Current Directions in Psychological Science
22(5) 367–373

Reprints and permissions:
sagepub.com/journalsPermissions.nav
DOI: 10.1177/0963721413484756
cdps.sagepub.com

Exploring and Enhancing Spatial Thinking: Links to Achievement in Science, Technology, Engineering, and Mathematics?

David H. Uttal[1], David I. Miller[1], and Nora S. Newcombe[2]
[1]Northwestern University and [2]Temple University

Abstract

Although neglected in traditional education, spatial thinking plays a critical role in achievement in science, technology, engineering, and mathematics (STEM) fields. We review this relationship and investigate the malleability of spatial thinking. Can spatial thinking be improved with training, life experience, or educational interventions? Can improving spatial thinking improve STEM achievement? Research indicates that the answer is "yes" to both questions. A recent quantitative synthesis of 206 spatial training studies found an average training improvement of 0.47 standard deviations. Training effects lasted for months in studies examining durability and transferred to tasks that differed at least moderately from training tasks. A few studies indicate that spatial training can improve STEM learning, although more research needs to be done on this issue. We argue that including spatial thinking in STEM curricula could substantially increase the number of Americans with the requisite cognitive skills to enter STEM careers.

Keywords

spatial thinking, STEM education, cognitive training, transfer

Spatial thinking is essential to both human adaptation and modern living. For instance, navigating in one's environment is required of most living species, and tools such as maps can help facilitate such reasoning for humans. Over the past decade, researchers in psychology, education, and a host of other disciplines have increasingly investigated the role of spatial thinking in science, technology, engineering, and mathematics (STEM) achievement. We review this research briefly, finding that spatial thinking is malleable and that inexpensive spatial interventions could potentially make a large difference in STEM education. Finally, we point out the research that remains to be done to test experimentally whether spatial interventions will indeed improve STEM achievement.

We define spatial thinking as the mental processes of representing, analyzing, and drawing inferences from spatial relations. These spatial relations could be relations between objects (e.g., relations between landmarks in a city) or relations within objects (e.g., the structure of the DNA molecule). In addition, one could analyze spatial relations as perceived and represented (e.g., seeing a key structure on an engineering sketch) or, additionally, imagine transforming spatial relations (e.g., mentally rotating a three-dimensional [3-D] object) (Chatterjee, 2008; National Research Council, 2006).

The Role of Spatial Thinking in STEM Learning and Achievement

Recent research indicates that spatial skills play a unique role in predicting which students pursue STEM-related careers. In a large nationally representative sample (n ~ 400,000), Wai, Lubinski, and Benbow (2009) found that spatial skills assessed in high school predicted which students would enter a STEM career 11 years later. This relation held even when controlling for verbal and mathematical cognitive skills. See Figure 1 for examples of the spatial tests used in Wai et al. (2009).

What accounts for this predictive correlation? One factor is probably that STEM fields directly call on these

Corresponding Author:
David H. Uttal, 2029 Sheridan Rd., Evanston, IL 60208
E-mail: duttal@northwestern.edu

