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Development and Training of Spatial Ability in Children

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Summary and concluding remarks

Summary of Findings

Rationale and Objectives

Children's spatial skills are fundamental to later success and achievement in the domain of science, technology, engineering and mathematics (STEM). Children and adolescents with better spatial skills in middle and high school are more likely to major in the STEM disciplines in college and to pursue STEM careers later in life (Shea et al., 2001; Wai et al., 2009). The great importance of STEM for the future of our complex technological society emphasizes the need for effectively identifying and nurturing spatial talent in children (Lubinski, 2010; Wai et al., 2009). The present thesis contributes to this need by 1) uncovering the developmental trajectories of different types of spatial ability in children between eight and twelve years old, 2) investigating psychological and social-environmental factors that contribute to individual differences in these trajectories, and 3) examining to what extent differences in spatial ability are malleable.

In this thesis, spatial ability was considered an umbrella term covering a collection of different abilities involving the mental representation and transformation of objects, such as rotation, folding, scaling, perspective taking, and navigating. These abilities were measured in different studies and by a variety of spatial tasks. In total, data were collected from about six hundred children between eight and twelve years of age, their teachers and parents. At this point in development, children have acquired basic skills in spatial thinking and are learning to make more complex and abstract spatial transformations (e.g., Crescentini et al., 2014). The goal of this thesis was to provide a comprehensive view on the development of spatial ability during this age period, the possibilities for training, and the mechanisms underlying individual variability of spatial ability. This thesis combined a developmental psychological perspective with a pedagogical-educational perspective. We investigated both information-processing and social-environmental mechanisms of learning. This final chapter presents a summary of the findings, followed by some concluding remarks on the contributions of this thesis to theory and educational practice.

Developmental Trajectories of Spatial Ability

The first goal of this thesis was to uncover the developmental trajectories of spatial ability in children between eight and twelve years of age. These trajectories were investigated in Chapter 2 by administering a variety of spatial tasks. Specifically, we

administered three existing object transformation tasks (i.e., the Mental Rotation Test, the Paper Folding Test, and the WISC Block Design test) and we developed two viewer transformation tasks (i.e., a navigation task and a scene rebuilding task, both with a perspective-taking component). In line with the developmental literature (Crescentini et al., 2014), the results showed that the rudimentary types of object transformation ability were present in children around eight years of age. The majority of the eight-year-old children performed above chance level on the mental rotation and paper folding test and were able to perform the simple items of the block design test. On the viewer transformation tasks, however, more than half of the eight-year-olds did not succeed on the simple items. They showed significant difficulties with accurately reconstructing the viewpoint of another person. Children's spatial ability continued to develop in the years thereafter. On both the object and viewer transformation tasks clear increases in children's accuracy and speed of performance were observed. For mental rotation, the largest increases were observed between eight and ten years of age, whereas for the paper folding, block design and viewer transformation tasks the largest increases were observed in children from ten years of age.

A central question is if different types of ability, characterized by separate strategies and developmental trajectories, can be observed in children's performance on spatial tasks. Factor analytic studies in adults showed that spatial ability can be differentiated into object and viewer transformation ability, each with its own dominant underlying strategy (i.e., rotating the object in mind vs. rotating oneself around the object) (e.g., Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Zacks & Michelon, 2005). Studies in children demonstrated that viewer transformation ability emerges at a later point in development (i.e., from eight years of age) than object transformation ability (i.e., from seven years of age) (Crescentini et al., 2014). In Chapter 2, we tested the hypothesis that the adult two-factor structure is also present in children between eight and twelve years of age. A sample of 217 children performed a battery of object and viewer transformation tasks. In children under ten years of age, no indications for a differentiation between object and viewer transformation ability were found. All spatial tasks loaded on one latent factor, suggesting that the same processes and strategies underlay performance on the object and viewer transformation tasks. However, from ten years onward, children's spatial performance was best represented by two latent factors, indicating that the children employed different processes and strategies for the object and viewer transformation tasks. Based on previous studies showing that viewer transformation ability emerges at a later point in development than object transformation

ability (Crescentini et al., 2014), and requires additional and (or) more effortful cognitive strategies (Huttenlocher & Presson, 1973), it was proposed that the second factor reflected the accomplishment of a separate viewer transformation strategy in children around ten years of age.

