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Spatial Thinking: A Missing Building Block in STEM Education

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> Science is more than a school subject, or the periodic table, or the properties of waves. It is an approach to the world, a critical way to understand and explore and engage with the world, and then have the capacity to change that world..."
>
> — President Barack Obama, March 23, 2015

Spatial thinking: What it is, and why it matters for STEM education

The United States faces two key challenges regarding Science, Technology, Engineering and Mathematics (STEM) education and training: seventy percent of our 15-year-old students score at or below standard levels on tests of math and science (OECD, 2012), and the demand for STEM jobs is outpacing the supply of potential employees (Halpern et al., 2007; U.S. Congress Joint Economic Committee, 2012). The Common Core State Standards for Math, the Next Generation Science Standards, and the focus on STEM within President Obama's Race to the Top initiative reflect these concerns.

One critical building block of success in STEM fields, however, is often overlooked: the ability to think *spatially*. Spatial thinking refers to a set of mental skills that enable us to reason about space and the relationships between objects. We rely on spatial thinking in daily life when we search for specific locations (e.g. where is the supermarket in relation to the library?), use representations of space (such as maps), or imagine what an object might look like rotated or resized. Although spatial skills are often assumed to be innate, evidence from research suggests that they can be taught and improved (Uttal et al., 2013).

Why might spatial skills be important to students' interest and achievement in the STEM fields? Scientific phenomena often involve spatial problems. Take, for example, Rosalind Franklin's discovery of the structure of the DNA molecule: she inferred its 3-dimensional structure from examining 2-dimensional images. America's K-12 students routinely confront spatial problems in science class. Understanding the phases of the moon, visualizing chemical structures, learning about plate tectonics, and reading a graph all rely upon understanding spatial information and phenomena. For example, a graph is a spatial depiction of scientific data used to communicate patterns, such as changes in global temperatures over time, and comprehending graphs requires the student to interpret the spatial patterns depicted. In short, students' spatial capabilities matter for their STEM success in school.

What the research says

- *Spatial skills in middle and high school predict future STEM success*

Longitudinal research over the last 50 years suggests that spatial thinking skills are strongly related to students' entrance into, retention in, and success within STEM disciplines (Shea et al., 2001; Wai et al., 2009). For example, the Project Talent study measured the spatial thinking skills of 400,000 high school students in a nationally representative sample in the 1960s and followed them for 11 years after high school graduation. Students with high spatial thinking skills were more likely to choose STEM majors in college, succeed within those majors, and choose to pursue STEM careers, compared to their peers with low spatial thinking skills. This was true even after controlling for the fact that those students tend to have higher mathematical and verbal skills as well. Other longitudinal studies, in which students' spatial thinking skills were assessed in middle school and followed for 20 years (Shea et al., 2001), or in preschool and followed through high school (Wolfgang et al., 2003), present similar findings.

- *Spatial thinking skills can be trained*

Intentional training can improve spatial thinking skills in both children and adults, the benefits of which are enduring and generalizable to new skills (Uttal et al., 2013). Studies point to three types of *experiences* that can facilitate spatial thinking: practicing spatial skills, such as mental rotation (imagining objects rotating in one's head), for a period of time (e.g., from just 45 minutes to 1 hour per week over 12 weeks); playing video games, such as Tetris, for 1 hour per week for 12 weeks; or participating in semester-long courses that engage spatial reasoning, such as an engineering drafting course. Such training improves performance among a broad spectrum of students: those considered gifted and talented (Miller & Halpern, 2013), students with both high and low spatial thinking skills (Terlecki et al., 2008), and males and females (Uttal et al., 2013).

Spatial skill development has been associated with engagement with spatial play activities, such as with puzzles, blocks, and shapes, among children under the age of 7 (Casey et al., 2008; Jirout & Newcombe, 2015). This association holds even after controlling for other variables, such as parental education, that might influence this relationship. For example, 2- to 4-year-old children who played with puzzles during 6 observational home visits performed better on a measure of mental rotation at $4^{1/2}$ years old than children who had not played with puzzles during home visits (Levine et al., 2011). This study also found that the frequency of play mattered; children who played with puzzles more often, tended to perform better. While such studies do not establish a causal relationship, the findings suggest that spatial play, such as with puzzles, may encourage the development of these skills.

- *Growing evidence suggests that improving students' spatial thinking can improve STEM outcomes.*

Emerging research suggests that bolstering college students' spatial thinking can improve academic achievement in chemistry (Small and Morton, 1983), engineering (Sorby, 2009), calculus (Sorby et al., 2013), and physics (Miller & Halpern, 2013) coursework. In each of these studies, researchers coached students in practicing spatial reasoning and then measured the effect upon a specific STEM outcome, such as calculus grades, compared to a control group, which had not received spatial training. This work focused primarily on college-aged populations. One study in elementary mathematics, however, showed that 6 -to 8-year-old children improved their accuracy on calculation problems such as 3 + ___ = 10 after having practiced mental rotation for 45 minutes. Children who had practiced crossword puzzles, in contrast, saw no such improvement (Cheng and Mix, 2014). This body of work is promising, but it remains to be seen whether these findings extend to larger cohorts of students and whether STEM outcomes can be improved by other methods, such as explicitly incorporating spatial thinking exercises into math and science curricula.

