Seeing Relationships

Using Spatial Thinking to Teach Science, Mathematics, and Social Studies

ILLUSTRATIONS BY LAURA MCCABE

By Nora S. Newcombe

Alchemists, who searched for centuries for a method of making gold from less valuable metals, may seem like scientists. After all, they *experimented*—that is, they combined various substances in various ways to see if they could manufacture gold. Yet alchemists are not commonly called scientists. They experimented rather blindly, without understanding the underlying system of elements and the mechanisms of their chemical combination. During the 18th and 19th centuries, mathematical formulations such as Boyle's law began to change alchemy into the science of chemistry. Still, the major event in systematizing our knowledge of elements and chemical reactions—and thus creating a real science—was the periodic table proposed by Dmitri Mendeleev in 1869. The periodic table is one of the most recognizable spatial structures in all of science. Its famous rows and columns organize the relationships among elements. For scientists, looking at the table allows for predictions, including the possible existence of undiscovered elements. For students, looking at the table may provoke questions that will deepen their understanding—for example, why are two elements alone at the top, at opposite sides of the table?

The use of spatial relationships to make scientific discoveries and to communicate mathematical and scientific insights is not unique to chemistry. Just 15 years before Mendeleev published

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his periodic table, a London physician named John Snow was confronting an epidemic of cholera. Many people thought at the time that cholera was caused by "miasma," or bad air, but Snow noted that the cholera cases were clustered—and wouldn't that be odd if the bad air hypothesis were true? Suspicious that the disease was actually caused by bad water, he made a map showing where sick people were living. He also placed marks on the map to indicate the locations of the pumps from which Londoners of the time obtained their water (see Figure 1 below). On this map, the clustering of cholera cases around the pump located on Broad Street was easily visible, which led Snow to conclude that water was more likely the problem than air. Snow has been called the founder of modern epidemiology, but he could just as well be called the founder of social studies. Maps are a potent tool in discovering how things go together in anthropology, geography, economics, sociology, and history.

Tables and maps are not the only powerful spatial learning tools. There are graphs and diagrams, photographs of objects seen through microscopes and telescopes, and sketches and drawings made both as records of observations and "on the fly," as people work to imagine and communicate scientific laws. Let's look at one more example of the power of spatial representations: how a graph can communicate about economics very clearly and in a way that provokes reflection and question-asking. The graph in Figure 2 (below right) of job losses and gains in the American economy over the past decade looks like a roller coaster ride. On closer examination, we see the job losses that occurred in the economic crisis of 2008–2009, and then we see a slow, steady rebound beginning in 2010, with growth at a rate pretty equivalent to growth before the downturn. We also see that this growth is not sufficient to get us back on track relative to where we might have been without the downturn. All of these facts, both the good news and the bad news, are simultaneously evident—at least to a student who knows how to read graphs.

The Role of Spatial Ability

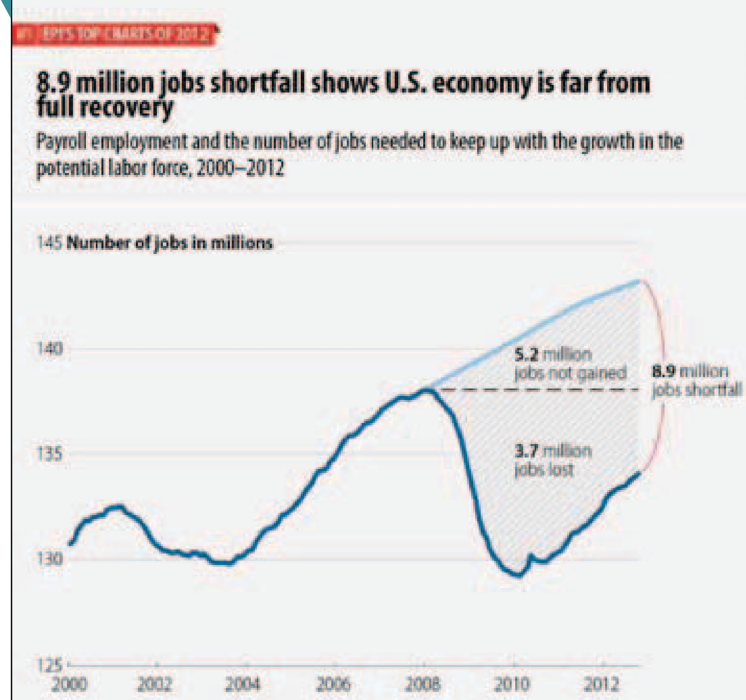
Ideally, learning science, mathematics, and social studies ought to be intensely spatial activities. And in some ways they are. Middle school science textbooks, for example, typically feature about one image per page.[1] Yet many students could use a lot more help in learning how to interpret these visualizations. Some students seem to cope better than others with the spatial demands of learning science and social studies, as well as with the spatial aspects of mathematics (including geometry, trigonometry, and graphing algebraic functions). Research shows that students high in spatial ability learn better from visualizations than students with lower spatial ability.[2] Likely as a consequence of such differences in learning, higher spatial ability predicts

> Teachers can help students strengthen their ability to learn spatially and benefit from studying visualizations such as maps and graphs.

