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Chapter 3

Educational Implications of Spatial Memory

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Additional information is available at the end of the chapter

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Abstract

Spatial memory is recruited during many classroom-based activities. As such, it is essential for both educators and students to understand how it operates in a classroom context. This chapter begins by providing a systematic overview of how spatial memory is used across a variety of academic domains including math, language arts, and science. It also reviews some of the typical characteristics of students who have relatively poor spatial memory abilities. Finally, it discusses how to best provide efficacious classroom support for these students. Taken together, it provides an accessible overview of the educational implications of spatial memory that educators and students can consider when trying to optimize learning in their classrooms.

Keywords: education, learning, academic achievement, teaching, memory

1. Introduction

Children spend a significant portion of their lives actively engaged in classroom activities designed to help them learn content, concepts, procedures, and skills. Many of these activities require the use of their spatial memory, yet many educators and students are not well versed in what spatial memory is or how it works. As evidenced in the other chapters in this book, spatial memory can be operationalized through a myriad of lenses. For the purpose of the current chapter, we will focus on spatial memory as it relates to the human ability to store spatial information in our minds for short periods of time and use that spatial information in our current thinking. In other words, spatial memory is the spatial workspace that students use in classrooms everyday. The amount of spatial information a student can hold and use in this workspace increases with age, but there are also individual differences in the amount of spatial information students of the same age can hold and use. Throughout this chapter we will refer to the upper limit of the amount of spatial information a student can hold and use at one point in time as spatial memory capacity.

Ample research highlights the central role a student's spatial memory capacity plays in his or her ability to succeed in school [1]. Considering this fact, this chapter aims to provide an overview of how spatial memory is used across academic domains, unpack characteristics of students who have small spatial memory capacities (relative to their peers), and outline evidence-based methods to support such students. Our hope is that this information can help position educators and students to optimize learning.

2. The role of spatial memory in academic learning

2.1. Math

Math content and, in turn, math pedagogy change substantially as a child progresses through school. Not surprisingly, the role spatial memory plays in math learning also evolves significantly throughout the course of schooling.

2.1.1. Preschool

The link between spatial memory and math achievement in preschool-age students has been well documented [2]. In fact, a preschooler's spatial memory capacity is among the best predictors of their performance on arithmetic problems [3] and having a small spatial memory capacity is associated with deficiencies in a preschooler's arithmetic abilities [4]. One reason for this link seems to be the critically important role spatial memory plays in linking number words with quantities under the Triple Code Model [5, 6]. More specifically, preschool students learn through explicit instruction that number words (e.g. seven) and symbols (e.g. 7) correspond to visual and spatial quantities (e.g. an image of seven tokens). With time they develop internal mental models that permanently link numbers words and symbols to their appropriate visual and spatial quantities. In doing so, they begin to categorize number words and symbols according to size [5, 6]. Then, preschoolers use these mental models to solve arithmetic problems by adding or subtracting spatially based 'token' representations to or from one another [4]. As you can imagine, the larger a preschoolers' spatial memory capacity, the more fluidly they can use their mental model to solve arithmetic problems [2]. The role spatial memory plays in how preschoolers solve arithmetic problems helps explains why they are more accurate when solving non-verbal arithmetic problems than verbal arithmetic problems [4].

2.1.2. Elementary school

Spatial memory continues to play a role in mathematical thinking when students enter elementary school, but its involvement begins to decrease as they age. In the first few years of elementary school, its role is still fairly central. There is a strong correlation between math ability and spatial memory capacity in first grade students; 7-year-old who have high overall math abilities also have large spatial memory capacities [2] and 7-year-old with low math performance perform worse on spatial memory tasks [1]. In fact, at this age, spatial memory capacity predicts more than 10% of ones math scores [2]. Furthermore, research shows that spatial interference severely impairs the ability of 6-year-old to solve arithmetic problems [1]. Taken together, this evidence suggests that in early elementary school, students still rely quite heavily on their spatial memory to do math.

However, as students continue on in elementary school, they shift towards using more verbal-based strategies to do math. It appears that this transition begins when students are about 8-year-old; spatial interference only slightly impairs the ability of 8-year-old to accurately complete math problems [1]. Keep in mind spatial interference significantly impaired the ability of 6-year-old to accurately complete math problems [1]. V*erbal* interference, however, causes severe impairment in 8-year-old math ability [1]. Corresponding, spatial memory predicts only 3% of 9 and 10 year olds' scores on math achievement tests, while it predicted 10% of the scores of 7-year-old [2]. And by age 10 or 11, spatial memory is no longer a statistically significant predictor of performance in addition, subtraction, or multiplication [7].

