference Test for Comparison with Previous Model

Model		χ^2	df	χ^2/df	p	CFI	RMSEA	$\Delta\chi^2$	Δdf	p
1	All rs free	35.22	24	1.47	.07	.955	.047	-	-	-
2	r_8 =1	35.57	25	1.42	.08	.957	.044	0.35	1	.55
3	$r_8=r_{9\text{-}10}$=1	36.86	26	1.42	.08	.956	.044	1.29	1	.26
4	$r_8=r_{910}=r_{11}$=1	44.94	27	1.66	.02	.927	.056	8.08	1	.004

Table 2.4. Standardized Factor Loadings for Model 3, Separately for the Different Age Groups (N = 217)

		8-yo. (n = 65)	9-10-yo. (n = 75)	11-yo. (n = 77)
Object Transformation	MRT	.56	.71	.65
	PFT	.31	.39	.61
	Block Design	.71	.87	.69
Viewer Transformation	Eye Spy – 180°	.39	.32	.32
	City Walk – 180°	.55	.67	.67
	City Walk – 90°	.39	.41	.67

Discussion

Factor-analytic studies in adults showed that object transformation tasks (e.g., mental rotation and mental folding tasks) and viewer transformation tasks (e.g., perspective-taking tasks) load on two distinct factors. It is argued that this dissociation of factors reflects the use of different spatial strategies for the two types of abilities. More specifically, in object transformation tasks one imagines the movement and transformation of an object, while maintaining the same mental position. In viewer

transformation tasks, however, one imagines the movement of the self around a stationary object. The main goal of the current study was to examine this distinction of object and viewer transformation ability in 8- to 12-year-old children. The results of the confirmatory factor analysis showed a clear effect of age on the factor structure of spatial reasoning. In children under 10.5 years of age, object and viewer transformation ability could not be dissociated. In children between 10.5 and 12 years of age, the two-factor model (i.e., comprising an object and a viewer transformation factor) provided a better fit compared to the one-factor model (i.e., no dissociation).

The results of the factor analysis suggest that children under 10.5 years of age did not employ different strategies for the object and viewer transformation tasks, while children above 10.5 years of age employed distinct spatial strategies for the object and viewer transformation tasks. We propose that the emergence of a second latent factor reflects children's emerging ability to make efficient and stable "self-rotations" when confronted with viewer transformation tasks. In line with previous studies showing difficulties with perspective taking in children up to ten years of age (Coie, Costanzo, & Farnill, 1973; Frick et al., 2014; Piaget & Inhelder, 1956; Rigal, 1996) and viewer transformation ability emerging later in development (i.e., between eight and nine years of age) than object transformation ability (i.e, from seven years of age) (Crescentini et al., 2014), we observed relatively poor performance on the viewer transformation tasks in the youngest age groups. Even on the simple items of these tasks, about fifty per cent of the children did not succeed.

From about 10 years of age, performance on the viewer transformation tasks improved significantly, suggesting that the children were getting grip on an efficient perspective-taking strategy. Studies with adults showed that successful perspective taking is accomplished by a mental self-rotation strategy. When employing this strategy, one mentally rotates the own body to the position of the target perspective (i.e., "mentally putting oneself in the shoes of the other") in order to encode the location and orientation of objects (Kessler & Thomson, 2010; Michelon & Zacks, 2006; Surtees, Apperly, & Samson, 2013b). This strategy is cognitively effortful, since it requires a continuous switching between the actual and imagined perspective (Epley, Keysar, Van Boven, & Gilovich, 2004), putting strong demands on the ability to hold and act on information. It is suggested that children's initial difficulties with this strategy are related to still developing inhibitory and working memory functions (Lin, Keysar, & Epley, 2010; Surtees & Apperly, 2012) and that the rapid development of these cognitive processes in middle childhood (Anderson, 2002; Best et al., 2009; Gathercole, Pickering, Ambridge, & Wearing, 2004),

may foster children's perspective-taking performance. The specific contribution of cognitive processes to children's spatial transformation abilities would be a noteworthy topic for further inspection in future research.

