Chapter 16. Shapes, blocks, puzzles and origami: From spatial play to STEM learning

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We often take for granted our reliance on spatial skills in everyday life, as well as in a variety of professional pursuits. Spatial skills help adults interpret charts, read maps and visualise things they cannot see. They are malleable and foundational skills that start developing early in life and contribute to children's learning and success in science, technology, engineering and mathematics (STEM). Play with spatial toys in early education and home settings offers a promising and underutilised avenue for supporting 21st century skills. In this chapter, we summarise evidence of relations between spatial skills and STEM success. We then present ways in which spatial play activities might support spatial and STEM skills with relatively minor additional investments of parents' or educators' time or money. Suggestions include practical tips for caretakers to use during play. Before concluding, we highlight areas for future research and consideration.

Shapes, blocks, puzzle and origami: From spatial play to STEM learning

There is a growing worldwide acknowledgement that spatial skills exercised during puzzle play, building with construction toys, solving mazes and creating origami are foundational in supporting learning in science, technology, engineering and mathematics (STEM). Spatial skills involve mental manipulation of information about objects in the environment (Uttal et al., 2013[1]) and these skills are malleable. However, educators have likely not exploited them to their full potential in propelling the skills necessary for the 21st Century. Play with spatial toys offers an avenue for addressing this need. Policies that promote spatial toys for parents or integrate them into preschool curricula would likely improve not only spatial skills, but school-age children's learning in a number of subject areas that are of critical worldwide importance.

Adults call on spatial skills every day. Putting together IKEA furniture, remembering where you parked your car, and even something as mundane as navigating in the dark for a midnight bathroom break all require multiple spatial skills. Though we often take these skills for granted, there are negative consequences to common spatial mistakes, like scraping your car as you pull out of a small parking space. Many minor mistakes are only an inconvenience, but spatial errors can be fatal. Improper strap placement when installing a child's car seat can render the seat ineffective. Careers, such as air traffic control, city planning, and architecture, require precise thinking about objects in space, and errors in these careers can be expensive and disastrous.

Activities in which children use their spatial skills may look very different from the spatial activities adults engage in, but the applications are equally varied. As children insert shapes into a sorter, they practice perceiving angles and sizes and manipulating each shape to align it with its slot. When parents name and describe shapes, children start associating those shapes and their features with their labels. Building with blocks, children can visualise the supports their tower needs to stand without toppling and practice remembering where they last saw a needed block. These seemingly playful activities, and many other experiences navigating and exploring their world, provide children the practice they need to perceive, manipulate, label, visualise and remember objects in space.

Despite their importance, spatial skills get exceedingly little attention in formal education. Playful spatial activities like building with blocks are often limited in early education classrooms (Miller, Almon and Cramer, 2009[2]). Instead, the focus is on explicitly teaching the "three R's" (reading, writing and arithmetic). Our tendency to ignore spatial skills might be, in part, due to a belief that people are simply either good or bad at them naturally (Newcombe and Stieff, 2012[3]). Many adults readily admit, without shame, that they have an awful sense-of-direction. Would those people admit if they could not read or do basic addition? We assume that most people can and should learn to read and do basic mathematics but rarely think that they should be competent in spatial skills.

Research demonstrates that both children and adults can improve through spatial training (Hawes et al., 2015[4]; Uttal et al., 2013[1]). In this chapter, we argue that spatial skills are a key part of early learning and build the foundation for development in STEM domains. We first summarise evidence of relations between spatial skills and STEM success. We then present ways in which spatial play activities might support spatial and STEM skills with relatively minor additional investments of time or money. Before concluding, we highlight areas for future research and consideration.

Spatial skills and science, technology, engineering and mathematics (STEM)

Recent decades have seen a global focus on STEM education to better prepare children for the 21st Century workplace. Despite increased attention, though, international rankings show that student performance in mathematics and science remain distressingly low, even for 15-year-olds in many resource-rich countries like the United States (OECD, 2013[5]). Attention to findings from the science of learning can address this problem. Ample evidence reveals empirical links between spatial skills and many STEM domains (Newcombe, 2017[6]). For example, correlational work indicates that individuals with stronger spatial skills perform better in STEM fields (Mix and Cheng, 2012[7]) and high school spatial skills predict later markers of success in STEM careers, like income, patents and achieving tenure at a university (Wai, Lubinski and Benbow, 2005[8]).