Multiple theories explain these age-related differences: a developmental theory, a novelty theory, and a domain specificity theory. The developmental theory purports that the age-related shift from spatial- to verbal-based strategies simply mirrors the developmental trajectories of spatial and verbal memory. Some suggest spatial memory develops earlier than verbal memory primarily because younger students are taught using spatial strategies, like finger counting [7]. The thought is that such spatial instruction early on may promote the development of spatial memory early on. Then, with age and the natural language development that comes with it, student's verbal memory development "catches up" allowing students to rely on more on their verbal memory. In addition, in about third grade, many schools actually begin to teach students to use explicit verbal strategies to solve math problems, like rote memorization (e.g., memorize that 8 times 7 is 56); this may in part explain when this is precisely the age we begin to see a diminishing role of spatial memory [3].

The novelty theory proposes that spatial memory is activated when *all* students, regardless of age, first learn a novel math skill [7]. Aligned with the novelty theory is data that shows spikes in the predictive power of spatial memory on math achievement each time a new subdomain of math is introduced [7]. For example, the predictive power of spatial memory in the subdomains of addition and subtraction spikes in first grade when these subjects are introduced, and then the predictive power decreases. There is a similar pattern among third graders; the spike in the predictive power of spatial memory on multiplication skills is dependent on the specific time a school introduces multiplication. The same goes for fourth graders with division [8]. It is worth noting that while the increases in the predictive power of spatial memory on multiplication and division exist, they are quite small [7]. Novelty theorists explain that this is because while students of all ages use their spatial memory when confronted with new and difficult math problems, older students more quickly develop verbal strategies for solving these types of problems [8].

Finally, the domain specificity theory proposes that spatial memory is associated with different math domains to different degrees [8]. For example, addition and subtraction may rely heavily on spatial memory because these problems are often solved by physical or visual manipulation, whereas multiplication and division may rely more on verbal memory because they are often solved by verbally memorized facts [8]. Empirical data offers some support for this theory; while spatial memory is associated with all math domains, the relationship between math achievement and spatial memory is indeed much stronger for addition and subtraction than it is for multiplication and division [8].

Ultimately, all theories highlight a general shift in the role spatial memory plays in math; in early elementary school its role is quite strong, but as students progress through elementary school its role lessens some.

2.1.3. Adolescence

The role of spatial memory on math does not disappear after elementary school, though. Aligned with the novelty theory, adolescents rely more on their verbal memory when solving math problems with which they are familiar, but they still seem to rely on their spatial ability as a back-up strategy when they encounter complex math problems [2, 3]. Other data corroborates that the role of spatial memory is not completely gone when students enter adolescence. For example, 14-year-old's spatial memory capacity is still significantly related to their standardized math scores [9]. Similarly, spatial memory at age 18 is positively correlated with performance on the math section of the SAT [10], and measures of mental rotation predict SAT math scores [11]. Furthermore, spatial memory in adolescence is a strong predictor of future success in math-related fields. Adolescents with greater spatial ability at age 13 are more likely to major in science, technology, engineering, or mathematics (STEM) in college and pursue a career in the STEM field [10]. In fact, more than 90% of people who have a PhD in a STEM-related field scored in the top quartile for spatial ability at age 11 [12]. So, despite the diminishing effect of spatial memory on math over time, it is important to note that its role does not seem to taper to nothing.

2.2. Language arts

2.2.1. Reading

Before considering the role spatial memory has on reading, it is essential to highlight that reading is a remarkably complex and dynamic process. Spatial memory is just one of many cognitive processes that work in concert when a child reads. Understanding this caveat, we will review what research tells us about the relationship between spatial memory and reading (1) achievement, (2) fluency, and (3) comprehension.

According to a meta-analysis of close to 300 studies, spatial memory can predict reading achievement in elementary, middle, and high school students [13]. In fact, spatial memory the best predictor of reading achievement of all the cognitive processes examined, which included auditory discrimination, auditory memory, auditory blending, auditory comprehension, visual discrimination, visual-motor integration, visual closure, visual association, visual–spatial relationship, and figure-ground discrimination [13]. Please note: the meta-analysis was not intended to be an exhaustive search of all the processes involved in reading; there are many processes related to reading that were not included that account for significantly more variance in reading ability than those included. However, when focusing in on this particular set of processes, the relative role of spatial memory is noteworthy [13].