While much research focused on the underlying strategies of object transformation ability in children, the literature is inconclusive on the underlying strategies in viewer transformation tasks. Adults were found to use a mental self-rotation strategy. That is, they mentally rotate their viewpoint, in order to align the own reference frame with the reference frame of the other (i.e., 'they put themselves in the shoes of the other') (Kessler & Thomson, 2010; Kozhevnikov & Hegarty, 2001; Michelon & Zacks, 2006). In Chapter 3, we examined if children, like adults, employ a mental self-rotation strategy when confronted with viewer transformation tasks. A sample of 245 children between eight and twelve years of age performed a task requiring them to navigate a route through a model city of wooden blocks, from 90° and 180° rotated perspectives. As hypothesized, older children were more accurate and faster on this spatial perspective-taking task than younger children. Above the effects of age, performance differences between children were related to differences in working memory capacity. To confirm the mental self-rotation hypothesis, better performance was expected in the 90° than in the 180° condition of the task. Larger rotation angles require larger distances to 'travel' from the own mental position to the target position, which takes more time and is more error prone (e.g., Kessler & Thomson, 2010; Michelon & Zacks, 2006; Surtees et al., 2013b). Interestingly, the results showed the reversed pattern. Children under ten years of age were less accurate, slower and committed more egocentric errors in the 90° than in the 180° condition. These findings support an alternative scenario in which children between eight and twelve years of age employ different strategies for different rotation angles. We propose that the children employed a mental self-rotation strategy for small rotations (i.e., 90°), but did not succeed in employing this strategy for larger rotations (i.e., 180°). In the 180° condition children may have employed an object transformation strategy. That is, they may have computed the route by rotating the city or the route, without rotating their mental position.

Together, these developmental patterns demonstrate that spatial ability is strongly 'under construction' in children between eight and twelve years of age. Children improve their accuracy and speed of performance with advancing age, and employ and practice new strategies, especially in viewer transformation tasks.

Individual Differences in Spatial Ability

The second goal of this thesis was to investigate psychological and social-environmental factors contributing to individual differences in the development of spatial ability. In our sample, large individual differences in children's spatial performance were observed, even among children of the same age and sex. Figure 7.1 depicts for 427 children, participating in different studies of this thesis, the distribution of scores on the Revised Vandenberg & Kuse Mental Rotations Test (Peters et al., 1995), separately for boys and girls. This mental rotation test is a widely used spatial ability test, requiring participants to mentally rotate and compare figures of cubes (see Figure 1.1). At the group level of analysis, boys had better performance on the mental rotation test compared to girls. Nevertheless, many individual girls performed better than many individual boys. Similar reasoning holds for the distribution across age groups. As a group, older children were better at mental rotation than younger children, but there was large overlap between the scores of the different age groups. There were eight-year-olds being particularly advanced, and twelve-year-olds being particularly delayed.

In Chapter 4 and 5, we investigated sources of these individual differences in spatial ability. These two chapters primarily focused on performance differences on the Revised Vandenberg & Kuse Mental Rotations Test (Peters et al., 1995). A growing body of evidence shows that boys outperform girls on this test, especially from ten years of age (Hoyek et al., 2012; Johnson & Meade, 1987; Neuburger et al., 2011; Titze et al., 2010a; Voyer et al., 1995).

Chapter 4 was grounded in current biopsychosocial theories of development, emphasizing that developmental outcomes result from interactions between biological, psychological and environmental factors. More specifically, in this study we tested the hypothesis that spatial play relates to individual differences in mental rotation performance, above differences in age, socioeconomic status, abstract reasoning and working memory. Importantly, we distinguished between different types of spatial play: construction activities, drawing/crafting activities, and outdoor activities. In a sample of 236 children between eight and twelve years old, boys showed better mental rotation performance than girls. Boys were more frequently engaged in spatial construction and outdoor activities at home, while girls were more frequently engaged in drawing/crafting activities. Results of the hierarchical regression analyses showed that after controlling for age, SES and general cognitive abilities, the quantity of spatial play related to mental rotation in the group of boys, but not in the group of girls. Relations between spatial play

and mental rotation were only found for construction and drawing/crafting activities. This study demonstrated the importance of considering (combinations of) factors at different levels when explaining differences in spatial ability between the sexes.