Figure 1

SOURCE: WWW.EN.WIKIPEDIA.ORG/WIKI/FILE:SNOW-CHOLERA-MAP.JPG.

Figure 2



SOURCE: ECONOMIC POLICY INSTITUTE, "CHARTING THE STATE OF THE U.S. ECONOMY: EPI'S TOP CHARTS OF 2012," WWW.EPI.ORG/PUBLICATION/TOP-CHARTS-2012. REPRINTED WITH PERMISSION.

interest and success in the STEM disciplines (science, technology, engineering, and mathematics). Even after accounting for verbal and mathematical ability, high school students with higher spatial scores are more likely to be working in the STEM disciplines during their adult lives.[3] Similarly, preschoolers who perform better on a test of spatial transformations are better at mathematics as 8-year-olds, even after accounting for verbal ability.[4] In addition, professionals in the STEM disciplines, especially the geosciences and geography, report being better able to navigate their environments than people working in other occupations.[5] Navigation, or "wayfinding," is a somewhat different kind of spatial ability than the mental rotation tasks (see box below) typically used to assess spatial ability, but navigation may be as important in STEM learning and social studies learning as mental rotation, likely because of the usefulness of maps.

What do these findings mean for teachers? We'll take a look at that issue in a moment. But to avoid any misunderstanding, let's begin by explicitly stating what the findings do *not* mean. First, they don't mean that verbal explanation is unimportant, or that expressing ideas in mathematical equations is wrong. Verbal, mathematical, and spatial presentations all have both strengths and weaknesses, and classroom practices should include all of these kinds of communication. Second, these findings don't mean that individual students have individual "learning styles,"* and that some students learn better by reading text and listening to lectures, while other students should study diagrams and graphs. In fact, there is currently little scientific evidence for the existence of learning styles.[6] Third, these findings do not mean that students with lower spatial ability should be directed to non-STEM occupations and encouraged to concentrate on humanities or business. Instead, teachers can help such students strengthen their ability to learn spatially and benefit from studying visualizations such as maps and graphs.

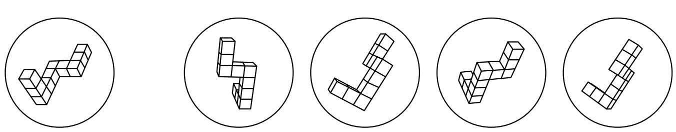
*For a detailed explanation, see "Do Visual, Auditory, and Kinesthetic Learners Need Visual, Auditory, and Kinesthetic Instruction?," by Daniel T. Willingham, in the Summer 2005 issue of *American Educator*, available at www.aft.org/newspubs/periodicals/ae/summer2005/willingham.cfm.

What Is Spatial Ability and How Is It Measured?

Spatial thinking concerns the locations of objects, their shapes, their relations to each other, and the paths they take as they move. Spatial ability is typically measured through tests that ask people to form accurate mental images of spatial relationships and then change them in some way. For example, a very common test item is to ask people to mentally rotate objects like this:

Look at this object:

Two of these four drawings show the same object. Can you find the two?



SOURCE: VANDENBERG, S. G., & KUSE, A. R. MENTAL ROTATIONS, A GROUP TEST OF THREE-DIMENSIONAL SPATIAL VISUALIZATION. *PERCEPTUAL AND MOTOR SKILLS*, 1978, 47, 599–604. © PERCEPTUAL AND MOTOR SKILLS 1978. REPRINTED WITH PERMISSION.

For more examples of how spatial ability can be measured, see the box on page 30 of "Picture This: Increasing Math and Science Learning by Improving Spatial Thinking," an article I wrote for the Summer 2010 issue of *American Educator*. It is available for free at http://bit.ly/bxTc5Q. –N.S.N.

Improving Spatial Ability

It may seem surprising to say that spatial ability can be improved. Intellectual abilities of all kinds are sometimes presumed to be fixed and immutable.† But we have known for decades that, in fact, schooling improves IQ.[7] Spatial ability is no exception to this rule. Together with colleagues at Northwestern University, I recently completed a meta-analysis that examined hundreds of studies of the effects of education and training on different kinds of spatial ability at different ages and for both genders.[8] We found that practicing tasks like mental rotation made performance on tests of this ability faster and more accurate. But simple practice can be boring, so it's important that we also found that relevant academic coursework, such as taking a drafting class, created improvements. So did informal recreational activities such as playing computer games like Tetris, in which falling shapes must be rotated to fit a matrix at the bottom of the screen. Even more important, we found that the spatial improvements created by such activities were durable, lasting at least several months (the longest interval tested in enough studies to be sure of the reliability of the findings). We also found that the improvements generalized, or transferred, at least to somewhat similar spatial tests; for instance, mental rotation training can help you imagine folding a piece of paper into a three-dimensional figure, rather than just helping with mental rotation.[9] Participants of all ages showed improvements too. It didn't seem to be the case that "you can't teach old dogs new tricks."

