MIND, BRAIN, AND EDUCATION

Early Education for Spatial Intelligence: Why, What, and How

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ABSTRACT—Spatial representation and thinking have evolutionary importance for any mobile organism. In addition, they help reasoning in domains that are not obviously spatial, for example, through the use of graphs and diagrams. This article reviews the literature suggesting that mental spatial transformation abilities, while present in some precursory form in infants, toddlers, and preschool children, also undergo considerable development and show important individual differences, which are malleable. These findings provide the basis for thinking about how to promote spatial thinking in preschools, at home, and in children's play. Integrating spatial content into formal and informal instruction could not only improve spatial functioning in general but also reduce differences related to gender and socioeconomic status that may impede full participation in a technological society.

Spatial thinking is often difficult. People frequently get lost or give directions that are difficult to follow or that contain mistakes. They get frustrated when attempting to put together "easy to assemble" furniture, and they yell at each other when trying to pack a small car for a long trip. However, such problems may seem like minor hassles when viewed against really important issues, such as illiteracy or failures to graduate high school. The attention of psychologists, educational researchers, and teachers is frequently focused on the basic skills of reading and writing, mathematics, and science. Should some of this energy also be devoted to improving spatial thinking? There are several crucial reasons why.

First, remember that spatial intelligence has evolutionary and adaptive importance. Any mobile organism must be able to navigate in its world to survive and must represent the spatial environment in order to do so. Moving further along the evolutionary timeline, the human ability to make tools is one of the hallmarks of our species. In order to create a successful tool, one must first imagine a shape that is relevant to a particular function, such as cutting or digging, and then fashion that shape out of larger forms.

Second, in line with this analysis of evolutionary demands, over a century of research in the psychology of intelligence and cognitive processes has established that spatial thinking is the principal complement to verbal thinking. Several examples drawn from multiple research traditions illustrate this point. Factor analytic research has shown that visualization is a well-defined component skill within general intelligence in adults (Carroll, 1993). Developmental testing shows a spatial/numeracy factor in preschool children (Bornstein, 2009) as well as in chimpanzees (Herrmann, Hernández-Lloreda, Call, Hare, & Tomasello, 2010). Spatial intelligence was one of the types of intelligence proposed in multiple-intelligence theory (Gardner, 1983). Approaches to working memory have distinguished between verbal working memory and the visuospatial sketchpad (Baddeley, 1986). Of course, controversy exists over some of these matters: for example, see McGrew (2009) on the psychometric approach to the structure of intellect, Waterhouse (2006) for a critique of multiple intelligences, and Kane et al. (2004) for evidence that domain specificity may not characterize working memory. Nevertheless, although the architecture of the human mind/brain has yet to be defined definitively, spatial functioning will likely be a relevant element in the solution.

Third, spatial thinking helps reasoning in domains that are not, on the surface, obviously spatial. For example, spatial metaphors and diagrams can be used to understand ordered relations (e.g., the ranking of Gross National Product among developing countries) or complex hierarchical relations (e.g., social relationships and biological taxonomies). Venn diagrams are used to solve logical problems. Maps do more than just show us where to go; they become tools for thinking in their

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capacity to display to us the distribution of variables such as population density or natural and economic resources. In fact, one of the most famous stories in epidemiology concerns a map prepared by a London physician, John Snow, during a cholera epidemic. At the time, the way in which cholera spread was unknown. Snow's map plotted the location of water pumps and the location of cholera cases and revealed how cases clustered around one particular contaminated pump.