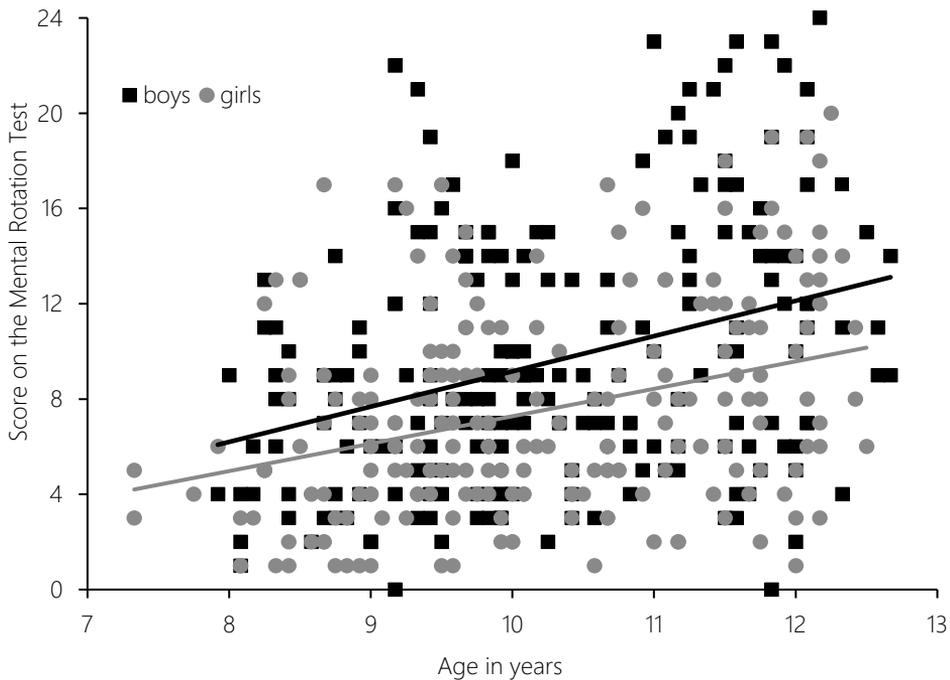


Figure 7.1. Distribution of the mental rotation scores of the boys ($n = 207$, $M = 9.60$, $SD = 5.45$) and the girls ($n = 220$, $M = 7.48$, $SD = 4.37$), participating in different studies of this thesis. The figure demonstrates that boys on average have higher scores than girls, but it also shows large overlap in the scores of both sexes.

Chapter 5 concerns a study investigating the presence of stereotypic beliefs on sex differences in spatial ability (i.e., the belief that ‘spatial is for boys’) and its relations to spatial performance in 237 ten- and twelve-year-old children. In the first part of this study we investigated children’s stereotypic gender beliefs with both an explicit (i.e., direct, conscious) and an implicit (i.e., indirect, unconscious) measure. The explicit measure involved a self-report questionnaire, requiring children to answer for twenty different spatial activities whether they considered the activities more boyish or more girlish. The implicit measure involved a computer task (i.e., a child version of the Implicit Association

Test, IAT) requiring children to categorize, as quickly as possible, words from two different categories (i.e., sex [boy/girl] and school subject [spatial/language]) in stereotype congruent (e.g., boy-spatial) and stereotype incongruent (e.g., girl-spatial) sorting conditions. The results showed that ten- and twelve-year-old children already had stereotyped beliefs about boys' and girls' appropriateness for and capabilities in the spatial domain. Boys had, both at the explicit and at the implicit level, stereotypic beliefs regarding spatial abilities (i.e., boys are superior to girls). Girls agreed with this stereotype at the explicit level, although they were less male stereotyped than boys. At the implicit level, however, they were gender-neutral (i.e., no sex is superior). These findings suggest that girls of this age are aware of the common belief that men are better in the spatial domain than women, but, interestingly, they do not personally endorse this belief yet.

In the second part of this study, we tested the hypothesis that stereotypical gender beliefs affect children's spatial performance. We manipulated children's stereotypic gender beliefs about spatial ability and examined the short-term effects of these manipulations on children's spatial test performance (i.e., mental rotation and paper folding), while controlling for children's pre-existing stereotypic beliefs. That is, an experimental study with a pretest – instruction – posttest design was performed. Between pretest and posttest children were instructed that either boys were better in the given spatial tasks, girls were better, or there were no sex differences. Based on studies in adults (Heil et al., 2012; Moè, 2009; Moè & Pazzaglia, 2006), we expected that inducing positive beliefs about the spatial capacities of the own sex would improve spatial performance. We found no differences between the three experimental conditions in progress between the pretest and posttest, suggesting that spatial ability in ten- and twelve-year-olds is not directly malleable by sex stereotypic instruction.

