Development and Training of Spatial Ability in Children

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1 General introduction

Why Studying Spatial Ability in Children?

Although children's spatial skills may not receive as much attention from teachers and parents as do children's accomplishments in language and mathematics, they are important for their everyday functioning and thinking (Vasilyeva & Lourenco, 2012). Spatial competence is basic to many of children's daily activities such as finding their way to school, playing games, doing sports, and performing academic tasks. Importantly, spatial ability provides a critical foundation for the development of scientific and mathematical thinking (e.g., Newcombe, Levine, & Mix, 2015). Children's spatial ability level has been shown to be a unique predictor of later success and achievement in the domain of science, technology, engineering, and mathematics (STEM) (Kell, Lubinski, Benbow, & Steiger, 2013; Shea, Lubinski, & Benbow, 2001). Our modern society strongly depends on STEM, thereby emphasizing the need for the identification and nurturing of spatial talent in children (Lubinski, 2010; Wai, Lubinski, & Benbow, 2009). This thesis contributes to this need by 1) uncovering the developmental trajectories of different types of spatial ability, 2) investigating psychological (e.g., working memory) and environmental factors (e.g., spatial activities at home) that contribute to individual differences in these trajectories, and 3) examining to what extent spatial skills are malleable. This thesis concentrates on children between eight and twelve years of age. The developmental literature to date has mainly focused on the origins of spatial ability in infancy and early childhood, but a detailed account of the development and malleability of the more complex spatial skills at older ages is still lacking. In this thesis we combine a developmental psychological perspective with a pedagogical perspective. We do not only investigate the fundamental cognitive information processes underlying spatial abilities, but also the social context in which these processes occur. We assume that pedagogical and educational experiences (i.e., with parents, teachers, peers, materials) serve as an important mechanism for spatial development. We carried out correlational and experimental studies, that all took place in the natural setting of the school. Together, the studies in this thesis comprise a comprehensive view on the development and training of spatial skills in children between eight and twelve years of age and the mechanisms underlying individual variability.

Different Types of Spatial Ability

Spatial ability is a universal aspect of human intelligence and is clearly separable from other cognitive processes, such as verbal and quantitative reasoning (Carroll, 1993; Gardner, 1993; McGee, 1979; Newcombe & Huttenlocher, 2003). Spatial ability is an umbrella term for a collection of different abilities involving the mental representation and transformation of objects. More specifically, it concerns the ability to imagine change or movement in the properties (e.g., size, shape, orientation, location) of objects, for example when they rotate, change scale by expansion or shrinkage, are cut in half or folded, or seen from a different perspective. A large variety of spatial tasks has been developed to measure ability in these different types of transformations (e.g., Newcombe & Shipley, 2012; Newcombe, Uttal, & Sauter, 2010).

By classifying the cognitive processes that are involved in these different spatial tasks, factor-analytic studies generally distinguished two main types of spatial ability, each characterized by a dominant transformation strategy (e.g., Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Zacks & Michelon, 2005). The first type concerns the so-called *object transformation ability*, the ability to imagine the movement and change of one or more objects, while staying in a stationary mental position (i.e., the object moves in mind). Object transformation ability is measured with for instance mental rotation tasks, requiring participants to imagine the rotation of an object (Figure 1.1) and paper folding tasks (Figure 1.2), requiring participants to imagine how a piece of paper will look after it has been folded and a hole has been punched in it.

The second type of spatial ability concerns *viewer transformation ability*, the ability to imagine oneself (as the observer) moving around an object or scene of objects and taking new perspectives to it. Viewer transformations are also known as 'egocentric transformations' or 'perspective transformations', because these transformations involve an imagined rotation of the egocentric perspective (i.e., the self). In adults, a frequently used task to examine viewer transformation ability is the laterality judgment task (or the 'own body transformation task'), in which participants are presented with images of bodies with one extended or colored limb. These images are rotated through various angular disparities and participants are required to make speeded laterality judgments about the extended or colored limb (e.g., 'is it the left or right arm?') (Figure 1.3). In children, viewer transformation ability is typically measured with perspective-taking tasks, often variations of Piaget's Three-Mountain Task (Piaget & Inhelder, 1956; Piaget & Inhelder, 1971) (Figure 1.4).