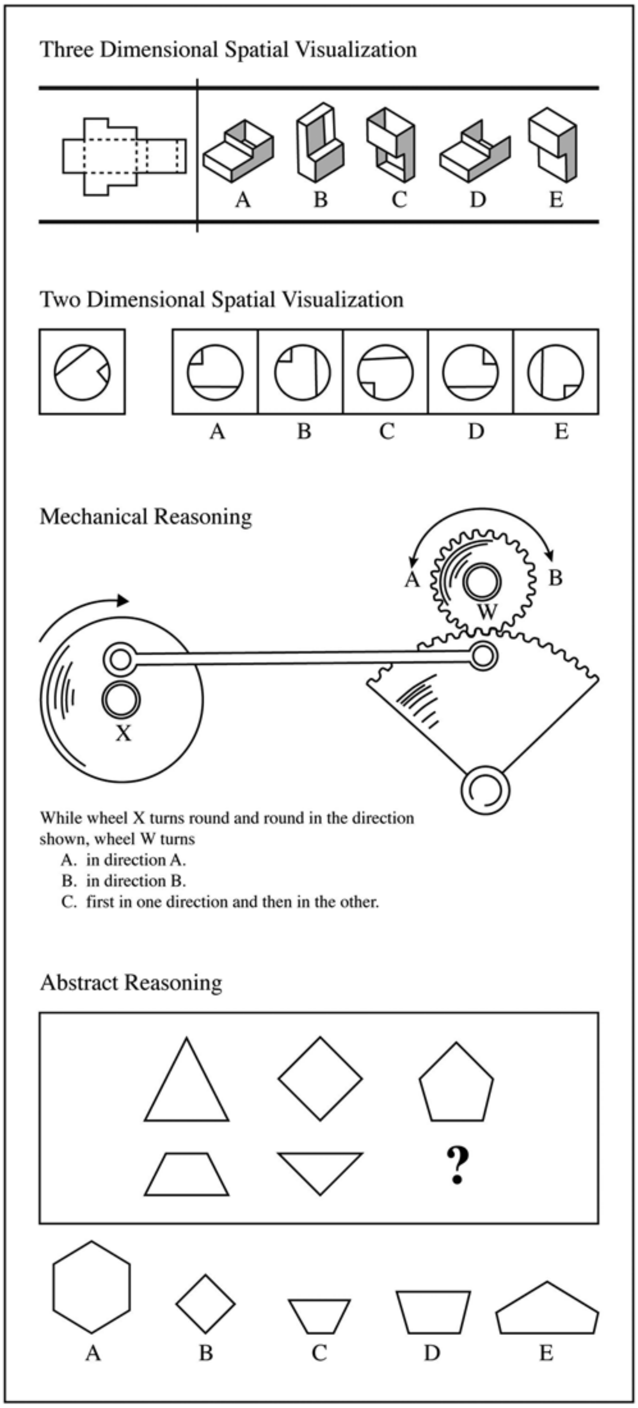

Fig. 1. Examples of spatial tests used in Wai, Lubinski, and Benbow's (2009) longitudinal study. Students' scores on these spatial tests in high school predicted which students would enter a STEM career 11 years later. **Three-dimensional spatial visualization:** Each problem in this test has a drawing of a flat piece of metal at the left. At the right are shown five objects, only one of which might be made by folding the flat piece of metal along the dotted line. You are to pick out the one of these five objects that shows just how the piece of flat metal will look when it is folded at the dotted lines. When it is folded, no piece of metal overlaps any other piece or is enclosed inside the object. Correct answer: A. **Two-dimensional spatial visualization:** In this test, each problem has one drawing at the left and five similar drawings to the right of it, but only one of the five drawings on the right exactly matches the drawing at the left if you turn it around. The rest of the drawings are backward even when they are turned around. For each problem in this test, choose the one drawing that, when turned around or rotated, is exactly like the basic drawing at the left. Correct answer: A. **Mechanical reasoning:** This is a test of your ability to understand mechanical ideas. You will have some diagrams or pictures with questions about them. For each problem, read the question, study the picture above it, and mark the letter of the answer on your answer sheet. Correct answer: C. **Abstract reasoning:** Each item in this test consists of a set of figures arranged in a pattern, formed according to certain rules. In each problem, you are to decide which figure belongs where the question mark is in the pattern. To do this, you have to figure out the rule according to which the drawings change, going from row to row, and the rule for the changes going from column to column. The items have different kinds of patterns and different rules by which the drawings change. The question mark in the lower right corner of each box shows where a figure is missing in the pattern. You are to decide which of the five figures under the pattern belongs where the question mark is. Correct answer: D. Adapted from "Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance," by J. Wai, D. Lubinski, & C. P. Benbow, 2009, *Journal of Educational Psychology, 101*, p. 822. Copyright © 2009 by the American Psychological Association. Adapted with permission.

skills; that is, they require analyzing and imagining transformations of spatial relations. For example, modern chemistry depends on thinking about the functional role of chemical spatial structures, ranging from relatively simple molecules to complex proteins and polymers. (See Kastens & Ishikawa, 2006, for a discussion of the role of spatial thinking in geoscience.) Spatial skills may also play a role in determining whether, and how well, STEM learners and practitioners use external spatial representations such as graphs, maps, or computer molecular models (Hegarty, 2010). In either case, given this importance of spatial thinking in STEM fields, it is educationally important to determine which aspects of spatial thinking can be improved and whether such improvements can facilitate STEM learning.

The Malleability of Spatial Thinking

To what extent does experience with spatial tasks improve spatial thinking? Prior research on this question has led to different conclusions. On one hand, some researchers have claimed that spatial training is highly effective. For example, Sorby (2009) found that a semester of a spatial training course improved spatial skills, and gains exceeded 1 standard deviation or roughly +15 IQ points. In contrast, other researchers have claimed that training effects are small or nonsignificant and do not transfer to other, nontrained tasks (Sims & Mayer, 2002). We aimed to resolve these diverging conclusions by conducting an exhaustive search of literature on spatial training (Uttal et al., 2013). We examined 2,545 relevant articles reporting studies on spatial training and, on the basis of systematic criteria, included 206 of them in our analyses. For example, we excluded studies that did not include behavioral measures, focused only on clinical populations, or did not use a causally relevant design (experimental, quasi-experimental, or before-after). About half of the included studies (54%) were unpublished. Using a technique known as meta-analysis, we combined the quantitative results of the individual studies to arrive at overall conclusions regarding the benefits of spatial training. We asked: How malleable are spatial skills? How long does training last? Does training transfer to other, nontrained tasks? Do some groups of people (e.g., women vs. men) benefit more from training?