Are There Sex Differences in Spatial Ability?

What about sex differences? Girls and women usually do not do as well as boys and men on tests of mental rotation, or on some other spatial tests, such as drawing water levels in tilted bottles[10] or constructing cognitive maps from navigation experiences.[11] Does this mean that women are less likely than men to succeed in STEM occupations, perhaps for some immutable biological reason? The answer is no. First, we have to keep in mind that differences between the sexes exist on the average, but that particular women are often better at spatial thinking than particular men. In fact, the distributions of ability for men and for women overlap so much that large numbers of women have better spatial abilities than large numbers of men. Second, we don't really know the causes of these sex differences in spatial ability,[12] and puzzling questions surround them. For example, sex differences are usually not observed in measures of mental imaging of folding two-dimensional paper into three-dimensional structures,[13] even though we know mental folding shares enough cognitive processes with mental rotation that training on one task improves performance on the other.[14] Third, and most important, the meta-analysis my colleagues and I recently completed showed that

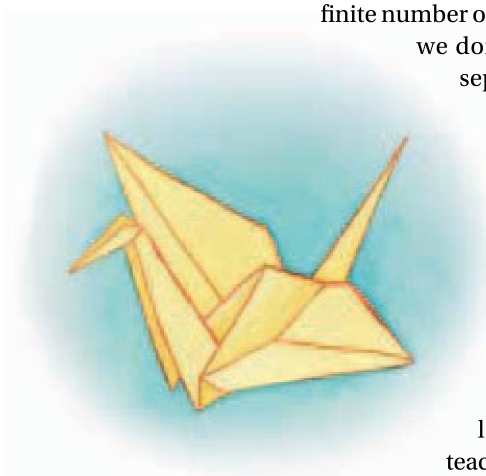
†For a thorough examination of IQ and how to increase it, see "Schooling Makes You Smarter," by Richard E. Nisbett, which begins on page 10 of this issue.

spatial ability is not immutable, and that improvements are very possible. So, there is reason to hope that sex differences could be eliminated through education. Although the meta-analysis indicated that males and females seem to improve in parallel, leaving everyone with better spatial thinking but with males (on average) still excelling,[15] better teaching methods as well as spatial videogames that are more engaging to girls[16] might change this state of affairs in the future.

Practical Consequences

There may be practical consequences to the fact that spatial ability can be improved through education and training. Take the case of engineering. The United States probably could use more engineers,[17] but engineering is a very spatial occupation. If we improved the spatial ability of high school graduates by as much as the meta-analysis tells us we can improve it, then many more people each year would be ready for rigorous training to become engineers. Of course, not everyone who has the requisite spatial ability would be attracted to engineering, and some people might not succeed in it for reasons other than intellectual ability, but the pool of people who might want to at least consider becoming engineers would be increased.

Studies have shown that improvements in spatial ability lead to better grades in chemistry and in physics, as well as to better essays on a problem in geoscience.



Is there direct experimental proof of the hypothesis that interventions that improve spatial ability lead to improved learning of science, mathematics, and social studies? The answer is yes, although many of the studies are new and more work remains to be done. For young children, it seems that training in spatial transformation skills can lead to better performance on arithmetic problems that require spatial representations of what is going on, such as missing addend problems like *3 plus what equals 7*.[18] In fact, the intervention does not need to be explicitly focused on spatial problems, and it can be an enjoyable recreational activity. An afterschool program in which children used arts and crafts materials to make designs (such as an *Ojo de Dios* created by weaving yarn around two sticks, or a pattern constructed using blocks or beads) also led to better math scores in an intervention study with at-risk children.[19] Arts programs have an effect on older students as well. In high school, students taking visual arts gained more in geometry knowledge over the year than students in a theater course or involved in playing squash.[20] For college students, studies with strong methodologies have shown that creating improvements in spatial ability leads to better grades in chemistry[21] and in physics,[22] as well as to better essays on a problem in geoscience.[23]

How Do We Integrate Spatial Learning into Our Crowded Curriculum?