Behavioral and fMRI studies provide additional evidence for the dissociation between object- and viewer transformation ability. Behavioral studies in adults observed different speed and accuracy patterns for object and viewer transformation tasks (e.g., Dalecki, Hoffmann, & Bock, 2012; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; Wraga, Creem, & Proffitt, 2000). In children, distinct developmental trajectories were observed for object and viewer transformations. Rudimental skills required for performance on object transformation tasks were acquired around seven years of age. Skills required for viewer transformation tasks were acquired after the age of eight (Crescentini, Fabbro, & Urgesi, 2014). Functional magnetic resonance imaging (*f*MRI) studies identified specific patterns of brain activation for object and viewer transformations in adults. Object transformations mainly involved the right temporo-parietal cortices and visuospatial cortical areas, whereas viewer transformations mainly relied on the left temporo-parietal cortices and motor areas (Wraga, Shephard, Church, Inati, & Kosslyn, 2005; Zacks, Vettel, & Michelon, 2003).

Together, these studies provide strong evidence that object and viewer transformations are two different abilities in adults. Recently, evidence for this dissociation in children between seven and eleven years of age was reported (Crescentini et al., 2014). To date, however, no studies have specifically tested the hypothesis that the dissociation between object and viewer transformations is also present in children, and at what age this possible dissociation emerges.

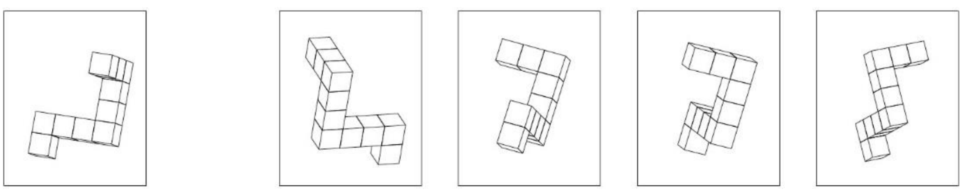

Figure 1.1. Revised Vandenberg Mental Rotations Test (Peters et al., 1995). This task requires the participants to determine as quickly as possible which two out of the four test figures on the right are rotations, and not mirror versions, of the target figure on the left.

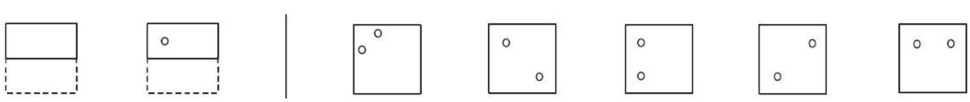

Figure 1.2. Paper Folding Test (Ekstrom, French, Harman, & Dermen, 1976). This task requires participants to choose out of the five pictures on the right, how a square piece of paper will look unfolded, after it has been folded and a hole has been punched in it (as shown on the two pictures on the left).

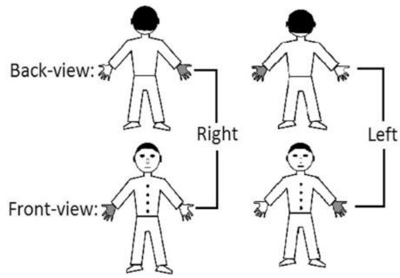

Figure 1.3. Own Body Transformation Task (Crescentini et al., 2014). This task requires participants to judge which of the manikin's hands was marked gray.

Figure 1.4. Three-Mountain task (Piaget & Inhelder, 1956, 1971). This task requires participants to 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, for example by selecting the photo that represents the rotated view.

Development of Spatial Ability

Spatial ability is a complex and effortful cognitive ability that develops uniquely in individuals. Children's levels of spatial performance increase with age. Studies with simplified versions of mental rotation and perspective-taking tasks (e.g., looking time and reaching paradigms) showed that young infants, toddlers and preschoolers already have some basic levels of spatial thinking available (e.g., Frick & Mohring, 2013; Moore & Johnson, 2008; Sodian, Thoermer, & Metz, 2007). However, on more complex spatial asks, children of about four years of age were found to confuse mirror-image pictures with rotated pictures in object transformation tasks (Frick, Ferrara, & Newcombe, 2013; Frick, Hansen, & Newcombe, 2013), and to choose the egocentric instead of the rotated answer option in viewer transformation tasks (Frick, Mohring, & Newcombe, 2014). During the elementary school years spatial processing becomes more efficient: children show more accurate and faster performance on both object and viewer transformation tasks (e.g., Frick et al., 2014; Hoyek, Collet, Fargier, & Guillot, 2012). Nevertheless, at the end of elementary school children still perform at a slower speed than adolescents and adults (e.g., Epley, Morewedge, & Keysar, 2004; Kail, Pellegrino, & Carter, 1980; Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990; Surtees & Apperly, 2012).