Fourth, a critically important application of spatial thinking is to the science, technology, engineering, and mathematics (STEM) disciplines. For example, Watson and Crick's discovery of the structure of DNA occurred when they were able to fit a three-dimensional model to Rosalind Franklin's flat images of the molecule—clearly a spatial task. Similarly, a geoscientist visualizes the processes that affect the formation of the earth, an engineer anticipates how various forces may affect the design of a structure, and a neurosurgeon visualizes particular brain areas from magnetic resonance imaging that may determine the outcome of a surgical procedure. Progress and performance in various STEM fields thus seem to be strongly tied to improving people's ability to reason about spatial configurations and their properties. There is real evidence to back up this proposition. Children and adolescents who have higher spatial skills in middle and high school are more likely to major in the STEM disciplines in college and to pursue STEM careers (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009).[1]

EVIDENCE OF MALLEABILITY

If spatial intelligence is theoretically and practically important, the immediate question is whether it can be improved—can children be educated in a way that would maximize their potential in this domain? There is, happily, mounting evidence that spatial thinking can be developed a great deal. It turns out that even people who are considered spatially proficient are not nearly as proficient as they could be and that people who consider themselves spatially lacking can attain higher levels of performance.

Most prior attempts to improve spatial skills via training have focused on *transformation processes*, such as the rotation and scaling of objects, rotation and scaling of arrays, and computation of the effects of viewer movement. A good deal of this research has involved mental rotation, not only because it is an important process but also because there are detailed accounts of the relevant cognitive processes, some excellent tests of the ability, and intriguing (if dismaying) reports of gender differences (see Newcombe, 2002, for an overview). Results of individual training attempts have varied. Some researchers have claimed that practice leads people to make fundamental changes in how they process spatial stimuli, leading to transfer to novel stimuli and new tasks (Bethell-Fox & Shepard, 1988). Specifically, there are findings that improvement in spatial processing can generalize to novel stimuli within the same task (Leone, Taine, & Droulez, 1993), to other tasks of the same general type (e.g., mental rotation; De Lisi & Cammarano, 1996), and to tasks that share underlying cognitive processes with the practiced task (Wallace & Hofelich, 1992). However, others have reported that improvements in one spatial task do not transfer to other spatial tasks (Heil, Rösler, Link, & Bajric, 1998; Stericker & LeVesconte, 1982). In fact, practice has often been studied in paradigms using the same stimuli multiple times (Kail, 1986), thus leaving open the possibility that any gains are confined to a very narrow range of items. A panel convened by the National Academy of Sciences concluded that transfer of spatial improvements has not been convincingly demonstrated and called for research aimed at determining how to improve spatial performance in a generalizable way (National Research Council, 2006).

When viewed in the aggregate, however, the body of literature on spatial training is actually quite encouraging. Baenninger and Newcombe (1989) conducted a meta-analysis of studies of spatial training done up through the 1980s. They found very clear improvements in spatial ability that were, as one would expect, more striking as training was longer and more thorough. Research subsequent to the meta-analysis has supported these conclusions. For example, it has been shown that time periods with greater amounts of school input (winter months) are associated with greater cognitive growth in the area of spatial operations in elementary school children than time periods with less school input (summer months) (Huttenlocher, Levine, & Vevea, 1998). Thus, it is likely that various educational techniques are benefiting children in the development of their spatial abilities. Additionally encouraging is the finding of a recent meta-analysis (Uttal, Hand, Meadow, & Newcombe, 2010) which includes studies completed since the Baenninger and Newcombe review. Again it was shown that there are substantial improvements in spatial skill from a wide variety of interventions, including academic coursework, task-specific practice, and playing computer games.

To illustrate this literature, let us consider two studies (Terlecki, Newcombe, & Little, 2008; Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008) that gave undergraduates extended practice or training on mental rotation, for a period more prolonged than many other studies. The studies found that the training effects observed after practice lasted for the following several months and generalized to other spatial tasks (something that has rarely been observed). These effects were also massive—far larger in fact than the size of the typical sex difference. Terlecki et al. (2008) investigated long-term effects of mental rotation training and addressed whether these training effects are durable, transferable, larger for those who trained with videogames as opposed to simple practice, different for men and women, or different for individuals of higher and lower initial ability. Undergraduates participated in semester-long weekly practice with the Mental Rotations Test

(MRT) or, additionally, played the video-game Tetris. Structural equation modeling showed large improvements in mental rotation with both test practice and video-game training; these gains were maintained several months later. Video-game training led to greater initial growth than practice alone, but final performance did not reliably differ. However, video-game training transferred to two other spatial tasks at levels exceeding the effects of practice; this transfer advantage was still evident after several months. MRT scores of men and women did not converge, but men showed faster initial growth and women showed more improvement after the first few weeks—especially women with lower levels of spatial experience.