These findings are exciting, but there is an obvious practical problem in acting on the experiments we have considered so far: there is little if any niche in the crowded curriculum to implement most of the interventions discussed, such as extensive practice in solving mental rotation problems or playing videogames. The lack of time is an increasing problem as children advance into middle and high school, where teachers often have too much content in science, mathematics, or social studies to communicate in a very finite number of class periods. Luckily, it turns out that we don't really have to engage students in separate spatial studies. We can "spatialize" the existing curriculum rather than conduct decontextualized spatial training, a strategy recommended in the report *Learning to Think Spatially*, which was published in 2006 by an expert panel convened by the National Research Council of the National Academies.‡

Spatializing the curriculum needs to begin with policymakers, curriculum developers, administrators, and teachers knowing more about spatial ability and understanding the need to infuse spatial thinking into the normal school day. As a simple example, the timetable for the day's activities in an elementary school classroom could be set up so that the shorter time periods take up a smaller space and the longer time periods take up a longer space, reinforcing the idea that graphic variation in spacing can have real meaning. There are many other strategies for developing spatial ability and skills in preschool and elementary school, such as doing jigsaw puzzles, promoting guided play with blocks and geometric shapes, and reading books with spatial words in them. Ideas for prekindergarten through grade 4 are presented in some detail in a previous article in *American Educator*.§ In the remainder of this article, let's take a look at some strategies for middle school and high school.

Strategies for Spatializing Middle and High School Curricula

In this section, we discuss four specific strategies for enhancing and supporting the spatial aspects of the science, mathematics, and social studies curricula. However, these four strategies are examples of what can be done, not an exhaustive list. The overarching concept is to embrace the spatial visualizations used for discovery and communication in these subject areas, helping students learn to read, discuss, and even create these visualizations. Doing so will aid the transmission of content and the future

‡To read this report online for free, go to www.bit.ly/Rw6uv.

§See "Picture This: Increasing Math and Science Learning by Improving Spatial Thinking," by Nora S. Newcombe, in the Summer 2010 issue of *American Educator*, available at www.aft.org/pdfs/americaneducator/summer2010/Newcombe.pdf.

learning of new content, and the meta-analysis indicates it will probably act as a spatial skills training of its own.

Teach Students How to Read Diagrams

Teachers might assume that their students can read the diagrams that appear on almost every page of science textbooks. In fact, many students often have little idea what the arrows in diagrams may mean, or how the zoom-outs or cutaways relate to the main diagram, and they often fail to read the captions and legends. Some students may rarely consult the diagrams at all, despite the fact that diagrams frequently present information that is not also presented in the verbal text. Consider a typical diagram such as the one shown below in Figure 3. What do the arrows mean, and why are they different colors? What is a cross section (and what is viewed from above)? Where exactly is the water, and where is the land? Identification of "three driving forces" is the goal of the diagram according to the title, but what will the student who fails to read the title learn from the diagram?

How can this situation be changed? One method is to improve the diagrams. Even students with low spatial ability learn more from improved visualizations.[24] However, teachers do not have time to rethink even half of the diagrams in their students' textbooks, so teachers should try to figure out which handful of diagrams are most critical for each course and focus on improving those. A second strategy is probably even more practical: teachers can take a little bit of time to teach diagram reading explicitly. Along with a team of colleagues, I have developed and evaluated workbooks that take just a few minutes here and there to communicate the importance of captions and legends, and to instruct students on the conventions of diagrams—for example, the various things that arrows can mean, including simple labeling, temporal ordering, causation, and so forth. These exercises, used in a 10th-grade biology class, had positive effects on students' ability to gain information from new diagrams.[25] And in turn, being able to read diagrams has positive effects on learning content. In one study, students learned more about the circulatory system when asked to explain diagrams than when asked to explain text.[26] In fact, diagrams may have positive effects on learning primarily when students actively engage with them in ways that support them in constructing explanations of scientific phenomena.[27]

> Active sketching enhances engagement, deepens understanding, requires reasoning, forces ideas to be made explicit, and supports communication in work groups.