These improvements with age in accuracy and speed of spatial performance possibly relate to developmental progress in underlying cognitive processes. Spatial ability comprises several sub-processes, such as *generating a mental representation* of the object or group of objects, *maintaining the representation* in working memory in order to use it for reasoning or problem solving, *scanning the representation* that is maintained in working memory in order to focus attention on some of its parts or properties, and *transforming the representation*, for example by rotating, shrinking or folding it (Heil & Rolke, 2002; Kosslyn et al., 1990). This analysis clearly shows that mental imagery, the capacity to generate mental images (i.e., "seeing with the mind's eye") is one of the important processes underlying spatial ability (Estes, 1998). In addition, spatial ability relates to basic cognitive processes, such as attention, working memory and inhibition (e.g., Kaufman, 2007; Lehmann, Quaiser-Pohl, & Jansen, 2014; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Qureshi, Apperly, & Samson, 2010; Wang & Carr, 2014) and to more general reasoning and problem-solving capacities, such as task decomposition and rule-based learning (Hegarty, 2010). These underlying cognitive processes strongly develop from early childhood through adolescence (e.g., Huizinga, Dolan, & van der Molen, 2006; Wimmer, Maras, Robinson, Doherty, & Pugeault, 2015), enabling more efficient and more complex spatial processing.

Individual Differences in Spatial Ability

Generally, older children perform better at spatial tasks compared to younger children. Large differences are however observed among children of the same age (e.g., Frick et al., 2014). Biopsychosocial theories of development argue that these developmental differences are not predefined at birth. Instead, they evolve from complex interactions between biological factors (e.g., individual variations at the biological-neural level, such as genetic, hormonal, and neurological influences), psychological factors (e.g., differences in cognitive capacities) and social factors (e.g., the input children experience at home and at school) (Bronfenbrenner & Morris, 2006; Halpern, 2013; Levine, Foley, Lourenco, Ehrlich, & Ratliff, 2016; Newcombe & Huttenlocher, 2003). The value of a biopsychosocial approach to individual differences has been clearly demonstrated for the development of young children's language and mathematics skills (e.g., LeFevre et al., 2009; Sénéchal, 2006). For spatial ability however, the additive effects of variations in environmental input, above differences at the biological and psychological level, are not systematically studied in children. The age period between eight and twelve years is an important time window for this kind of analyses. During this age period rapid development takes place in underlying cognitive processes, such as working memory and inhibition (Huizinga et al., 2006). At the same time, this age period is characterized by strong environmental influences on cognitive development. Children are exposed to formal schooling and education for many hours a week and spend a lot of their free time in informal learning activities with their parents, siblings and friends.

The biopsychosocial approach is also useful to explain sex differences in spatial ability. Sex differences are an important topic in research on spatial ability, given the importance of spatial ability for success in the fields of STEM and girls' underrepresentation in these domains. The general finding is that men outperform women on some spatial tasks, and particularly on mental rotation tasks (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995). Sex differences in mental rotation ability emerge during the course of childhood, and are clearly manifest in children around ten years of age (Hoyek et al., 2012; Johnson & Meade, 1987; Neuburger, Jansen, Heil, & Quaiser-Pohl, 2011; Titze, Jansen, & Heil, 2010a). Explanations for these sex differences are found at different levels. They range from biological explanations, such as differences in testosterone levels (e.g., Courvoisier et al., 2013), and psychological explanations, such as sex differences in working memory capacity and strategy use (Janssen & Geiser, 2010; Kaufman, 2007; Tzuriel & Egozi, 2010; Wang & Carr, 2014), to social-environmental explanations, such as boys' more frequent participation in spatial activities like building and constructing (e.g., Baenninger & Newcombe, 1995; Jirout & Newcombe, 2015). Identifying the factors that are critically involved in the emergence of sex differences may inform intervention programs aimed at nurturing spatial talent in both boys and girls.