Together, these two chapters showed individual differences in the spatial domain, not only in children's spatial test performance, but also in their engagement in spatial activities at home and in their stereotypic gender beliefs. An important question in these studies was whether individual differences in spatial test performance were associated with certain characteristics of the child and the environment. The results showed that explanations for individual differences in spatial ability can be found at different levels, from biological factors like sex and age, to psychological factors like abstract reasoning and working memory, and social-environmental factors like the amount of spatial input at home. The factors at these different levels interact with each other. For example, the relations between spatial play and spatial ability are different for children with different background characteristics (i.e., sex, age, cognitive capacities, family socioeconomic

status). Information on these underlying mechanisms of spatial development is essential for the design of effective intervention programs.

Malleability of Spatial Skills

The third and final goal of this thesis was to examine the malleability of spatial skills. This is an highly relevant topic, as it informs us on the possibilities to nurture spatial talent in children.

Chapter 6 tested the hypothesis that spatial input positively *affects* (and not only relates to, see Chapter 4) spatial performance. In this study we provided a short and easy-to-adopt classroom intervention with a diverse set of spatial play materials to 8- to 10-year-old children. The set of play materials consisted of tangible spatial toys, typically found in the home context, such as blocks, marble runs, board games and puzzles. We compared pretest-posttest progress between the intervention group ($n=70$) and a control group ($n=72$) on two object transformation tasks (mental rotation, paper folding) and a viewer transformation task (i.e., spatial perspective taking). There were no differences between the intervention and control group in progress on the two object transformation tasks. Larger improvements were found for the intervention group compared to the control group on the viewer transformation task. Given previous findings that, in general, boys are more frequently involved in spatial play experiences at home compared to girls (e.g., Baenninger & Newcombe, 1995; Nazareth et al., 2013; Robert & Héroux, 2004), and children from high socioeconomic status groups receive more spatial input at home compared to children from low socioeconomic status groups (e.g., Bradley & Corwyn, 2002; Levine et al., 2005), we investigated whether training progress was related to sex and socioeconomic background of the child. We did not find such interactions, suggesting that, on average, these groups improved equally after training.

This chapter provides some tentative support for the hypothesis that spatial skills, and especially viewer transformation skills, are malleable by spatial input and practice in children around ten years of age. It remains to be established whether short-term spatial interventions are powerful enough to overcome sex and SES differences resulting from many years of differential spatial experiences.

Concluding Remarks

The current thesis focused on the development and malleability of spatial ability in children between eight and twelve years old. The five chapters of this thesis made novel contributions to important issues in the field, with implications for future research and (educational) practice.

Insights in the Development and Malleability of Spatial Ability

This thesis provides several empirically supported insights for a developmental account on spatial ability in children. Whereas the majority of previous studies on spatial ability focused on the early development of spatial ability in children up to age eight, this thesis examined the development of more complex and abstract spatial skills in children between eight and twelve years of age. This thesis demonstrates rapid development in spatial ability during this age period. That is, by the age of eight most children have some rudimentary ability in performing object transformations (i.e., rotating, folding, and piecing objects together into more complex configurations), but still have difficulties with viewer transformations (i.e., accurately reconstructing a scene of objects from a rotated perspective). From ten years of age, children become more accurate and faster on both object and viewer transformation tasks, and importantly, they continue to acquire new and more complex spatial strategies.

This thesis shows that children under ten years of age employ one dominant spatial strategy: the object transformation strategy. This strategy refers to the ability to mentally rotate and transform (scenes of) objects from a stationary viewpoint. Interestingly, in children above ten years of age, two spatial transformation strategies are present: the object transformation strategy and the viewer transformation strategy (Chapter 2). The viewer transformation strategy involves the ability to mentally move oneself around (scenes of) objects, that is, to mentally take the perspective of another person (i.e., the object does not move, but the perspective of the person moves). This is a cognitive demanding strategy, as it requires the child to ignore and suppress the own perspective while representing and transforming the other person's perspective. This conflict between perspectives places strong demands on the developing working memory and inhibition systems. This is illustrated by the findings of Chapter 3, showing that children were able to employ this strategy for small rotation angles (i.e., 90 degrees). For 180 degrees rotations, however, in which the distance between the own and target perspective is larger and the rotation process cognitively more demanding, the majority of children reverted to an object transformation strategy. The period around ten years of

age can therefore be considered a period of significant transition in spatial ability, in which children are experimenting and practicing with different strategies. Although twelve-year-old children's spatial reasoning is not yet fully efficient and free of error, the underlying structure of their spatial ability resembles that of adults (Chapter 2).