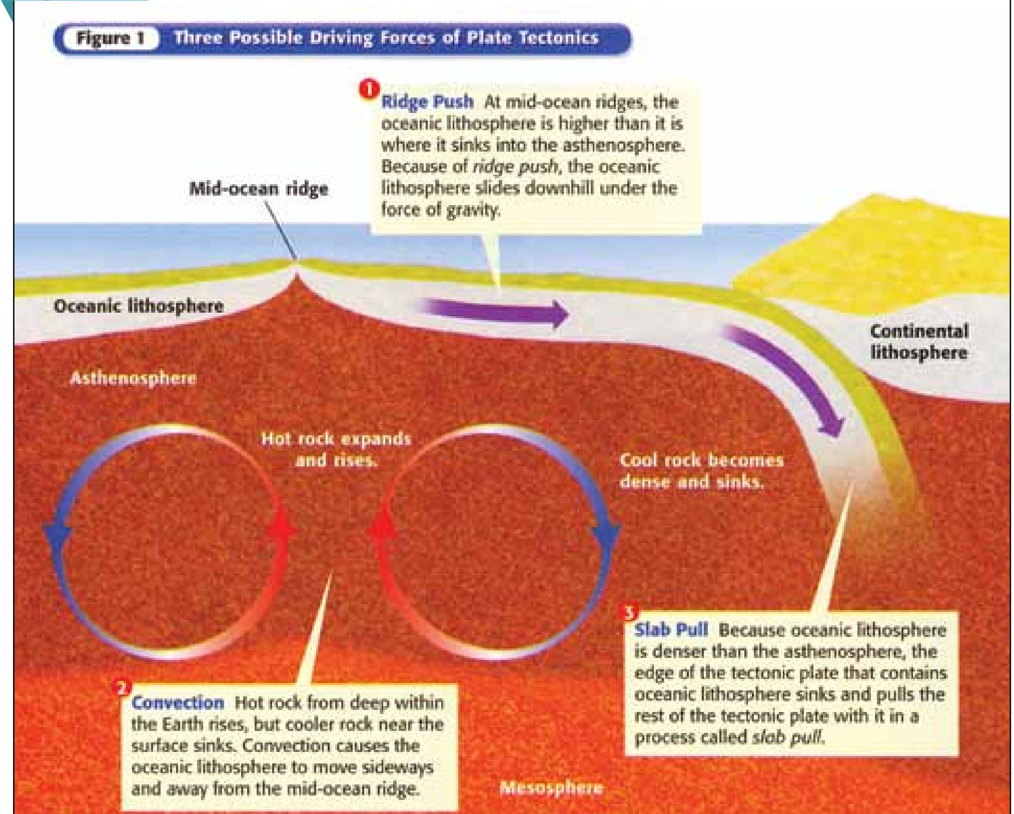
Encourage Students to Sketch

Scientists often draw as they make observations, or as they strive to develop ideas in conversations with other scientists. But students are typically asked to interpret visualizations created by others, rather than being asked to do their own sketching. Research reveals five reasons why active sketching is a good idea: it enhances engagement, deepens understanding, requires reasoning, forces ideas to be made explicit, and supports communication in work groups.[28] For example, Figure 4 (on page 31) shows a student's drawing from a project in which children between 10 and 13 used drawing to learn about evaporation. It is easy to see the engagement and reflection that went into creating it.[29]

Use Maps and Tools from Geographic Information Systems

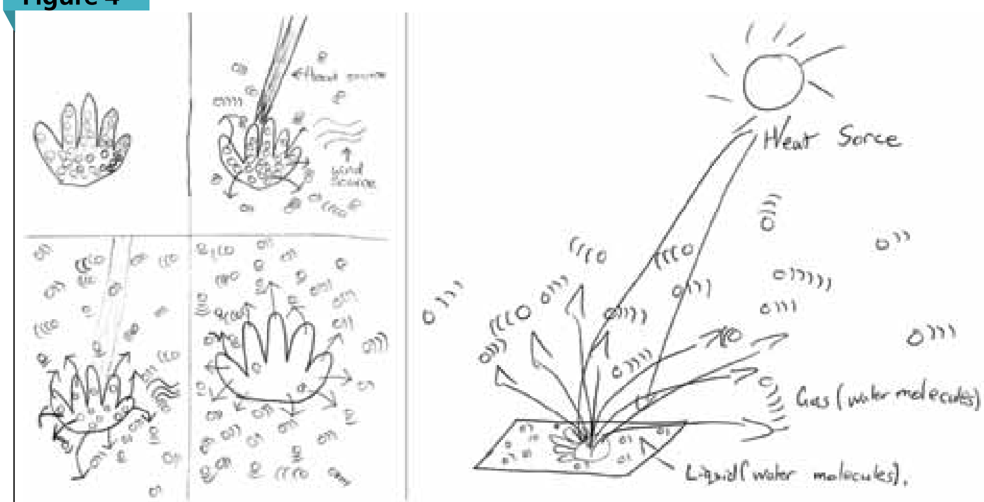
Geographic information systems (GIS) are technical tools of great power, involving overlays of maps of different distributions to create hypotheses and lay bare relationships. In fact, that is essen-

Figure 3



SOURCE: *HOLT SCIENCE & TECHNOLOGY: INSIDE THE RESTLESS EARTH*, TEACHER'S EDITION (HOLT, RINEHART AND WINSTON, 2007), 110.

Figure 4



SOURCE: SHAARON AINSWORTH, VAUGHAN PRAIN, AND RUSSELL TYTLER, "DRAWING TO LEARN IN SCIENCE," *SCIENCE* 333, NO. 6046 (2011): 1096–1097. REPRINTED WITH PERMISSION FROM AAAS.

tially what John Snow did—he overlaid a map showing cases of cholera with a map showing the locations of pumps. Learning GIS thoroughly requires several courses at the university level. But luckily, more user-friendly versions of GIS have been developed that can serve as tools in middle and high schools. One initial project was My World GIS, but most school-friendly GIS packages are now provided by the Environmental Systems Research Institute (Esri), which also supports user communities, archives sample lessons, and holds an annual conference.* The use of GIS for curriculum support is exemplified in the development of a Geospatial Semester† for high school students, in which the students are challenged to solve real-world problems using GIS techniques.[30] For example, one student worked on this question: What are the best locations for bears in a national park, given elevations, food sources, and the need to keep the bears reasonably distant from hiking trails? Another student investigated this problem: Where should we best locate wind farms on the East Coast of the United States, given shipping routes, bird migration patterns, and proximity to electrical grids? The teaching of history is also increasingly using maps and interactive mapping techniques.[31] Stanford University's Geospatial Network, for example, has used GIS to better understand the history of the Roman Empire in the context of the possible transportation routes of the time.‡ The "Roman road" acquires real meaning when analyzed in this way.