Some evidence even suggests that spatial memory may plays a role in reading fluency, or the ability to read text quickly, accurately, and with appropriate prosody [14]. Verbal memory plays a larger role, of course [15, 16], but students with fluency reading disorders show reduced verbal *and* spatial memory capacities compared to typically developing readers. An understanding of the specific type of spatial memory that might be involved is still emerging, but it seems that it might have something to do with the ability to move visual material in the mind, as students with reading fluency disorders do equally well as those without reading disorders on tasks utilizing static spatial memory tasks that do not involve reading [17].

When we turn to reading comprehension, the evidence is somewhat clouded. There is a strong relationship between overall "working memory" (verbal and spatial memory taken together) and reading comprehension [16, 18]. Yet, studies that have attempted to determine the unique contribution of spatial memory compared to verbal memory have found little evidence that spatial memory contributes anything to reading comprehension *above and beyond* verbal memory. With that said, it is clear that students construct spatially-based mental models of situations described in text and update the models as they continue to read [19]. Importantly, student's ability to construct and update these spatial mental models is predictive of reading comprehension for elementary, middle, and high school students [19], a clear suggestion that some aspect of spatial memory *does* play a role.

2.2.2. Writing

There is also some evidence that links spatial memory to early writing ability. For example, researchers found that spatial memory accounts for a unique proportion of the variance in student's spelling and independent text writing skills in preschool and kindergarten, even when controlling for verbal memory [20]. As students age, the importance of verbal memory increases as they become more practiced writers and transcribers and can maintain more complex strings of sounds in their minds. But in the early stages of writing, the spatial memory appears to be in high demand as students practice producing novel visual representations of formerly solely auditory information [20].

2.3. Science

Most of the work exploring the ways in which students use spatial memory during science focuses on scientific thinking, as opposed to science test scores. And, indeed, spatial memory appears to be critical to a student's ability to think like a scientist. This makes sense when considering that a student who has superior spatial memory is able to create mental models of complex scientific ideas and then mentally manipulate those models, an ability necessary for scientific thinking [21]. For example, when a scientific theory that is initially presented in words or as an equation, it is often then mentally transformed into an abstract spatial representation, such as a graph or model. Moreover, the process of scientific investigation often involves reconciling a theory-based spatial model with a competing data-based spatial model. According to the Next Generation Science Standards, this type of scientific investigation is encouraged in simple formats in elementary school and quite complex formats in high school and college. And it is certainly a process career scientists use; researchers observed that scientists often use visualization to mentally manipulate models and modify theories when confronted with disconfirming data [22]. Clearly, the visualization and imagery components of spatial memory are necessary for scientific investigation.

It is not surprising then that ample evidence suggests spatial memory abilities can be used to predict later success in scientific fields [23–27]. Spatial memory is also predictive of scientific creativity [12, 21] and students who have superior spatial memory become expert engineers or physical scientists at much higher rates than those who do not have such abilities [12].

For these reasons many argue that spatial memory measures should be regularly administered as a way to identify future talent in scientific domains [28], especially considering the need to identify and nurture scientific and technical talent is a national priority [29, 30]. But despite the potential utility, spatial ability has not been used as a way to identify promising future scientist students, nor has it been incorporated into K-12 scientific curricula or instruction. Many researchers have noted this neglect and have noted that is especially surprising in today's globally competitive world [31]. Richard E. Snow expressed his perplexity when saying:

> *"There is good evidence that [spatial ability] relates to specialized achievements in fields such as architecture, dentistry, engineering, and medicine. Given this plus the longstanding anecdotal evidence on the role of visualization in scientific discovery,. .. it is incredible that there has been so little programmatic research on admissions testing in this domain* ([32], p. 136)*."*

Instead, verbal ability is most often used to determine an individual's suitability for a position that requires a college degree, such as a scientist or engineer, while spatial memory has been used to determine suitability for trade work, such as a technician or mechanic [33]. We hope this chapter can provide educators with a better understanding of the power of spatial memory and will, in turn, be in a position to use it to identify future talent.

3. Characteristics of students with poor spatial memory

Thus far we have outlined how spatial memory is an underlying cognitive process used across a variety of academic tasks, including math, language arts, and science. Considering this, it makes sense that students with poorly developed spatial memory might struggle in these academic areas, and there is plenty of literature to show that this is the case [34–37]. Evidence suggests poor or underdeveloped spatial memory is related to a host of general classroom behaviors, as well. Furthermore, there is data to suggest that particular demographic groups may develop spatial memory abilities at different rate than other demographic groups. To best position teachers to be able to effectively set all students up for success, we will outline these characteristics below.