In a second training study, Wright et al. (2008) investigated whether intensive long-term practice leads to change that transcends stimuli and task parameters. College students were tested on three cognitive tasks: a computerized version of the Shepard-Metzler (Shepard & Metzler, 1971) MRT, a mental paper-folding task (MPFT), and a verbal analogies task. Each individual then participated in daily practice sessions with either the MRT or the MPFT over 21 days. Postpractice comparisons revealed transfer of practice gains to novel stimuli for the practiced task as well as transfer to the other, nonpracticed, spatial task. The transfer was symmetric: as great from MRT to MPFT and vice versa. These findings indicate that practice improves performance on spatial tasks, beyond simply training for shortcuts that allow successful manipulation of specific stimuli. Improvement in the nonpracticed spatial task was greater than in the verbal analogies test, and thus improvement was not merely because of greater ease with computerized testing.

Overall, it is clear that spatial training works, in a way that generalizes to new stimuli and novel tasks, and is durable over time. For participants of low ability, it appears that there is an initial hump to get over, but if they persevere through a period of slow improvement, faster improvement eventually occurs. These conclusions are not the end of the story, however. There is more to find out in future research. For example, how wide is transfer? Is improved spatial skill causally related to better STEM performance, and if so which specific skills translate to better performance in which subject areas? What are the neural correlates of better scores, and would such data give us new ideas about more targeted training methods?

Of course, these studies involved adults. What about early spatial development? A focus on spatial skills should likely begin in the first 5 years of life, given evidence that early education generally pays the biggest dividends for later achievement (Heckman, 2006). What is the nature of early spatial processing, and how can caregivers and educators best interact with children to support their acquisition and development of these skills? Examining what is known about the early development can provide a good basis for answering this question. Two particularly important and well-studied skills are the ability to imagine transformations of the orientation of objects (e.g., mental rotations) and the ability to imagine the consequence of observer movements around arrays of objects (i.e., perspective taking). Mental rotation is the skill for which the strongest evidence exists currently for positing relations with STEM learning, and both mental rotation and perspective taking have been extensively studied from a variety of approaches, including research that has adopted developmental, cognitive, psychometric, and neuroscientific methods. There are interesting similarities and differences between mental rotation and perspective taking, illustrating the necessity of careful analysis of spatial skills in order to gain a deep understanding of spatial development.

MENTAL TRANSFORMATIONS IN INFANTS AND PRESCHOOLERS

There are two basic kinds of spatial transformations. On the one hand, one can mentally transform *objects*: for example, imagine objects changing their orientation when they rotate, changing scale by expansion or shrinkage, being cut in half or folded, and so on. On the other hand, one can imagine *oneself*, as the observer, taking new perspectives and moving with respect to objects and arrays of objects. Research on mental rotation (imagined object movements) and perspective taking (imagined observer movements) goes back to Piaget and Inhelder (1956, 1971). They proposed that initially only egocentric and static representations are available. According to them, it is not until 7–10 years of age, during the concrete operational stage, that children start to differentiate viewpoints and become able to represent movements of objects in space, manipulate mental images, and anticipate the outcome of events. However, subsequent studies on the early emergence and development of these abilities show that they can emerge earlier than Piaget and Inhelder claimed and also demonstrate considerable development across the preschool years. These descriptive facts are important for well-informed intervention.