Support Students in Understanding Very Large and Very Small Spaces and Times

Understanding scale is fundamental in science education. Science is replete with very small distances (atoms) and very large distances (galaxies) as well as very short time scales (nanoseconds) and very long time scales (the age of the Earth). Social studies is less extreme, but time periods are long relative to students' lifetimes, spatial distances among cultures can be much greater than students easily understand, and economics can involve larger numbers than they usually encounter. Scale comprehension is difficult. However, scaling can be improved. My colleagues and I built on the fact that people typically represent magnitude information in a hierarchically organized structure, in which their lifetime, for example, is nested within the history of the United States, which is nested within recorded history, and so on.[32] We created an intervention to help students understand the age of the Earth. Half the students in an undergraduate introductory-level geology class were given multiple opportunities to progressively align time to a constant spatial scale in a linear representation and to locate all previous scales relative to the current scale. The other half of the class served as the control group. The intervention group demonstrated a more accurate sense of the relative durations of geological events and a reduction in the magnitude of temporal location errors relative to the control group. These findings are clearly only a starting point, but they suggest that cognitive science will soon be ready to help teachers communicate more effectively about the very challenging concept of scale.

Science, mathematics, and social studies are deeply spatial subjects. Currently, students who come to class with higher levels of spatial ability take more easily to learning in these areas, but this fact does not mean we cannot teach in a way that maximizes learning for all. Spatial ability can be improved both inside and outside the classroom, as well as by instruction in other subject areas, notably the visual arts. Spatializing the curriculum by including and explicitly teaching the spatial symbol systems that lie at the heart of science, mathematics, and social studies is an achievable and worthwhile goal. ☐

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*To learn more about My World GIS, see www.myworldgis.org/myworld. To investigate Esri software and support, see www.esri.com/Industries/k-12/education/educators.

†To learn more about Geospatial Semester, see www.isat.jmu.edu/geospatialsemester.

‡To see this GIS approach to the Roman Empire, go to www.stanford.io/XyK0SY.

Endnotes

1. Scott W. Slough, Erin M. McTigue, Suyeon Kim, and Susan K. Jennings, "Science Textbooks' Use of Graphical Representation: A Descriptive Analysis of Four Sixth Grade Science Texts," *Reading Psychology* 31, no. 3 (2010): 301–325.

2. Tim N. Hoffler, "Spatial Ability: Its Influence on Learning with Visualizations—A Meta-Analytic Review," *Educational Psychology Review* 22, no. 3 (2010): 245–269.

3. Jonathan Wai, David Lubinski, and Camilla P. Benbow, "Spatial Ability for STEM Domains: Aligning Over 50 Years of Cumulative Psychological Knowledge Solidifies Its Importance," *Journal of Educational Psychology* 101, no. 4 (2009): 817–835.

4. Elizabeth A. Gunderson, Gerardo Ramirez, Sian L. Beilock, and Susan C. Levine, "The Relation between Spatial Skill and Early Number Knowledge: The Role of the Linear Number Line," *Developmental Psychology* 48, no. 5 (2012): 1229–1241.

5. Mary Hegarty, Raymond D. Crookes, Drew Dara-Abrams, and Thomas F. Shipley, "Do All Science Disciplines Rely on Spatial Abilities? Preliminary Evidence from Self-Report Questionnaires," *Spatial Cognition VII* (2010): 85–94.

6. Harold Pashler, Mark McDaniel, Doug Rohrer, and Robert Bjork, "Learning Styles: Concepts and Evidence," *Psychological Science in the Public Interest* 9, no. 3 (2008): 105–119.

7. Stephen J. Ceci, "How Much Does Schooling Influence General Intelligence and Its Cognitive Components? A Reassessment of the Evidence," *Developmental Psychology* 27, no. 5 (1991): 703.