In all chapters, large differences between children in spatial ability were observed. In line with previous research, the current thesis shows that spatial ability differences are related to sex and age of the child. Moreover, spatial development strongly relates to development in other cognitive domains. Both object and viewer transformations are effortful cognitive processes that involve the generating, comparing, and holding of spatial information. These processes rely on children's abstract reasoning capacities and require additional processes from the attention, inhibition and working memory system (Chapter 3, 4). Especially in late childhood, when these functions increasingly resemble the capacities of adults (e.g., Huizinga et al., 2006), more complex and abstract mental transformations are enabled. Improvements in inhibition allow for increased ability to ignore perceptual input and inhibiting motor output during mental transformations, and increases in working memory capacity allow for larger amounts of spatial information to hold and act on.

Besides the role of these cognitive factors, this thesis demonstrates the additive effects of social-environmental factors, such the amount of spatial experience, in explaining differences in spatial ability in eight- to twelve-year-old children (Chapter 4 and 6). Importantly, factors at the psychological and socio-environmental level interact with each other. For example, Chapter 4 showed that the relation between spatial play and mental rotation is different for boys and girls, while controlling for age, SES, and differences in cognitive capacities. Differences in spatial skills are the result of years of different experiences. That is, small initial differences between children, for example in spatial ability and self-confidence, may affect the quantity and quality of spatial activities (e.g., playing with blocks, cars, puzzles) they seek out or are encouraged to pursue, which in turn affect their spatial ability and self-confidence, et cetera.

Despite the accumulating effects of years of differential experiences, individual differences in late childhood are not fixed. Chapter 6 showed that viewer transformation skills can be improved by children's participation in spatial play activities in the classroom. The period around ten years of age is an important time window for such interventions, as children of this age are in a developmental phase of transition and are experimenting with new spatial strategies. Moreover, girls of this age are aware of common stereotypes

about sex differences in the spatial domain, but they do not personally endorse such beliefs (Chapter 5). Thus, although children between eight and twelve years of age form a very diverse group, differing in spatial ability level, cognitive maturation, prior spatial experiences, and stereotypic beliefs, the nurturing of spatial talent is certainly possible.

Directions for Future Research

This thesis emphasizes the importance of combining the study of developmental stages with the study of individual differences in spatial ability research. Research on viewer transformation ability has largely focused on developmental stages, while research on object transformation ability has concentrated on individual differences (Newcombe et al., 2010). Integrating both types of studies in longitudinal study designs and in broad samples of children may contribute to a comprehensive framework on the developmental trajectories of object and viewer transformation ability and the factors contributing to individual differences.

In order to achieve this, new experimental paradigms are needed that cover broader age ranges and measure successive levels of sophistication in the same ability. Ideally, these measures are suitable for use with both children and adults. In addition, I argue for assessment instruments that enable systematic one-to-one comparisons across levels of object and viewer transformation ability, as was previously done by Huttenlocher and Presson (1973). A first step in developing such paradigms is to further decompose the spatial ability construct. Whereas this thesis provides evidence for a differentiation of object and viewer transformations in children, more fine-grained distinctions are possible. That is, spatial transformations can be performed on different types of representations: 1) object/viewer transformations on *static* (i.e., non-moving) representations (e.g., changes in texture, color of the object), 2) object/viewer transformations on *dynamic* (i.e., moving) representations (e.g., rotating, folding, scaling, cross-sectioning the object), and 3) object/viewer transformations on *relational* representations (e.g., changes in the relations between objects and/or reference frames) (e.g., Newcombe & Shipley, 2012; Uttal et al., 2013). It can be hypothesized that these representation-transformation combinations are different in complexity and follow different developmental trajectories.

Instead of focusing on accuracy and speed of performance on spatial tasks, further examination of spatial strategies is warranted. Investigating the types of errors children commit at different levels of representation complexity may reveal the child's difficulties in the solution process. Studies on children's strategy use in mental rotation tasks have demonstrated that the type of strategy may be indicative for the child's

developmental stage (e.g., Hawes, LeFevre, et al., 2015; C. Quaiser-Pohl et al., 2010). The application of a similar approach to viewer transformations, distinguishing between immature and more mature strategies, would shed more light on the developmental trajectory of this ability. A combination of descriptive analyses (e.g., thinking aloud protocols) and state-of-the-art statistical analyses (e.g., latent class analyses) may be an effective technique for the close examination of individual differences in development (C. Quaiser-Pohl et al., 2010). One central question is whether children use one viewer transformation strategy at all ages, jump from immature to more mature strategies during development, or always have different strategies at their disposal and use them interchangeably. Quantitative and qualitative comparisons with adolescent and adult performance may help answering such questions.