3.1. Poor spatial memory and classroom behavior

Beyond academic achievement, students with poor *general* memory also tend to demonstrate a set of common classroom behaviors. Teachers of students with relatively weak general memory capacity typically judge (elementary school aged) students as highly inattentive and have having high levels of distractibility [38]. They are also described as often forgetting that they are currently doing and failing to remember instructions and, in turn, not being able to complete everyday classroom tasks [34]. They are not hyperactive, though. Instead, these students exhibit reserved behavior profiles and struggle the most with attention in large group activities led by the teacher [38]. Furthermore, poor general memory has shown to be associated with a lack of creativity in complex problem solving and poor self-monitoring of own work among older students [34, 38]. These studies, along with others, paint a picture of a student who has difficult time remaining on task and focused, which is a precursor to learning. Most studies on this topic have measured how spatial and verbal memory *taken together* (i.e., what most refer to as general working memory) impact classroom behavior. More research need be done to determine how these behavioral problems can be linked specifically to the spatial memory subcomponent, but it is clear that both spatial and verbal memory contribute to the behaviors [38].

3.2. Poor spatial memory and demographics

There is also some burgeoning evidence linking spatial memory profiles with demographic groups. Girls and boys are far more alike than different on most measures of intelligence and cognitive processing, but they do differ in spatial memory. Females have been found to underperform males on spatial memory tasks as early as preschool and through high school [39–41]. A variety of psychobiological factors contribute to these gender differences [39], but the differences seem malleable. As a result, the spatial gender difference has been the impetus for many interventions.

Neighborhood type seems to be another demographic characteristic that is associated with differences in spatial memory. Our own research measured the verbal and spatial memory abilities of students living in rural and urban poverty. The students living in rural poverty had significantly smaller spatial memory capacities compared to the students living in urban poverty [42]. Interestingly, this weakness was specific to spatial memory. The students living in rural poverty had larger verbal memory capacities than the students living in urban poverty [42]. This work indicates that there is some relationship between impoverished rural contexts and spatial memory development, although the specific environmental factors associated with the relationship are still under investigation.

Finally, additional evidence shows students with fetal alcohol syndrome (FAS) exhibit impaired spatial memory. Specifically, those with FAS consistently demonstrate constructional apraxia, in addition to a wider range of spatial deficits [43]. While this link has been documented for some time, further research needs to determine the antecedents and consequences among students with FAS.

There are a variety of psychobiological and environmental variables that impact spatial memory development of these demographic groups, as well as typically developing students. The current consensus is that some demographic groups, like those we mention, are exposed to variables that impede the development of spatial memory and/or not exposed to variables that promote its development. Clearly, it is essential that future research determine the psychobiological and environmental factors at play so intervention and prevention work can be effectively designed and implemented.

4. Interventions to support spatial memory weaknesses

Aligned with the notion that spatial memory is (1) malleable and (2) associated with educational success, much effort has gone into trying to determine how one can improve a student's spatial memory. The types of interventions that have been designed and/or tested can be categorized into two subtypes: training of spatial memory and classroom adjustments to reduce the required load.

4.1. Training of spatial memory

Uttal and colleagues performed a meta-analysis of more than 200 studies to investigate the magnitude, durability, and generalizability of training on spatial skills [44]. They concluded that training effects of spatial skills have a moderate effect (Hedges's g = 0.47), are stable over time, and transfer to other spatial tasks. From this, they highlight how a "spatially enriched education could pay substantial dividends" (p. 352).

Aligned with this conclusion, there is evidence of success for spatial interventions for young students that include the use of increased spatial language, maps and models, as well as jigsaw puzzles [45]. Additionally, early building block skills have been linked to spatial ability; Casey and Andrews developed a spatial intervention that uses storytelling and block building to increase spatial skills in young students, particularly spatial visualization and mental rotation [46]. Specially, a teacher reads aloud a story in which the characters instruct the students to build specific structures with blocks. The intervention was successful in improving the spatial skills of kindergarteners, and as a result Casey and Andrews suggest that structured block building should be included in classrooms to develop the spatial skills of students [46].