Neuroscience offers converging evidence for spatial and STEM skill links. For example, a brain area called the intraparietal sulcus is active when we think about either spatial problems or mathematical magnitudes (Ansari, 2008[9]). Also, certain developmental disabilities involve deficits in both 1) spatial or visual working memory; and 2) learning about mathematics fundamentals like numbers (Szűcs, 2013[10]).

Though more research is required to fully understand the underlying mechanisms, longitudinal work with preschoolers suggests causal links between spatial and STEM skills (Verdine et al., 2017[11]). In addition, benefits of strong spatial skills for STEM outcomes appear to exist regardless of socio-cultural factors like parent education or ability levels in other domains, like executive functioning (i.e. the abilities to control impulses and think flexibly) (Verdine et al., 2014[12]). Support for early spatial development could therefore have broad impacts and, by all current indications, help children from a broad range of nations and cultural situations to learn STEM subjects.

Improving spatial learning

The data from basic science point towards practical applications to support spatial skill development in early childhood. Children's spatial and mathematics skills and the relations between these skills emerge by preschool (Verdine et al., 2017[11]). Although there are a limited number of spatial intervention studies for young children, early indications are promising for important and long-term influences of early training. Mental rotation training, for instance, can positively impact later spatial skills (Hawes et al., 2015[4]), and activities like creating patterns with shapes and building with blocks (Brock et al., 2018[13]) can influence STEM-related skills.

Informed by such research, Head Start and the Common Core Standards have increased their emphasis on spatial concepts. Further, the National Research Council (2006[14]) suggested spatial instruction be blended into the existing curricula. These steps for formal education are promising, but since young children spend most of their time outside of school, experiences in more informal settings are also key to supporting spatial and STEM skills.

Playful learning as a promising pedagogy

Research from the science of learning shows that children learn best when cognitively engaged in activities that present content meaningfully and through social interaction (Hirsh-Pasek et al., 2015[15]). This would suggest that "playful learning" might offer one evidence-based way to facilitate spatial learning and the foundations for STEM development (Hirsh-Pasek and Golinkoff, 2011[16]).

Playful learning encompasses both free play and guided play (Hirsh-Pasek and Golinkoff, 2011[16]). Free play has been characterised by children's unconstrained exploration of objects and situations; guided play is tantamount to constrained tinkering. In guided play, children continue to be in charge, but they do so in a supportive environment that will lead them towards a learning goal. Adults might support children's play by populating the environment with specific toys meant to promote spatial play and by using spatial language. Adults might also scaffold children's learning by asking provocative questions or providing commentary. Based on existing empirical literature, we focus here on a few, readily available, concrete and small-scale playful activities that exemplify promising opportunities for early spatial and STEM learning.

Playful activities

Shapes

Many toys and activities for toddlers and preschoolers feature circles, squares and other geometric shapes. Shape sorters, which require children to insert shapes into matching openings, provide opportunities to manipulate objects in space and to use objects' spatial properties to decide how they fit together. With other toys, too, as children stack shapes, press them to play songs and so forth, there are opportunities for them to learn new words to describe objects, compare and contrast shapes, and count and measure sides or angles. They can also see how shapes relate to each other (e.g. a square can be split into two right triangles). Especially with adult support, children can also use shape toys to identify and complete patterns (e.g. solving for "x" in ▲■■:▲■x). Data suggest that pattern work likely helps children build skills useful in early mathematics (Rittle-Johnson et al., 2015[17]), and the symbolic and analogical reasoning involved relate to broader STEM skills.

One concern about shape toys is that most do not feature a wide variety of shapes (Resnick et al., 2016[18]). Triangles, for example, are usually only represented in the "typical" equilateral form; few toys feature more "atypical" right, isosceles or scalene triangles. This focus on one iconic version might lead children to misunderstand shape categories. For instance, children might believe that all triangles have a point on the top and equal length sides rather than three sides and three angles. Concept learning research suggests that exposure to little shape variety likely contributes to delays in knowing shapes' defining features (Satlow and Newcombe, 1998[19]). While teachers tend to ask children to identify shapes, they less often ask questions or add information to help students learn the features that actually define them (Sarama and Clements, 2004[20]), though such help can be effective. Researchers showed 4- to 5-year-old children typical and atypical real shapes as well as "fake" shapes (e.g. three sides with a gap between two of them) (Fisher et al., 2013[21]). The experimenter used one of three approaches to teaching the differences: a guided play approach to explore distinctions together, a didactic approach where the child was told the differences, or an approach where children played freely with the shapes without adult involvement. Children in guided play showed the strongest ability to identify both typical and atypical real shapes, showing that young children can learn unfamiliar defining features of shapes and that guided play can support these gains. In a forthcoming study, authors of this chapter found that simply including more shape variety got children and adults to use more spatial language during a play session.