Spatial training was effective

The overall effect size of training was 0.47 standard deviations or roughly +7 IQ points. This is considered a moderate effect size and indicates that spatial skills are malleable. Many different training methods (e.g., playing video games, practicing spatial tests, or taking an engineering graphics courses) improved spatial skills. Although we found large variability in training effects across individual studies, we found no overall difference across the three training categories we coded (video game vs. spatial task vs. course training). Hence, a variety of training methods can substantially improve spatial skills.

Spatial training was durable

Although most studies (67%) measured spatial skills only immediately after training, some studies measured spatial skills weeks or months after training. In these longitudinal studies, training effects persisted despite delays of up to 4 months (e.g., Feng, Spence, & Pratt, 2007). Of course, those researchers may have used particularly intensive training because they knew that participants would be tested after a long delay. Nevertheless, those studies show that well-designed, intensive training can have lasting benefits.

Spatial training transferred

We defined *transfer* as improved performance on spatial tasks not directly covered in training. Transfer tasks that were very similar to the training tasks (e.g., mental rotation with 3-D vs. 2-D figures) were coded as near transfer, but substantially different transfer and training tasks were coded as far transfer (Barnett & Ceci, 2002). The effect sizes for overall improvement, near transfer, and far transfer were remarkably similar. In other words, participants improved by approximately 0.5 standard deviations on nontransfer, near-transfer, and far-transfer measures. Of course, as in studies measuring durability, studies measuring transfer may have deliberately used more intensive training. Nevertheless, those studies still demonstrate that well-designed training can yield improvements that transfer. In summary, many different training methods can yield effective, durable, and transferable improvements in spatial skills.

The meta-analysis also sheds light on why prior researchers have reached divergent conclusions regarding training benefits. For example, variation in control group tasks probably contributed to the variation in results. Some control groups included tasks that were likely to improve spatial skills, such as practicing spatial tests, whereas other control groups completed only nonspatial filler tasks, such as playing the card game solitaire. We found that control group improvements were surprisingly high, often exceeding 0.4 standard deviations. As expected, control groups with spatial (vs. nonspatial) filler tasks improved most, and variations in the type of control groups and how much these groups improved affected the overall effect of training. Thus, even the improvement in control groups speaks to the malleability of spatial thinking; taking spatial tests in itself served as a form of spatial training. Even though control groups sometimes improved, training groups still improved more overall.

Our analyses also indicated that children and adults, as well as women and men, responded equally to training. Although children (younger than 13 years) improved slightly more than adolescents or adults, this difference was not statistically significant. Further research comparing children and adults in the same study is necessary to determine whether this difference represents a real developmental difference in malleability. Likewise, although women and men improved equally, further research with more intensive training is necessary to determine whether intensive training can narrow the male advantage often found in some spatial skills (Terlecki, Newcombe, & Little, 2008).

How Does Spatial Training Work?

Researchers have proposed numerous mechanisms to explain the large training-related improvements in spatial skills. We consider three candidate mechanisms here. First, training may influence task-specific or process-specific factors such as better encoding of test stimuli (Sims & Mayer, 2002), more efficient transformational processes (Kail & Park, 1992), or more adaptive strategies (Stieff, 2007). Evidence exists for each factor. However, Uttal et al.'s (2013) findings regarding transfer rule out an account that is only test- or task-specific. For instance, participants would not improve on a transfer spatial test if they improved only in encoding test-specific stimuli.

Hence, any model of improvement must account for these process-based changes as well (Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008).

These transfer effects have also led some researchers to consider a second possible mechanism concerning basic cognitive resources such as spatial attention or memory. For instance, Feng et al. (2007) found that playing an action video game improved participants' ability to simultaneously attend to multiple locations in a large field of view. Other research finds that video-game players can more rapidly encode and process visual-spatial information (Dye, Green, & Bavelier, 2009)—an ability key to many spatial tasks. Improving working-memory or attentional resources might allow for better encoding or transformation of the represented information (see Chein & Morrison, 2010).