8. David H. Uttal, Nathaniel G. Meadow, Elizabeth Tipton, Linda L. Hand, Alison R. Alden, Christopher Warren, and Nora S. Newcombe, "The Malleability of Spatial Skills: A Meta-Analysis

(Continued on page 40)

School Ties

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says, so too should teacher preparation programs focus on subject-matter expertise plus child development, a basic science of teaching. Though he has yet to convince these institutions that teachers are child developers, he remains undeterred. "That's work to be done," he says, adding in his unassuming way, "I'm around until that happens."[30] ☐

Endnotes

1. James P. Comer, *Maggie's American Dream* (New York: New American Library, 1988), 86–87.

2. James P. Comer, phone interview by the author, January 22, 2013.

3. James P. Comer, Edward T. Joyner, and Michael Ben-Avie, *Six Pathways to Healthy Child Development and Academic Success: The Field Guide to Comer Schools in Action* (Thousand Oaks, CA: Corwin, 2004), 17.

4. James P. Comer, interview by the author, October 22, 2012.

5. Comer, interview, October 22, 2012.

6. Comer, interview, October 22, 2012.

7. James P. Comer, *Leave No Child Behind: Preparing Today's Youth for Tomorrow's World* (New Haven, CT: Yale University Press, 2004), 131.

8. Comer, *Leave No Child Behind*, 132.

9. Comer, *Leave No Child Behind*, 133.

10. Comer, *Leave No Child Behind*, 17.

11. Comer, *Leave No Child Behind*, 22.

12. Comer, interview, October 22, 2012.

13. Comer, interview, October 22, 2012.

14. Comer, interview, October 22, 2012.

15. James P. Comer, "Educating Poor Minority Children," *Scientific American* 259, no. 5 (November 1988): 8.

16. Comer, phone interview by the author, October 23, 2012.

17. Comer, interview, October 22, 2012.

18. James P. Comer, *What I Learned in School: Reflections on Race, Child Development, and School Reform* (San Francisco: Jossey-Bass, 2009), xx–xxi.

19. Thomas D. Cook, Farah-Naaz Habib, Meredith Phillips, Richard A. Settersten, Shobha C. Shagle, and Serdar M. Degirmencioglu, "Comer's School Development Program in Prince George's County, Maryland: A Theory-Based Evaluation," *American Educational Research Journal* 36, no. 3 (Fall 1999): 584–585.

20. Comer, Joyner, and Ben-Avie, *Six Pathways to Healthy Child Development and Academic Success*, 16.

21. Camille A. Farrington, Melissa Roderick, Elaine Allensworth, Jenny Nagaoka, Tasha Seneca Keyes, David W. Johnson, and Nicole O. Beechum, *Teaching Adolescents to Become Learners: The Role of Noncognitive Factors in Shaping School Performance; A Critical Literature Review* (Chicago: Consortium on Chicago School Research, June 2012).

22. Valerie E. Lee, Julia B. Smith, Tamara E. Perry, and Mark A. Smylie, *Social Support, Academic Press, and Student Achievement: A View from the Middle Grades in Chicago* (Chicago: Consortium on Chicago School Research, October 1999).

23. Charles M. Payne, "Demanding and Supporting Success: Collective Memories of Great Teaching," *American Educator* 35, no. 1 (Spring 2011): 16.

24. Payne, "Demanding and Supporting Success," 15.

25. James J. Heckman, "The Economics of Inequality: The Value of Early Childhood Education," *American Educator* 35, no. 1 (Spring 2011): 34.

26. Angela Lee Duckworth, Heidi Grant, Benjamin Loew, Gabriele Oettingen, and Peter M. Gollwitzer, "Self-Regulation Strategies Improve Self-Discipline in Adolescents: Benefits of Mental Contrasting and Implementation Intentions," *Educational Psychology* 31, no. 1 (2011): 23.

27. Comer, interview, October 22, 2012.

28. Comer, interview, October 22, 2012.

29. Comer, interview, October 22, 2012.

30. Comer, interview, October 22, 2012.

Seeing Relationships

(Continued from page 31)

of Training Studies," *Psychological Bulletin* (published online, June 4, 2012; print forthcoming).

9. Rebecca Wright, William L. Thompson, Giorgio Ganis, Nora S. Newcombe, and Stephen M. Kosslyn, "Training Generalized Spatial Skills," *Psychonomic Bulletin & Review* 15, no. 4 (2008): 763–771.

10. Ross Vasta and Lynn S. Liben, "The Water-Level Task: An Intriguing Puzzle," *Current Directions in Psychological Science* 5, no. 6 (1996): 171–177.

11. Toru Ishikawa and Daniel R. Montello, "Spatial Knowledge Acquisition from Direct Experience in the Environment: Individual Differences in the Development of Metric Knowledge and the Integration of Separately Learned Places," *Cognitive Psychology* 52, no. 2 (2006): 93–129.

12. Diane F. Halpern, Camilla P. Benbow, David C. Geary, Ruben C. Gur, Janet Shibley Hyde, and Morton Ann Gernsbacher, "The Science of Sex Differences in Science and Mathematics," *Psychological Science in the Public Interest* 8, no. 1 (2007): 1–51.