Stereotypic beliefs (i.e., the common belief that 'spatial is for men') may be one of the important factors to explain sex differences in children's spatial ability. Research with adults demonstrated effects of stereotypic gender beliefs on spatial performance (e.g., Heil, Jansen, Quaiser-Pohl, & Neuburger, 2012; Moè, 2009; Moè & Pazzaglia, 2006). These studies experimentally manipulated participants' beliefs about sex differences in spatial ability, by instructing the participants that either men are better than women on spatial tasks, women are better than men, or that there are no sex differences. Positive effects on spatial test performance were found for both men and women when the own sex was instructed to be superior. Similar effects may be expected in late childhood. Children at this age have developed awareness of stereotypes (McKown & Weinstein, 2003) and make important steps in the development of self-concepts of ability (Berk, 2013). However, the literature is inconclusive whether children of this age (already) endorse stereotypic beliefs on sex differences in spatial ability. There is some evidence that the common stereotype 'spatial is for men' is present at an explicit (i.e., conscious) level in ten-year-old boys and girls (Ruthsatz, Neuburger, & Quaiser-Pohl, 2012). Studies on implicit (i.e., unconscious) gender beliefs have not yet been performed in this age group. In addition, studies investigating the effects of gender beliefs on spatial performance showed inconsistent findings in ten-year-old children. One study found no effects at all (Titze, Jansen, & Heil, 2010b), the other observed improvement in girls and deterioration in boys in the 'girls better' and gender-neutral condition (Neuburger, Jansen, Heil, & Quaiser-Pohl, 2012).

Malleability of Spatial Skills

Given the prominent role of spatial ability for achievement in the STEM domain, it would be of great importance to nurture spatial talent in children. Many individuals assume that their spatial capacities are innate and immutable (i.e., "I am bad at navigating, thanks to my mother's genes"). However, there is a growing body of evidence demonstrating the malleability of spatial skills by training and practice. Correlational studies showed positive associations between children's participation in spatial activities, such as playing with blocks and puzzles, and their spatial skills. Children who participated more frequently in spatial play activities at home performed better on spatial tasks (e.g., Jirout & Newcombe, 2015; Nazareth, Herrera, & Pruden, 2013; Robert & Héroux, 2004). In addition, intervention studies demonstrated positive effects of spatial training on spatial performance. The meta-analysis of Uttal and colleagues (2013) on more than 200 intervention studies in adults and children demonstrated that training can have durable and transferable effects on spatial skills. Most previous attempts to improve children's spatial skills were focused on practicing object transformation ability. The effectiveness of a large variety of training programs practicing these transformation skills, from playing Tetris computer games, to juggling, block building, and origami lessons, has been demonstrated (De Lisi & Wolford, 2002; Jansen, Titze, & Heil, 2011; Taylor & Hutton, 2013). To date, no studies have tested the trainability of viewer transformation skills in elementary school children. Only a small number of training studies with adolescents (David, 2012) and adults (e.g., Pazzaglia & De Beni, 2006; Piburn et al., 2005) demonstrated the malleability of this type of ability.

In order to foster the possibilities for nurturing spatial talent in specific groups of children, more evidence is needed with regard to child factors that relate to training progress. That is, children with different initial levels of spatial ability and/or experience may respond differently to the same training. In this respect, the sex of the child is a frequently examined factor. It may be expected that girls improve more from additional input than boys because girls are less often engaged in spatial activities in their free time (e.g., Jirout & Newcombe, 2015). However, the meta-analysis of Uttal and colleagues (2013) demonstrated that overall no differences between the sexes in training response are observed (see also Baenninger & Newcombe, 1989). Other factors, such as the socioeconomic background of the child, may also mediate the effects of training, as children from families with low income and low education often have less access to spatial resources such as toys, puzzles and games compared to children living in high SES environments (e.g., Bradley & Corwyn, 2002; Brooks-Gunn & Markman, 2005; Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005). It may be hypothesized that providing children with additional spatial input at schools may diminish the sex and SES differences in spatial experience, and improve spatial performance.