It might be argued that we did not adequately measure viewer transformation ability, as both the Eye Spy task and the City Walk task can be solved by 'simply' using object transformation strategies (i.e., moving the object, but not the self). For example, the Eye Spy task is explicitly introduced to the children as a viewer transformation task ('Imagine sitting on my chair and looking through my eyes, what would the scene look like?'), but children may have completed this task by mentally rotating the single objects one by one from their own mental 'position' (i.e., employing object rotation). Although we did not investigate children's solution strategies explicitly, we included several attributes to the viewer transformation tasks to reassure that the majority of children would consider the viewer transformation strategy. First, we used rotation angles of 90° and more, to elicit mental position changes and to discourage visual matching strategies (Janczyk, 2013; Kessler & Thomson, 2010; Kozhevnikov & Hegarty, 2001). Second, to stimulate perspective changes, we developed a task with a navigation component. Navigating the route required children to compute the left-right and front-back directions, which is most effective when the own body is used a reference point. In addition, we used objects that represented large objects that typically remain stationary in the environment (i.e., buildings, trees), since these are more likely to elicit viewer transformations compared to small objects that are typically manipulated manually, such as the blocks in the Mental Rotation and Block Design test (Zacks & Michelon, 2005).

Another point of discussion concerns the factor-analytic research strategy. In this study, we investigated whether children use the same computations and strategies across different measures. This method involves a top-down factor analytic approach. However, most spatial tasks require several spatial and non- spatial abilities (e.g., encoding, manipulating, and comparing spatial forms, decomposing the task, applying rules and maintaining representations in memory). The extraction of only 'basic' spatial ability (such as object or viewer transformation ability) without measuring individual differences in some of the other abilities is therefore impossible (e.g., Carroll, 1993; Hegarty & Waller, 2004). Future work might profit from a bottom-up approach, as advocated by Hegarty (2010). According to this approach, not children's test scores, but their strategies should be the starting point of the study. These strategies can be uncovered by using thinking-aloud or eye-tracking methods. Identifying and classifying the different spatial strategies children use when solving spatial tasks might be beneficial to the identification of a child's

developmental stage of spatial reasoning (see e.g., C. Quaiser-Pohl, Rohe, & Amberger, 2010).

In conclusion, the current study showed a clear developmental pattern in the factor structure of spatial reasoning, demonstrating that between ten and eleven years of age object transformation ability starts to differentiate from viewer transformation ability. These findings have important implications, as they provide further empirical support for a comprehensive developmental model on spatial reasoning, including separate developmental trajectories for object and viewer transformation ability. Since this developmental pattern seems to show parallels with the development of cognitive control functions such as working memory, inhibition and cognitive flexibility, it would be of great interest to investigate in future work the relative contribution of these functions to spatial development in children (see also Crescentini et al., 2014; Zacks & Michelon, 2005). A more practical implication of our findings concerns the identification and training of spatial potential in children. Children's spatial ability level is considered an important predictor for later success and achievement in the field of STEM (e.g., Lubinski, 2010; Wai et al., 2009). In our modern society, depending heavily on science and technology, attention for the spatial talents of children is of vital importance. Our study demonstrates that it is important to include both spatial components in diagnostics and training. Especially the period of middle childhood may be a critical time window for spatial education and intervention. Between 8 and 12 years of age, spatial processes are actively developing and specializing, suggesting that they are malleable and susceptible to environmental influences during this interval (see also Zelazo & Carlson, 2012).