Development of Mental Rotation

Studies using looking-time paradigms with infants as young as 4 months have shown evidence for precursors of mental rotation (Hespos & Rochat, 1997; Rochat & Hespos, 1996). These paradigms have even detected early sex differences, with male infants showing more evidence of mental rotation than female infants (Moore & Johnson, 2008; Quinn & Liben, 2008). However, despite these interesting findings, data on very early mental rotation need to be interpreted with caution. Research paradigms used with infants differ from those used with older children and adults in several ways and do not necessarily measure the same ability. For instance, infants in many of the looking-time studies had the opportunity to watch a substantial proportion of the movement in the familiarization phase, whereas mental rotation paradigms used with older children and adults (Cooper & Shepard, 1973; Shepard & Metzler, 1971) typically present static stimuli. Thus, the infants did not have to mentally initiate the transformation, but merely to continue and extrapolate an ongoing or recently presented movement. Mental continuation of movement may be easier than starting a mental transformation from a static state. In fact, Frick and Wang (2010) showed that, although infants of 16 months looked longer at improbable outcomes of object rotations, even when they had to initiate the mental rotation, this pattern did not appear in 14-month-old infants, quite a lot older than the infants who have been argued to be showing mental rotation in the studies mentioned above. However, Frick and Wang also found that 14-month-olds who had less than 2 min of hands-on training with a turntable looked longer at the improbable outcome. This suggests that active motor experience increases infants' ability to predict the outcome of transformations.

The Frick and Wang (2010) experiments might be taken to indicate a substantial ability to mentally rotate objects in 14-month-olds, even though some prior experience might be necessary to activate this ability. However, there are other reasons to think that mental rotation is far from fully developed even in later infancy. Örnkloo and von Hofsten (2007) found that it was not until 22 months that infants could mentally rotate objects in order to successfully fit them through holes, and a recent study has also shown that there is considerable developmental progress in this ability from 15 to 30 months (Shutts, Örnkloo, von Hofsten, Keen, & Spelke, 2009).

Research on mental rotation abilities has also revealed important individual differences in 3.5- to 5.5-year-olds (Frick & Newcombe, 2009). Some children in this age range perform above chance on a mental rotation task using a touch screen paradigm. On the other hand, some children perform chance at level and show flat response time curves, suggesting that they do not mentally rotate the stimuli. These results challenge Marmor's (1975, 1977) results, which she interpreted to suggest that, at the age of 4–5 years, children are able to perform mental rotations. Even though widely accepted at the time, there has always been some controversy about this conclusion (reviewed by Newcombe, 2002). Other studies have failed to replicate Marmor's results (Dean & Harvey, 1979), and, in line with our results, analyses of individual children's response time patterns (Estes, 1998) suggested that only a small proportion of 4-year-olds appeared to apply a mental rotation strategy. Marmor (1977) also found that training children to use a mental rotation strategy did not have a significant effect, from which she concluded that 4- and 5-year-olds can spontaneously use and evoke mental rotations. However, a later replication study showed that, with training, twice as many 5-year-olds produced linear reaction time patterns that are indicative of a mental rotation strategy (Platt & Cohen, 1981).

Furthermore, mental rotation has been shown to continuously strengthen through early childhood (Estes, 1998; Levine, Huttenlocher, Taylor, & Langrock, 1999; Okamoto-Barth & Call, 2008). Several recent studies with children in kindergarten through elementary school suggest that motor activity and what has been called "embodied thinking" may play an influential role especially in young children's mental transformation abilities. These studies showed similar developmental trends in the degree to which mental rotation was impaired by concurrent incompatible manual rotations (Frick, Daum, Walser, & Mast, 2009) and hand postures (Funk, Brugger, & Wilkening, 2005), or in how mental spatial transformations were facilitated by concurrent compatible hand movements (Frick, Daum, Wilson, & Wilkening, 2009).

Development of Perspective Taking

There are several kinds of perspective taking, known to be graded in difficulty (for overviews of this literature, see Newcombe, 1988; Newcombe & Huttenlocher, 2000). The easiest kind of perspective taking involves predicting what will be seen after an actual physical movement. This prediction requires spatial memory and transformation when the target object or array is hidden, but the physical movement also transforms relations in regards to the frame of reference, making the task easier. The task is more difficult when the observer does not physically move but must imagine hypothetical movement (Huttenlocher & Presson, 1973).