- *Spatial skills are an important component of school readiness and early math skills.*

There is an apparent link between early mathematics skills and spatial reasoning, which suggests that the latter forms a component of school readiness (Verdine et al., 2014a). For example, block-building skills are related to emerging math skills in pre-school children (Verdine et al., 2014b). In one study, the research team gave three-year-olds a block model (several different colored mega-blocks pieces, arranged in a specific configuration) and asked them to recreate the model using individual blocks. The team then compared accuracy on this task with general mathematical ability, such as asking children to count as high as they could without making a mistake or giving the researcher a specific number of objects, such as 4 crayons. The children who copied the block model more ably performed better on the math tasks. This finding is not causal, but it suggests that the relationship between spatial skills and math achievement begins as early as age 3.

Conclusions and Implications

Spatial thinking skills are an important building block of scientific thinking. There is growing recognition of the importance of spatial thinking skills for STEM achievement and these skills have begun to appear in education standards, such as the Common Core State Standards for math and the Next Generation Science Standards. However, very little research on spatial thinking has been translated into PreK-12 educational practices and evaluated for effectiveness. As such, many questions remain. Do interventions that target students' spatial thinking skills lead to improved outcomes in the classroom? What works in teacher preparation programs in this domain? How does professional development on spatial thinking influence teachers' attitudes and self-efficacy? Does equipping child-care and Pre-K programs with spatially rich education centers that include blocks, puzzles, and 2- and 3-dimensional shape games, nurture a capacity and an interest in science and math? Given our country's focus on STEM in K-12 education, evaluating the effect of improving spatial thinking skills in different classroom contexts could prove a critical task that bears long-term fruit for our students.

Works Cited:

Casey, B. M., Andrews, N., Schindler, H., Kersh, J. E., Samper, A., & Copley, J. (2008). The development of spatial skills through interventions involving block building activities. *Cognition and Instruction*, 26(3), 269-309.

Cheng, Y. L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development*, 15(1), 2-11.

Halpern, D. F., Benbow, C. P., Geary, D. C., Gur, R. C., Hyde, J. S., & Gernsbacher, M. A. (2007). The science of sex differences in science and mathematics. *Psychological Science in the Public Interest*, 8(1), 1-51.

Jirout, J. J., & Newcombe, N. S. (2015). Building Blocks for Developing Spatial Skills Evidence From a Large, Representative US Sample, *Psychological science*, 26(3), 302-310.

Miller, D. I., & Halpern, D. F. (2013). Can spatial training improve long-term outcomes for gifted STEM undergraduates? *Learning and Individual Differences*, 26, 141-152.

Newcombe, N. S. (2010). Picture This: Increasing Math and Science Learning by Improving Spatial Thinking. *American Educator*, 34(2), 29.

Newcombe, N. S. (2013). Seeing Relationships: Using Spatial Thinking to Teach Science, Mathematics, and Social Studies. *American Educator*, 37(1), 26.

OECD (2012). Education at a Glance 2012: OECD Indicators, OECD Publishing. http://dx.doi.org/10.1787/eag-2012-en

Shea, D. L., Lubinski, D., & Benbow, C. P. (2001). Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study. *Journal of Educational Psychology*, 93(3), 604.

Small, M. Y., & Morton, M. E. (1983). Research in College Science Teaching: Spatial Visualization Training Improves Performance in Organic Chemistry. *Journal of College Science Teaching*, 13(1), 41-43.

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, 31(3), 459–480.

Sorby, S., Casey, B., Veurink, N., & Dulaney, A. (2013). The role of spatial training in improving spatial and calculus performance in engineering students. *Learning and Individual Differences*, 26, 20-29.

Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology*, 22(7), 996-1013.

U.S. Congress Joint Economic Committee (2012). STEM Education: Preparing for the Jobs of the Future. A Report by the Joint Economic Committee Chairman's Staff Senator Bob Casey, Chair. April, 2012.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: a meta-analysis of training studies. *Psychological Bulletin*, 139(2), 352.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2014a). Finding the missing piece: Blocks, puzzles, and shapes fuel school readiness. *Trends in Neuroscience and Education*, 3(1), 7-13.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., Newcombe, N. S., Filipowicz, A. T., & Chang, A. (2014b). Deconstructing building blocks: Preschoolers' spatial assembly performance relates to early mathematical skills. *Child Development*, 85(3), 1062-1076.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, 101(4), 817.

Wolfgang, C., Stannard, L., & Jones, I. (2003). Advanced constructional play with LEGOs among preschoolers as a predictor of later school achievement in mathematics. *Early Child Development and Care*, *173*(5), 467-475.