Acknowledgements

Appendix A

Factorial Validity and Reliability of Viewer Transformation Tasks

Factorial validity. To validate the underlying factors of the viewer transformation tasks, we performed confirmatory factor analyses on the Composite scores (see Table A2.1). We compared model-fit with a χ^2-difference test. For the Eye Spy task, the two-factor model (0° rotated vs. 180° rotated, eight items each) fitted the data significantly better compared to the one-factor model in which all sixteen items loaded on one factor ($\Delta\chi^2$ (5) = 567.93, p < .001). The two-factor model fitted the data well (χ^2/df < 2, CFI > .90, RMSEA < .08). For the City Walk task, we compared three models: a one-factor model in which all twelve items loaded on one latent factor, a two-factor model with a non-rotation factor (i.e., a 0° factor, indexed by the four corresponding items) and a rotation factor (indexed by the four 180° items and the four 90° items), and a three-factor model with a 0° factor, a 180° factor and 90° factor (each indexed by the four corresponding items). The three-factor model fitted the data best (3-factor model vs 2-factor model: $\Delta\chi^2$ (2) = 245.48, p < .001). The three-factor model delivered a good fit to the data: χ^2/df < 2, CFI > .95, RMSEA < .08.

Reliability. After establishing the internal factor structure per task, we computed Cronbach's alphas for the resulting subscales. All values were satisfactory with Cronbach's alphas ranging between .81 and .88 (see Appendix B). None of the scale items had a corrected item-total correlation lower than .20, indicating that they were measuring the same and elimination of items was not necessary.

Table A2.1. Model Fit Indices of The Confirmatory Factor Analyses on Single Task Level (N = 217)

	χ^2	df	χ^2/df	RMSEA	CFI	AIC
Eye Spy						
1-factor model	756.89	104	7.28	.17	.519	820.89
2-factor model (0° vs 180°)	188.96	99	1.91	.07	.934	262.96
City Walk						
1-factor model	558.52	54	10.34	.21	.621	606.52
2-factor model (0° vs 180/90°)	324.24	53	6.06	.15	.799	371.24
3-factor model (0° vs 180° vs 90°)	78.76	51	1.54	.05	.979	132.76

Appendix B

Descriptive Statistics per Age Group (Mean Accuracy and Speed in s, % of Children Scoring 0) in the Different Conditions of the Viewer Transformation Tasks, Including the Results of the ANOVAs and Cronbach's Alpha for each Subscale

		max	range	8-yo. (*n*=65)	9-10-yo. (*n*=75)	11-yo. (*n*=77)	$F_{(2,217)}$	Post-hoc	α
Eye Spy									
0°	Accuracy	8	1-8	6.66 (1.50)	7.01 (1.22)	7.70 (0.93)	13.41*	8 = 9-10, 11 > 9-10	.88
	Speed	120	5.38-39.88	13.57 (5.50)	14.11 (5.02)	11.72 (4.09)	4.98*	8 = 9-10, 9-10 > 11	
	% scoring 0			1.5	1.3	1.3			
180°	Accuracy	8	0-7	0.62 (1.31)	0.97 (1.62)	1.84 (2.22)	9.14*	8 = 9-10, 11 > 9-10	.81
	Speed	120	5-72.75	18.11 (7.27)	18.52 (8.95)	20.23 (11.03)	1.07	8 = 9-10 = 11	
	% scoring 0	100		70.8	60.0	48.1			
City Walk									
0°	Accuracy	4	0-4	3.51 (1.11)	3.52 (0.99)	3.69 (0.73)	0.84	8 = 9-10 = 11	.82
	Speed	180	6.5-46.5	21.82 (6.83)	20.04 (6.10)	14.68 (4.65)	29.18*	8 = 9-10, 9,10 > 11	
	% scoring 0			7.7	2.7	2.6			
180°	Accuracy	4	0-4	1.40 (1.40)	1.51 (1.46)	2.13 (1.62)	5.09*	8 = 9-10, 11 > 9-10	.85
	Speed	180	2-180	74.41 (38.66)	59.85 (31.15)	57.06 (36.63)	4.73*	8 > 9,10, 9,10 = 11	
	% scoring 0	100		36.9	36.0	24.7			
90°	Accuracy	4	0-4	0.64 (1.22)	1.00 (1.37)	1.57 (1.54)	8.08*	8 = 9,10, 9,10 > 11	.88
	Speed	180	12.5-180	77.05 (44.25)	60.10 (33.05)	60.64 (35.24)	4.51*	8 > 9,10, 9,10 = 11	
	% scoring 0	100		70.8	52.0	37.7			