In infant studies, there is usually actual movement around an array, which makes perspective taking easier. Roughly at an age when infants are becoming more mobile and are able to move around on their own, they begin to develop some perspective-taking ability when they move. For instance, a study with 8-month-olds (Bai & Bertenthal, 1992) showed that infants' locomotor status predicted their ability to keep track of the location of an object when they changed their position. In this study, a toy was hidden in one of two identical wells on a table and the infants searched for the toy after being moved to the opposite side of the table. Creeping infants (infants who were able to move on hands and knees without their bellies touching the floor) predominantly searched in the correct well, whereas crawling (with bellies touching the floor) and precrawling infants showed below-chance searches. Furthermore, two experimental studies indicate that infants are better at keeping track of a hidden object if they themselves actively move to a new position. In one study (Acredolo, Adams, & Goodwyn, 1984), infants were trained at 12 and 18 months to find an object hidden in one of two identical wells in a Plexiglas box. When allowed to search for the toy from the opposite side of the box, correct searches predominated at 18 months. A similar study (Benson & Uzgiris, 1985) showed that even 10- to 11-month-old infants predominantly searched in the correct well, if they actively crawled to the new vantage point, as opposed to being passively carried there by a parent. Newcombe, Huttenlocher, Drummey, and Wiley (1998) asked children ages 16–36 months to search for objects hidden in a rectangular sandbox, after they had walked to the opposite side of the box. In this study, children moved in a curtained environment and had to search for the object in a homogenous space, as opposed to the studies above that used two distinct hiding places. Hence children needed to rely primarily on dead reckoning. Nevertheless, children across this age range performed above chance.

Whereas in the studies described above the observers actually moved to a new location, other research has directly investigated *imagined* observer transformations in young children. Rieser, Garing, and Young (1994) tested whether children were able to imagine a distant spatial layout and then imagine a change in perspective. Children sat at home and were asked to imagine how their classroom would look like, first from their own seat, and then from their teacher's seat, and to point to different locations in their classroom. Children at 3.5 years and older were accurate and rapid in their pointing, but only if they were instructed to imagine walking from their seat to the teacher's seat while actually walking a similar path and turning consistently with the to-be-imagined heading.

Even though the above studies reveal surprising abilities at very young ages, the tasks are quite different from the classic Piagetian perspective-taking tasks (e.g., Three Mountains Task: Piaget & Inhelder, 1948/1956), in which children had to choose which of several pictures would show what they would see if they moved around an array. In Rieser et al.'s task, there is minimal competing sensory input because perspectives were imagined in a dark room. In Piaget and Inhelder's picture selection task, there is a competition between the perceptually present surround and the one that must be imagined. There are other ways than turning out the lights to reduce this competition. Newcombe and Huttenlocher (1992) asked preschoolers to imagine how a layout located immediately in front of them would look from different viewpoints, using a verbal question that highlighted a particular spatial relation (What object would be closest to you?). Their results showed that 3- to 5-year-olds were able to indicate the location of objects relative to another viewpoint, although the 3-year-olds often responded egocentrically, that is, relative to their own current perspective. However, children of this age were completely unable to cope with Piaget and Inhelder's original task: selecting which of four pictures would show the array from the imagined perspective. In a study with older children that provided the basis for the later study of preschoolers, Huttenlocher and Presson (1973) found that even third- and fifth- graders still made numerous egocentric errors in classic perspective-taking tasks using arrays of pictures, although they performed much better in response to verbal questions that focused on particular spatial relations than with the picture-selection task. Thus, it appears that the real challenge in perspective-taking tasks during the school years is not the mental transformation that underlies the ability to imagine someone else's perspective per se, but ignoring one's own perspective and perceptual surroundings.

Mental Rotation Versus Perspective Taking

Huttenlocher and Presson (1973, 1979) showed that performance in observer rotation (or perspective-taking) tasks differed considerably from performance in array rotation (or mental rotation) tasks and that the degree of difficulty in the two tasks was not influenced by the same factors. These results have been corroborated by further behavioral studies that showed performance differences between observer rotation and array or object rotation tasks in adults. For instance, different response time functions have been found in object rotation tasks and observer rotation tasks. Object rotations typically show a linear increase in response time as a function of angle of rotation; that is, larger rotations typically take longer (Cooper & Shepard, 1973; Shepard & Metzler, 1971). On the other hand, when participants are instead asked to imagine themselves rotating, this linear increase in reaction times has not always been found (Jola & Mast, 2005; Wraga, Creem, & Proffitt, 2000; Zacks, Mires, Tversky, & Hazeltine, 2000). In a factor analytic study, Hegarty and Waller (2004) compared several measures of mental rotation and perspective-taking abilities and concluded that measures of perspective taking and mental rotation are dissociable, while correlated, in adults. They argued that these two types of spatial transformations rely on different cognitive operations, although they may also share some common processes, such as generating and maintaining mental representations (Kosslyn, 1994).

