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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.

1. 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 and 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. Prac-

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tically, 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.

1.1. 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 and 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 and 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 and Waller, 2004; Kozhevnikov & Hegarty, 2001). Additional evidence for the dissociation of these two abilities in adults has been derived from behavioral and brain studies.

1.2. 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, Hoffmann, & Bock, 2012; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; Wraga, Creem, & Proffitt, 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 et al. (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 and Wilson, 2010).

More evidence for the multi-faceted nature of spatial ability stems from functional magnetic resonance (*f*MRI) 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, Shephard, Church, Inati, & Kosslyn, 2005; Zacks, Vettel, & Michelon, 2003). Thus, evidence from multiple research methods suggests that object and viewer transformation ability reflect two distinct, albeit correlated, abilities in adults.

1.3. 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, & Newcombe, 2013; Frick, Mohring, & Newcombe, 2014; Jansen, Schmelter, Quaiser-Pohl, Neuburger,