A third, but more tentative, mechanism regards how spatial training interacts with social-psychological variables. Social-psychological factors such as spatial anxiety (Ramirez et al., 2012), confidence (Estes & Felker, 2011), and gender stereotypes (Campbell & Collaer, 2009; Moè & Pazzaglia, 2006) influence spatial performance. These findings suggest that exposure to spatial activities may make tasks in spatial tests more familiar and therefore less threatening or anxiety provoking. Of course, none of these candidate mechanisms is mutually exclusive, and the truth may lie in some interaction between them.

Can Spatial Training Improve STEM Learning?

The studies reviewed thus far indicate that spatial thinking is malleable and that some forms of training can endure and transfer to other skills. However, the majority of the studies reviewed thus far have focused only on spatial outcomes. As we noted earlier, spatial thinking may play a particularly important role in STEM fields. These fields require using external spatial representations (e.g., graphs, computer visualizations, etc.), and there are spatial aspects to even simple STEM reasoning, such as young children's use of the number line (Gunderson, Ramirez, Beilock, & Levine, 2012). Hence, can spatial training improve STEM learning? Relatively few training studies have directly addressed this question, but those that have found encouraging results. For instance, Sorby (2009) invited engineering undergraduates who failed a spatial test to participate in a 3- to 4-month spatial training course that used sketching exercises (see Fig. 2). Students who chose to take the course had higher grades in several subsequent STEM courses. Women who took the course were also more likely to persevere in engineering rather than switch majors. However, because students self-selected into the course, these longitudinal differences might be explained by other confounding factors. For instance, students who choose to take the course may have started out with higher levels of motivation or help-seeking attitudes.

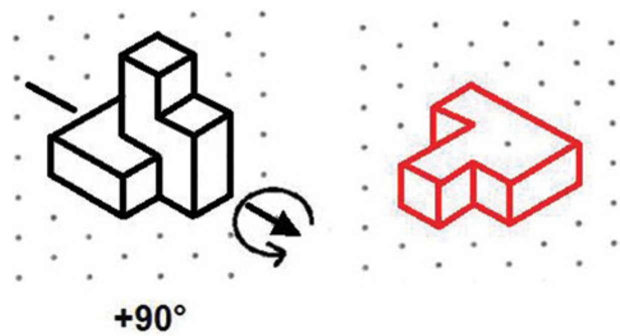

Fig. 2. Sample workbook problem from Sorby's (2009) spatial training. On 2-D sketch paper, students are asked to mentally rotate the left 3-D object 90° around the indicated axis and then sketch the correct rotation (shown in red) on the dot paper to the right. Sorby (2009) and Miller and Halpern (in press) found that using such workbook materials improved grades in subsequent STEM courses. Adapted from "Introduction to 3-D spatial visualization: An active approach," by S. A. Sorby & A. F. Wysocki, 2003, Clifton Park, NY: Thomson-Delmar Learning. Copyright © 2003 Thomson-Delmar Learning. Adapted with permission.

Miller and Halpern (in press) extended this research in two major ways: (a) using random assignment to control for individual student differences, and (b) investigating benefits among highly gifted STEM undergraduates (e.g., 28% had perfect SAT Mathematics scores). Such undergraduates are disproportionately more likely to become STEM innovators. Compared with a randomized control condition, Miller and Halpern found that 12 hours of Sorby's (2009) training improved grades in a challenging calculus-based physics course by one-third of a letter grade (approximately 0.4 standard deviation units). These findings are particularly impressive because training challenged and benefitted those students who already had high initial spatial skills. Gains in science learning were evident up to 2.5 months after training, although they did not last 8 to 10 months after training. In sum, the available evidence indicates that spatial instruction can improve STEM learning in some instances (see also Sanchez, 2012; Stransky, Wilcox, & Dubrowski, 2010).

Other Approaches to Using Spatial Thinking in STEM Education?

The approaches described thus far focus mostly on training with abstract objects (e.g., Fig. 2) that are not particularly connected to any specific STEM domain. One important question is how these approaches could help learners integrate spatial thinking with domain-specific content knowledge. In this regard, it may be helpful to develop spatial thinking in the specific educational contexts in which it used. For instance, in Kolvoord, Charles, and Purcell's (in press) *Geospatial Semester*, high school students solved complex real-world problems by using an interactive spatial visualization technology known as geographic information systems (GIS). Practicing scientists use GIS to solve geographic problems by overlaying multiple layers of spatial information. For instance, in the *Geospatial Semester*, one high school student used GIS to decide how to relocate bears in the Shenandoah National Park by simultaneously viewing and considering mountains, food sources, and human transportation routes. Systematic analyses of interview data suggested that the course promoted spatial-based approaches for solving other novel geography problems.