This research raises the question of whether imagined observer rotations and object rotations recruit the same brain areas. Evidence from neurophysiological studies in adults suggests that tasks that require object-based spatial transformations and those that require viewpoint changes depend on different neural processes (Creem et al., 2001; Kosslyn, Digirolamo, Thompson, & Alpert, 1998; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999). For instance, lesions to right posterior cortex were associated with selective impairments at object rotation tasks, whereas lesions to left posterior cortex were associated with selective impairments in the ability to navigate and to imagine oneself turning, as in following a route on a map (for a review see Zacks et al., 1999).

Summary

Mental rotation and perspective-taking skills are present in some precursory form in toddlers and preschool children, but they undergo considerable development during this time and into middle childhood, and they also show important individual differences. Furthermore, despite their superficial resemblance, mental rotation and perspective taking seem to be dissociable abilities that are affected by different performance factors and involve different neural processes. However, the two abilities have in common that their developmental progress is closely linked to motor development, and motor activity has been found to facilitate performance in both kinds of tasks. Presumably, children's mental spatial transformation abilities can profit from active movement, by allowing them to tap into well-established and fine-tuned links between action and cognition that are primarily used for keeping track of the environment during movement and for tracking objects during manipulation of them.

IMPLICATIONS

These are ideal circumstances for intervention. First, infant studies suggest that a basis for development is established early, in the form of rudimentary types of spatial transformation skills. Second, research suggests that spatial transformation skills continue to develop through early childhood, so interventions across a wide range of ages may still have a significant impact on children's cognitive development. Third, because individual differences in spatial thinking are malleable, chances are good that spatial thinking may be fostered by effective technology and education. Fourth, effects of motor experience and various kinds of training effects have been reported, so there are at least some initial ideas and tools available for translating this research toward the improvement of children's mental transformation and spatial skills.

So what exactly should caregivers and educators be doing? There are two different, but not mutually exclusive, approaches. One approach is to bring spatial thinking *into* the classroom, preferably in ways that tap into everyday experience and embodied knowledge. Another approach is to encourage learning *out of* the classroom, by giving children ample opportunities to experience space and practice spatial skills at home and in play. There are three areas in which caregivers and educators may seek to improve spatial skills: in preschool settings, through semi-structured use of media in the classroom or at home and by providing opportunities for free play.

Getting Spatial Thinking Into Preschool Education

A report titled *Learning to Think Spatially*, issued by the National Research Council (2006), highlights the deficits in our current understanding of spatial thinking in the classroom. There is still a lack of specific knowledge of what kinds of experience lead to improvement, how spatial thinking may be best infused across curricula, and how to optimally incorporate new technologies, such as geographic information systems, especially in the younger grades. What kinds of teaching best support spatial learning? The hope is that better instruction could not only improve spatial functioning in general but also reduce differences related to gender and socioeconomic status (Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005), which may impede full participation of all people in increasingly technological society.

Fortunately, there is a wealth of spatial material available for preschool play, much of which may be further leveraged with some knowledge of the processes of spatial learning. Jigsaw puzzles, for example, seem ideal for spatial learning. In fact, research has found that doing jigsaw puzzles is correlated with the spatial thinking of preschoolers, especially when coupled with spatial language related to the challenges of the puzzle (e.g., *can you find all the pieces with a flat edge*?) (Levine, Ratliff, Huttenlocher, & Cannon, 2010). Additionally, it has been found that spatial language does not have to be planfully produced—simply interacting with spatial materials such as blocks leads adults to use more spatial language when playing with their children (Ferrara, Golinkoff, Hirsh-Pasek, Newcombe, & Shallcross, 2010).