If toy developers incorporate more atypical shapes into toys and adults purposely draw children's attention to a variety of exemplars, we can better support early shape knowledge. At the intersection of spatial, language and mathematical skills, shape knowledge is as an important aspect of preschoolers' school readiness, with even kindergarten Common Core curriculum drawing on students' shape knowledge.

Blocks

Construction toys like blocks are relatively affordable, widely available and invite children to experiment with different shapes and sizes. After placing a heavy block atop an unsteady tower, children might also better understand physics concepts, like gravity, as they watch the tower fall. They might then visualise other constructions, increasing their skills in mentally manipulating spatial representations. Such block play involves spatial problem solving and basic engineering.

Using interlocking blocks for new constructions or to recreate models also offers early mathematics practice. Children can count blocks or compare pieces that are four studs long to those that are only two. This play likely promotes concepts of units and part-whole relations, which support understanding of magnitudes, numbers and fractions.

Block play is enjoyable at many ages, which has three advantages: 1) purchases are a long-term investment compared to toys that are quickly "outgrown"; 2) children of mixed ages can learn through each other in joint play; and 3) adults enjoy participating, making it a natural venue for guided play. Though some of the mechanisms for how block building might support specific spatial or mathematical skills are still somewhat speculative, we have seen that children who perform better on spatial construction tasks or who play with more blocks have better spatial skills later (Verdine et al., 2014[12]). Mounting evidence from training studies also shows that experience with construction activities is causally related to growth in spatial skills (Brock et al., 2018[13]).

Puzzles

Another activity for providing spatial education that can be fun for all ages is puzzle assembly. With many puzzles on the market, we can also find puzzles with themes and difficulty levels that are appealing to any child. Vygotsky's zone of proximal development theory suggests that children learn new skills best when challenged but not faced with overly difficult tasks. Many children start with wooden peg-board puzzles that simply require matching the images and shape of each piece to a space in a board. Next is often wooden puzzles with pieces that still overlay directly on an image, but the pieces all fit together inside one large indentation. Finally, children graduate to interlocking jigsaw puzzles where the picture to be replicated (often on the box top) is a different scale, and the builder has to figure out the overall size and shape. Jigsaw puzzle difficulty depends on the size, number and shape of the pieces and on the complexity of the target image.

With so much variety, puzzles can provide opportunities for children of all ability levels to learn and building any of these puzzles involves spatial skills. When children use individual pieces to create the goal image, they tap into part-whole knowledge. They will become faster and more skilful if they develop ways both to predict the appearance of missing pieces and to find them. Adults often help by suggesting children start with a jigsaw puzzle's outer borders, since straight edges will then identify the best candidates. A shape-focused strategy might become increasingly effective as puzzle difficulty increases, based on the number of pieces and repeating patterns (Verdine et al., 2008[22]). Children also might create mental representations of what missing pieces must look like by studying the shapes of the holes they will fill. If unused pieces are in the wrong orientation on the table, the search might invoke mental and physical rotation skills, too.

Though there is still much to learn, current evidence suggests that puzzle building is a good spatial activity. A study of elementary-aged children's puzzle building found high, positive correlations between puzzle performance and mental rotation, spatial perception, and spatial visualisation (Verdine et al., 2008[22]). Another study showed that 2- to 4-year-old children who played with puzzles at home had better spatial skills at 4.5 years old, even after controlling for parents' education, income and language (Levine et al., 2012[23]). Children using harder puzzles experienced more parent engagement and spatial language exposure, too. These results are consistent with puzzle building promoting spatial skills, especially with appropriately difficult puzzles and the supportive context of guided play.

Origami

In origami and other paper building activities, like making paper airplanes, the goal is to fold a piece of paper to create a particular shape, often recreating a model provided through step-by-step diagrams or live demonstration. Children trying to produce a specific crane design must recognise the relation between the model and their own piece of paper, imagine the necessary transformations, and determine if their folds are correct. Origami can also expose children to new spatial terms and concepts, such as mirror images, which are foundational for mental rotation skill development. We know that young adults asked to think aloud while doing origami projects include spatial terms in their speech and produce behaviours indicating spatial concepts (Taylor and Tenbrink, 2013[24]). Researchers have also found increases in spatial skills following origami activities (Taylor and Hutton, 2013[25]), suggesting the origami experience might cause gains.

Techniques for supporting spatial development during play

Regardless of the activity, research identifies specific techniques that are effective for spatial support, and these techniques emerge organically during guided play.