Block building can also be a successful tool to improve the spatial memory among older students. Eight-year-old who participated in a block building intervention performed better on mental rotation tasks and had increased activity in the parahippocampus, a brain region that is involved in spatial memory [47]. In addition, playing the computer game Tetris has been linked to increased mental rotation skills in 8-year-old; thus, computer-based interventions can be used in schools to improve students' spatial abilities [48]. Finally, adding spatially challenging activities to school classes can help improve the spatial skills of students [44]. High school students who were trained to use two and three dimensional representations in a physics course performed better on the spatially demanding task of reading a topography map [44].

4.2. Classroom adjustments to reduce required load

In addition to interventions, suggestions have been made about how teachers can make adjustments to their classrooms to reduce the load placed on students' spatial memories during any given activity, thereby allowing them to succeed. Gathercole and Alloway's eight-step approach is among the best known and it was designed to help teachers manage students' spatial memory load and reduce the disruptive effects that heavy spatial memory loads have on learning [49]. The first step of this approach is for teachers to recognize spatial memory weaknesses by monitoring students for errors including incomplete recall, failure to follow directions, place-keeping errors, and task abandonment [49]. The second step is to monitor students' spatial memory during classwork by asking students for the details of their classwork and what they intend to do next and the third step is for teachers to assess the spatial memory demands of classroom activities [49]. Step four encourages teachers to then reduce the spatial memory loads of classroom activities if the demands exceed the spatial memory capacities of students [49]. To do so, teachers shorten the number of items to be remembered; increase familiarity of information students need to remember; turning multi-step tasks into independent steps; and providing and encouraging the use of memory aids, such as number lines or printed notes [49]. The fifth step is for teachers to be conscious of processing demands that increase spatial loads [49], as students may have the spatial memory capacity to succeed in classroom activities, but simultaneous processing tasks may cause working memory failures [49]. The sixth step is for teachers to repeat important information often and encourage students to request the repetition of this information [49]. The seventh the seventh step is for teachers to encourage the use of memory aids like number lines, counting devices, Dictaphones, dictionaries, teacher notes, and wall charts can help reduce the processing demands and storage load of a classroom activity [49]. Finally, the eighth step is for teachers to help students develop memory-relieving strategies [49]. Importantly, Gathercole and Alloway claim teachers can reduce the memory load by following the aforementioned steps *without reducing* the amount of content taught and, in turn, learned [49].

4.3. Health and spatial memory

It is also worth mentioning that there are behavioral and medical conditions that can hurt one's memory abilities. For example, regular tobacco use decreases memory function because the overall amount of oxygen that the brain receives is reduced [50]. Sleep patterns are also related to our ability to consolidate and retrieve information from our memory; if one wakes up frequently in the night or gets less than the recommended amount of sleep for their age, consolidation and retrieval can be negatively impacted in the short term [51]. Nutrition is essential for overall brain function, as well, and ample research has shown that deficiencies in specific vitamins (i.e., B1, B12, and E) can negatively affect memory [52]. Considering, it is not surprising that work has explored if and how nutritional supplements can improve memory. While the work is young and large scale, longitudinal, methodologically sound studies on young healthy humans have not yet been completed, there are promising results from studies about the potential positive impact of a variety of supplements on memory including ginko biloba, omega-3 fish oil supplements, Huperzine A, the amino acid Acetyl-L-carnitine, Bacopa, and the hormone DHEA. [53]

5. Conclusion

In conclusion, let us consider Jane, an 8-year-old student. Despite her best efforts and those of her teachers, Jane struggles to keep up with the academic progress of her classmates. She is a hard worker and very well liked by her peers, but her math, reading, and science scores are in the lowest quartile of her class. Jane has started to become discouraged by the fact that she cannot seem to keep pace with her classmates. As a result, she is beginning to complain to her parents that she "doesn't like school" and "doesn't want to go to school." At the most recent parent teacher conference Jane's teacher brought up that Jane has a hard time following her instructions. What is important for teachers, parents, and students like Jane to understand is that it is possible that her current spatial memory capacity may be one of the underlying mechanisms that explain her struggles. Fortunately, Jane's teachers can make the aforementioned classroom adjustments to lower that spatial load of classroom activities for Jane in ways that will not reduce learning. Simultaneously, research suggests that Jane may benefit from some training in spatial memory strategies. Jane should also consider her current health and behavioral tendencies, such as sleep and nutrition. Also, perhaps most importantly, if Jane is able to identify and understand the underlying cause of her difficulties, she may feel less discouraged and more hopeful as she continues though her education.

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