Furthermore, recent research findings suggest a close relationship between children's learning of object names and the emergence of object shape recognition (for an overview, see Smith, 2009). Smith (2003) found that the number of object names in children's vocabularies was a better predictor of children's shape recognition than was age. Similarly, Jones and Smith (2005) showed delays in visual object recognition in children with delayed vocabulary development.

Learning the names of geometric shapes such as circle, square, and triangle is another common activity in the preschool, and one often included as a goal in early math curricula, but it can be enhanced by the inclusion of odd-looking as well as standard examples (i.e., a scalene triangle as well as an equilateral triangle). Highlighting perceptually different types of triangles may bolster children's comprehension of what a real triangle is. Showing these kinds of shapes supports learning that triangles are any closed figure formed by three intersecting lines, rather than believing that a triangle is a particular perceptually arresting instance (Fisher, Nash, Hirsh-Pasek, Newcombe, & Golinkoff, 2009; Satlow & Newcombe, 1998). Active exploration, in combination with dialogic enquiry (e.g., questions that pose a dilemma or prompt curiosity), has been found to be especially beneficial for learning geometric shapes—even more so than direct instruction (Fisher, Ferrara, Hirsh-Pasek, Newcombe, & Golinkoff, 2010).

Research shows that children as young as 3 years appreciate the relations between maps or models and the real world (DeLoache, 1990; Huttenlocher, Newcombe, & Vasilyeva, 1999; Shusterman, Lee, & Spelke, 2008). Thus, maps can be introduced into classrooms as early as kindergarten, as shown in the *Where Do I Live?* curriculum plan devised by Marcia Harris (2010) of the Brookside School in Michigan. The use of maps as a spatial educational tool may be further supplemented by a variety of classroom activities. For example, children may be asked to find objects hidden in the classroom on the basis of a treasure map. In a first step, children could be asked to hide some objects according to a location on a map. Research has shown that placement tasks are easier as opposed to retrieval tasks and develop 6 months earlier on average (Huttenlocher, Vasilyeva, Newcombe, & Duffy, 2008). In a second step, children could be asked to find objects, according to the information on a map. And finally, they could be asked to put stickers on maps or create their own maps to help them remember where objects are hidden or to help a friend find a hidden object.

Purposeful Use of Media

The use of new media is taking up an increasing amount of children's play time. Computer games are becoming more and more popular, and many infants under 2 years of age are watching TV on a regular basis (Zimmerman, Christakis, & Meltzoff, 2007). But as Paracelsus used to say, "*Dosis sola facit venenum*"—the dose makes the poison, and the right dose differentiates a poison from a remedy. The use of new media in a purposeful way and in moderation may have beneficial effects and provide us with tools for semi-structured education. As reported earlier, research involving new media has shown that playing the computer game Tetris facilitated mental rotation skills in undergraduates and even resulted in long-term transfer effects on other spatial tasks (Terlecki et al., 2008). In another study that explored the effects of playing a multiplayer computer game on learning of simple machines in 10- to 11-year-olds (Annetta, Mangrum, Holmes, Collazo, & Cheng, 2009), it was found that girls did just as well as boys. The authors concluded that using computers and computer games can potentially make science more attractive for females and enhance female performance in science.

Some educational video and TV producers have recently taken notice of the importance of spatial thinking. For example, the popular children's book protagonist *Curious George* now encounters spatial challenges, such as getting lost in a maze, on his TV show. But how well can young children learn from watching TV? A study that compared effects of action experience and observational experience on 14-month-olds' mental rotation performance (Frick & Wang, 2010) indicated that observational experience did not have the same beneficial effects as action experience. This suggests that merely watching someone else performing actions might have little effect on children's spatial learning. So, what are the chances that children learn if this person is only virtually present via TV? A study by Troseth and DeLoache (1998) showed that 2-year-olds were much more likely to use spatial information from a TV screen when they were led to believe that they were looking through a window. Furthermore, Reiser, Tessmer, and Phelps (1984) showed that 4-year-olds were better able to identify numbers and letters that had been presented in a video 3 days earlier, if a live experimenter interacted with them during the video presentation. Thus, learning from TV seems difficult at best and has more of a chance of success if accompanied by social interaction and if a direct connection between what is perceived on the screen and the real world is made clearly evident. However, even though some evidence speaks to the educational value for 3- to 5-year-olds of some TV shows (such as Sesame Street), to date there is no conclusive evidence of benefits for children younger than 3 years (for a review, see Christakis, 2009). At the same time, TV often replaces other activities with guaranteed developmental benefits, such as social interaction, creative play, or even simply sleep.