Spatial language

For example, children might put the red block atop the green one as the adult comments, "Wow – you put the triangle on top of the square. Can you find another triangle?" When using guided play with blocks, adults model not only simple shape names, but also descriptions of spatial features, as in, "Are there any smaller triangles in the pile? Do you think it will balance on its point?" Exposure to spatial terms in everyday activities is linked to better spatial skills. In one study, 14- to 46-month-olds whose parents used more spatial terms with them produced more spatial language (concurrently and at 54 months) and scored higher on spatial tasks at 54 months (Pruden, Levine and Huttenlocher, 2011[26]). Other researchers showed preschoolers where they were hiding an object near a box and described the location using either spatial descriptors (e.g. "on the box") or generic language (e.g. "here") (Loewenstein and Gentner, 2005[27]). When researchers asked the children to find another object hidden in an analogous location in another box, those who heard spatial descriptors were more successful than those who heard generic descriptors. Such results suggest that adults can infuse guided play with spatial terms to support spatial learning.

Gestures

Similarly, adults can model and respond to the use of gestures in guided play. If their hands are free, adults might intuitively use gestures that illustrate what they are saying aloud, including their spatial language. For example, during origami, adults can gesture with their right and left hands accordingly, saying, "Now, fold the right side and the left side in so the edges meet in the middle of the piece of paper." Children whose parents accompany more of their spatial language with gestures produce more spatial language themselves (Cartmill et al., 2010[28]), likely supporting their spatial skills. Importantly, children's and adults' gestures sometimes communicate spatial information that is not clear from speech alone (Sauter et al., 2012[29]). Gestures are important aspects of communication that facilitate spatial learning during play.

Future directions

While the current research points to the value of spatial play, further work on the causal relations between different types of spatial activities and gains in specific STEM skills will help further solidify recommendations for interventions. Besides blocks, puzzles and other concrete manipulatives, there is a growing number of digital apps available. More research is needed to better understand how they might facilitate early spatial and STEM skills (Hirsh-Pasek et al., 2015[15]), but a number of chapters in this book indicate that well-designed technology products and other digital media can be useful in education (Chapter 8, by Forbus and Uttal; Chapter 9, by Barron and Levinson; Chapter 10, by Llorente, Moorthy and Dominguez; Chapter 11, by Okita). Regardless of the medium, we also need more data on group and individual differences in the benefits gleaned from spatial play, how much of this play is "enough", and how long effects will last.

Conclusion: Maximising benefits of spatial play

An initial step towards providing early spatial education is ensuring access to toys like shape sorters, blocks, puzzles and origami that lend themselves to spatial play. Even if children then play freely, they will likely encounter spatial experiences. Using guided play, teachers, parents, other adults or older siblings can inject spatial language and gestures and draw attention to spatial components, while still respecting children's direction and interests. Play partners can also adapt to address design features of toys and activities that limit spatial experiences, like having only one type of triangle.

Spatial skills are central to STEM learning, and their malleability suggests that it is worth our effort to promote their development. While further research is needed to identify specific benefits of various activities and test the theoretical links, we already have good evidence that spatial play can increase children's spatial skills. With a general pedagogical approach of playful learning, we can and should embrace these activities and infuse children's play with opportunities to build foundational spatial knowledge.

Policy implications

As a policy, and at a bare minimum, schools should have the suggested spatial materials available to students to use in time they are given for free play. Once materials are in place, teachers can be educated about the importance of spatial skills and encouraged to use the materials. Because many of these spatial materials can be used in fun and playful ways, children tend to enjoy them, which makes it easier for teachers to focus on adding value to their instruction as opposed to managing classroom behaviour. Finally, the general indications are that time spent on spatial training has as much benefit for performance on STEM subjects as time spent on STEM curricula (Lowrie, Logan and Ramful, 2017[30]). Therefore, though it makes sense to try to integrate spatial training into existing instruction, it appears that students across the world would benefit from these recommendations even if some of the time they spend on spatial training replaces time spent on the traditional STEM-focused curricula.

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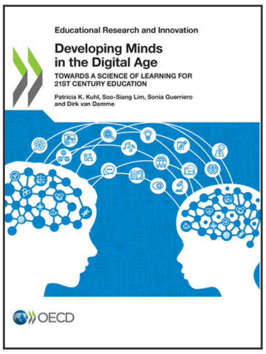
Educational Research and Innovation
Developing Minds in the Digital Age
TOWARDS A SCIENCE OF LEARNING FOR 21ST CENTURY EDUCATION
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