Thesis Aims and Outline

The main aim of this thesis is to improve our understanding of individual differences in spatial development, and the malleability of these differences, in children between eight and twelve years of age. The developmental literature to date has mainly focused on the early origins of spatial ability in infancy and early childhood, but a detailed account of the development and malleability of the more complex spatial skills later in childhood is still lacking. A focus on the time window between eight and twelve years will render more insight in possible developmental milestones in spatial ability and the mechanisms underlying individual variability (Crescentini et al., 2014).

This thesis comprises five chapters. The data described in these chapters were collected in three different studies, all performed at elementary schools (Grades 3 through 6). The first two chapters of this thesis focus on the developmental trajectories of different types of spatial ability. The aim of these chapters is to show that spatial ability is not fully acquired until twelve years of age, and that large individual variability exists in children’s performance and in the way they approach spatial problems.

Chapter 2 tests the hypothesis that the dissociation between object and viewer transformation ability - which is strongly established in adults - is also present in the spatial reasoning of children between eight and twelve years old. Using a confirmatory factor analysis, we examined whether children's performance on different object and viewer transformation tasks could be best represented by one factor (i.e., no dissociation) or by two factors (object transformation ability can be distinguished from viewer transformation ability). We investigated these one- and two-factor models at different ages in order to observe at what age a possible dissociation would emerge.

Chapter 3 investigates developmental changes and strategy use in viewer transformation ability (i.e., spatial perspective taking) in children between eight and twelve years old. Spatial perspective taking is the ability to mentally represent and understand how objects in space appear to another person. We examined this ability with a task requiring children to navigate a route through a scene of wooden blocks, from 90° and 180° rotated perspectives. We compared children's accuracy and speed of performance across age groups and rotation angles, and classified the types of errors they committed. We tested two hypotheses: 1) children's perspective taking improves between eight and twelve years of age, and this improvement is specifically related to increases in working memory; 2) children use, like adults, a mental self-rotation strategy during spatial perspective taking.

The next three chapters of this thesis focus on explanations for individual differences in spatial ability and the malleability of these differences. In these three chapters, we adopt a biopsychosocial approach, assuming that differences in spatial ability within and between the sexes are not fixed and immutable, but the result of interactions between factors at different levels (i.e., biological, psychological, social).

Chapter 4 examines the relations between different types of spatial play activities and spatial ability, while controlling for differences in age, SES, and general cognitive abilities. The focus in this chapter is on mental rotation, the only spatial ability showing consistent sex differences, with men outperforming women. We tested hypotheses that 1) boys participate more frequently in certain types of spatial play compared to girls; 2) the relation between spatial play and mental rotation is stronger for boys than for girls; especially for play involving construction activities.

Chapter 5 also focuses on individual differences in children's spatial ability, but now we investigated the role of stereotypic gender beliefs (i.e., the belief that spatial is for boys). First, we tested the hypothesis that stereotypic gender beliefs on spatial ability are already present in ten- and twelve-year-old children. We used both an explicit measure (i.e., a self-report questionnaire) and an implicit measure (i.e., an IAT computer task). Second, we experimentally manipulated children's beliefs about sex differences in spatial ability by instructing the children that either boys are better in spatial tasks than girls, girls are better, or there are no sex differences. We hypothesized that positive instructions about the ability of the own sex would have positive effects on children's mental rotation and paper folding performance, as was observed in studies with adults.

Chapter 6 reports an intervention study, which aimed to strengthen the argument that spatial input affects (and not only relates to) spatial skills. Employing a pretest-posttest control group design, we tested the hypothesis that a classroom intervention with spatial toys (i.e., blocks, puzzles, board games) has positive effects on children's object and viewer transformation skills. Differences in training effectiveness between boys and girls and children from different socio-economic backgrounds were examined, as previous research indicated significant differences between these groups in spatial experience at home.

Finally, in Chapter 7, the Summary and Concluding Remarks section, the findings of the different studies are integrated and discussed in light of current theories on spatial ability. The thesis will be concluded with implications for research and educational practice.