Surprisingly little is known about the role of underlying cognitive processes such as working memory and executive functions for spatial development (e.g., Lehmann et al., 2014). Knowledge of the development of working memory and executive functions needs to be integrated with research on spatial functioning to create full understanding. The role of these underlying cognitive processes can be investigated by for example longitudinal study designs focusing on the intertwined development of these processes, or by studies investigating the effects of working memory training (i.e., enhancing the amount of information that participants can think about and act on) on spatial performance.

Furthermore, the integration of findings from fundamental studies with findings from intervention studies could improve our understanding of the underlying mechanisms of spatial development. A multi-disciplinary approach allows for finding answers to questions such as: Who profits from which type of training? What types of spatial play activities are most beneficial to promote spatial thinking? Is it possible to teach transformation strategies and at what age? Do more basic cognitive skills like memory and attention also improve? Can training affect children's beliefs about their own ability in the spatial domain? Ideally, intervention studies include more than one type of training, to compare and optimize different methods, and include more than one age group, to compare effects at different developmental phases.

The effective identification and nurturing of spatial talent in late childhood needs a clear description of the factors constituting spatial talent at this age. Or in other words, what characterizes children who are exceptionally good at spatial thinking? Hegarty (2010) argues that spatial intelligent children are proficient in flexibly combining spatial

transformation strategies with more analytic strategies. Analytical strategies help to simplify and oversee a spatial task, for example by decomposing it into smaller and simpler subtasks. This decreases the load on working memory and other cognitive processes, enabling fast and accurate execution of spatial transformations. Especially in late childhood, when children learn to master more abstract and complex spatial skills, such analytical strategies may play a prominent role in spatial thinking.

Implications for (Educational) Practice

Insights from this thesis can be helpful when designing interventions that are better suited to the spatial needs of children between eight and twelve years of age. First, given the dissociation between object and viewer transformation ability, both types of ability should be included in diagnostics and training of spatial ability in children of this age. As both types of transformation rely on different processes and strategies, there may be clear performance differences within children. That is, a child who is proficient at object transformation tasks is not necessarily proficient at viewer transformation tasks, and vice versa.

As clearly shown in this thesis, spatial play activities have positive effects on spatial performance in this age group, and children differ in their participation in these activities in their spare time. This is a strong argument for the integration of this type of activities in the school curriculum, also in the higher grades of elementary school. When teaching spatial skills, individual differences between children should be taken into account. Ideally, one should not solely base the level of instruction complexity on sex or chronological age, as there are large performance differences between children of the same sex and age. Teachers should be aware of the developmental changes in spatial ability, including the changes in strategy use. For example, findings that children progressed from 'guessers' to 'mirror-confused' to 'successful mental rotators' in mental rotation (Hawes, LeFevre, et al., 2015) suggest a natural instructional sequence to follow when teaching or training this ability. For viewer transformations these trajectories are not yet as clear, but the period around ten years of age seems a period of significant experimentation with this type of strategy, providing useful opportunities for intervention. Probably, one may find means of presenting material at multiple levels of complexity, making it appropriate for children with a range of abilities. At elementary schools, for example, spatial projects around photography may be an attractive way to develop - at different levels of ability - a sense of shifting viewpoints. Positive experiences with spatial activities may improve children's confidence in their own ability, which may encourage them to participate in spatial

activities in their spare time and to make STEM-related educational and occupational choices.

Taken together, the three important take-home messages of this thesis are: 1) spatial ability is under construction in children between eight and twelve years of age, in that children of this age acquire new and more complex spatial skills and strategies; 2) in this age group, large individual differences exist between children, not only in spatial ability, but also in spatial experience and spatial beliefs. Small differences in young children may develop into large differences at older ages, as a consequence of differences in cognitive maturation and spatial experience; 3) spatial ability is not fixed or inherent, but can be achieved by adequate input and practice. Teachers and parents should provide all children, regardless of their sex, age and socio-economic background, with appropriate spatial activities at school and at home, giving them fair chances to successfully participate in our modern technological society.