13. Justin Harris, Kathryn Hirsh-Pasek, and Nora S. Newcombe, "Understanding Spatial Transformations: Similarities and Differences between Mental Rotation and Mental Folding," *Cognitive Processing* (published online, February 9, 2013; print forthcoming).

14. Wright et al., "Training Generalized Spatial Skills."

15. Uttal et al., "The Malleability of Spatial Skills."

16. Melissa S. Terlecki and Nora S. Newcombe, "How Important Is the Digital Divide? The Relation of Computer and Videogame Usage to Gender Differences in Mental Rotation Ability," *Sex Roles* 53, nos. 5–6 (2005): 433–441.

17. Deborah D. Stine and Christine M. Matthews, *The U.S. Science and Technology Workforce* (Washington, DC: Congressional Research Service, June 30, 2009).

18. Yi Ling Cheng and Kelly S. Mix, "Spatial Training Improves Children's Mathematics Ability," *Journal of Cognition and Development* (published online, September 19, 2012; print forthcoming).

19. David W. Grissmer, Andrew J. Mashburn, Elizabeth Cottone, Wei-Bing Chen, Laura L. Brock, William M. Murrah, Julia Blodgett, and Claire Cameron, "Play-Based After-School Curriculum Improves Measures of Executive Function, Visuospatial and Math Skills and Classroom Behavior for High Risk K–1 Children" (paper to be presented at the biennial meeting of the Society for Research in Child Development, Seattle, April 2013).

20. Lynn T. Goldsmith, Ellen Winner, Lois Hetland, Craig Hoyle, and Candace Brooks, "Relationship between Visual Arts Learning and Understanding Geometry" (paper to be presented at the biennial meeting of the Society for Research in Child Development, Seattle, April 2013).

21. Melinda Y. Small and Mary E. Morton, "Research in College Science Teaching: Spatial Visualization Training Improves Performance in Organic Chemistry," *Journal of College Science Teaching* 13, no. 1 (1983): 41–43.

22. David I. Miller and Diane F. Halpern, "Can Spatial Training Improve Long-Term Outcomes for Gifted STEM Undergraduates?," *Learning and Individual Differences* (published online, March 29, 2012; print forthcoming).

23. Christopher A. Sanchez, "Enhancing Visuospatial Performance through Video Game Training to Increase Learning in Visuospatial Science Domains," *Psychonomic Bulletin & Review* 19, no. 1 (2012): 58–65.

24. Hoffler, "Spatial Ability: Its Influence on Learning with Visualizations."

25. Jennifer G. Cromley, Anthony C. Perez, Shannon Fitzhugh, Jacqueline C. Tanaka, Nora S. Newcombe, Thomas F. Shipley, and Theodore W. Wills, "Improving Students' Diagram Comprehension with Classroom Instruction," *Journal of Experimental Education* (forthcoming).

26. Shaaron Ainsworth and Andrea Loizou, "The Effects of Self-Explaining When Learning with Text or Diagrams," *Cognitive Science* 27, no. 4 (2003): 669–681.

27. Jennifer G. Cromley, Bradley W. Bergey, Shannon Fitzhugh, Nora S. Newcombe, Theodore W. Wills, Thomas F. Shipley, and Jacqueline C. Tanaka, "Effects of Three Diagram Instruction Methods on Transfer of Diagram Comprehension Skills: The Critical Role of Inference while Learning," *Learning and Instruction* (forthcoming).

28. Shaaron Ainsworth, Vaughan Prain, and Russell Tytler, "Drawing to Learn in Science," *Science* 333, no. 6046 (2011): 1096–1097; and Kenneth Forbus, Jeffrey Usher, Andrew Lovett, Kate Lockwood, and Jon Wetzel, "CogSketch: Sketch Understanding for Cognitive Science Research and for Education," *Topics in Cognitive Science* 3, no. 4 (2011) 648–666.

29. Ainsworth, Prain, and Tytler, "Drawing to Learn in Science."

30. Robert A. Kolvoord, Michael Charles, and Steve Purcell, "What Happens after the Professional Development: Case Studies on Implementing GIS in the Classroom," in *Teaching Science and Investigating Environmental Issues with Geospatial Technology*, ed. James MaKinster, Nancy Trautmann, and Michael Barnett (New York: Springer, forthcoming).

31. Amy Hillier and Anne Kelly Knowles, eds., *Placing History: How Maps, Spatial Data, and GIS Are Changing Historical Scholarship* (Redlands, CA: Esri Press, 2008).

32. Ilyse Resnick, Thomas F. Shipley, Nora S. Newcombe, Christine Massey, and Theodore W. Wills, "Examining the Representation and Understanding of Large Magnitudes Using the Hierarchical Alignment Model of Analogical Reasoning," in *Proceedings of the 34th Annual Conference of the Cognitive Science Society*, ed. Naomi Miyake, David Peebles, and Richard P. Cooper (Austin, TX: Cognitive Science Society, 2012).

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