Especially for younger children, books are more appropriate and—as opposed to TV and videos—may be more likely to involve parent–child interactions. Even though books only contain static pictures, they can also help children understand spatial transformations, if adults read them with the children and stimulate their imagination. There are a number of spatially challenging books that parents or teachers can read with their children, for example *Zoom*, a book in which attention continually zooms into finer and finer levels of detail; verbal and gestural support for children in dealing with the conceptual and graphic challenges has been found to predict children's scores on spatial tests (Szechter & Liben, 2004).

Free Play and Active Experience

It is important to keep in mind that preschool children need to play, refine their motor skills, and practice their imaginative abilities (Hirsh-Pasek, Berk, Singer, & Golinkoff, 2008). It is through play and direct physical experience that children gather most of their knowledge about the laws and rules of the world they live in. Studies on children's intuitive knowledge about physical laws have shown that, even though they might not have abstract, verbal, or conceptual knowledge about spatial events, they often show surprising perceptual-motor knowledge. For example, Krist, Fieberg, and Wilkening (1993) showed that, even though children were not able to adjust the speed of a ball that was propelled off a table, so that it would hit different targets on the ground from different heights, they were able to *throw* the ball with accurate speed. Moreover, active movement has repeatedly been shown to improve performance in spatial tasks (Acredolo et al., 1984; Benson & Uzgiris, 1985; Frick & Wang, 2010; Frick, Daum, Wilson et al., 2009; Rieser et al., 1994). In the classroom, there is not always space to move and actively explore, but luckily it has been shown that even merely encouraging elementary school children to gesture can enhance their ability to reason about spatial transformations, including mental rotation (Ehrlich, Levine, & Goldin-Meadow, 2006, 2009). Using their hands may help children to mentally simulate spatial transformations, possibly by reducing (or "outsourcing") working memory load or by taking advantage of prewired mechanisms of sensory-motor coordination.

Even entirely internalized simulations can help children understand spatial events. Asking children to imagine where things will go when dropped can improve their understanding of gravity and motion. Preschoolers are prone to think that dropped objects will appear directly below where they were released, even when they are dropped into a twisting tube whose exit point is quite far away, but when asked to *visualize* the path before responding they do much better. Simply being asked to wait before answering does not help—visualization is key (Joh, Jaswal, & Keen, in press).

A common and pivotal aspect of all of these suggested activities is to do them *with* the children. Caregivers and educators can then provide children with spatial language that may help them categorize and abstract relevant aspects of their spatial environment, draw their attention to analogies and differences, or simply motivate thought and exploration of space. Opportunities to practice spatial skills are omnipresent: at home, in school, on the way to the supermarket, or on the breakfast table. Spatial tasks and challenges are everywhere: Which way does the sheet fit on the bed? Does the left shoelace go over or under—and which one is the left? Will the groceries fit in one bag? Which shapes do I get if I cut my bagel the other way—and will it still fit in the toaster? For young children, these questions are challenging and provide ample opportunities to learn and think about space. Caregivers and educators simply need to take a step back to recognize these learning opportunities and guide children on their exploration of space.

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NOTES

1 So far, however, the evidence relates only to visualization skills, which are more easily assessed with psychometric tests than navigation skills. Future work is needed to address whether certain kinds of spatial skills are more related to STEM achievement than others or whether each skill has some relevance. For example, Snow's use of a cholera map might be more tied to thinking relevant to navigation than to visualization skill.

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