Other educational approaches that incorporate spatial thinking include using sketching software to facilitate learning of spatial concepts (Forbus, Usher, Lovett, Lockwood, & Wetzel, 2011) or computer spatial visualizations to conduct virtual scientific experiments (Linn & Eylon, 2011). These contextualized approaches may be necessary for students to learn and apply the daily practices of scientists and engineers. Training with abstract objects may be effective only early in STEM learning (Uttal & Cohen, 2012), and future research should compare the merits of these different approaches. Figure 3 indicates the potential payoff of investing in such research. As shown, spatial training would approximately double the number of people with the level of spatial skills associated with being an engineer. This result indicates the need to develop evidence-based materials for enhancing spatial thinking in both formal and informal education.

To realize these goals, the National Science Foundation founded the large-scale Spatial Intelligence and Learning Center (SILC). SILC is an interdisciplinary collaboration among several universities (Temple University, University of Chicago, Northwestern University, University of Pennsylvania), involving researchers from psychology, education, geology, neuroscience, medicine, engineering, and several other fields. While advancing basic theory on spatial thinking, SILC catalyzes new research that gives both formal and informal educators the tools they

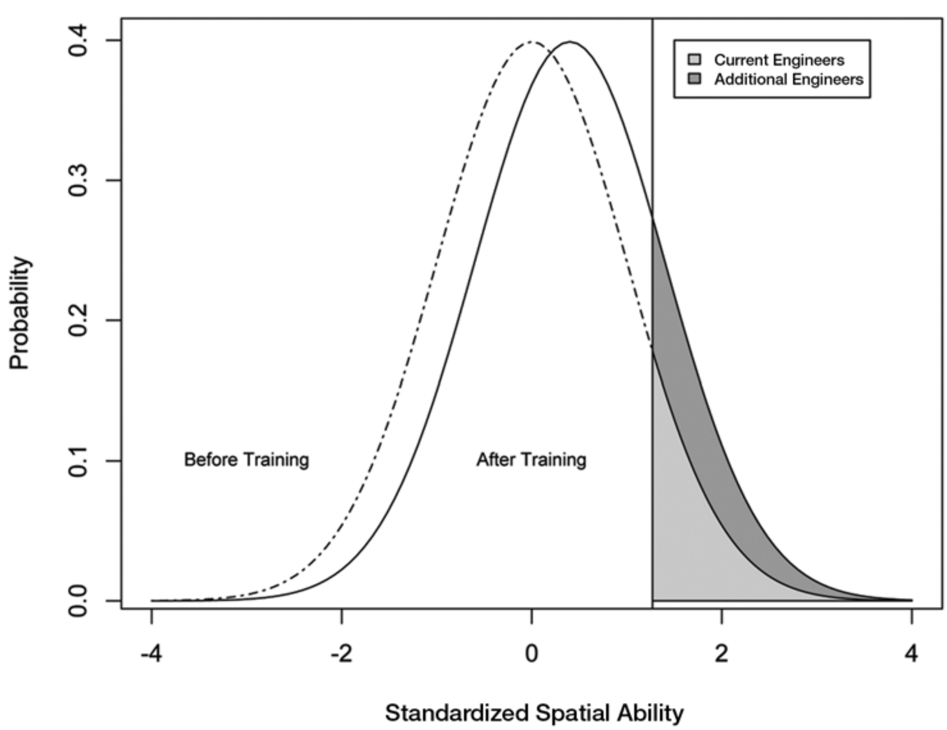

Fig. 3. The distribution of spatial skills before (dotted line) and after (solid line) spatial training. The shaded parts of the distributions illustrate the possible consequences of training on the percentage of individuals with spatial skills similar to those of engineers. Improving spatial skills by 0.40 standard deviations (the most conservative estimate of training improvements in the meta-analysis by Uttal et al., 2013) would approximately double the number of people with spatial skills exceeding those of an average engineering college graduate. Data from Wai, Lubinski, and Benbow (2009) and Wai, Lubinski, Benbow, & Steiger (2010). Reprinted from "The malleability of spatial skills: A meta-analysis of training studies," D. H. Uttal, N. G. Meadow, E. Tipton, L. L. Hand, A. R. Alden, C. Warren, & N. S. Newcomb, 2013, *Psychological Bulletin*, 139, p. 369. Copyright © 2013 American Psychological Association. Reprinted with permission.

need to enhance spatial thinking across the curriculum. SILC's Web site (http://www.spatiallearning.org) contains resources for researchers and educators, including testing instruments, research papers, electronic mailing lists, and conference information relevant to spatial thinking. The websites TeachSpatial (http://www.teachspatial.org) and Web-based Science Inquiry Environment (http://wise.berkeley.edu) also contains many excellent educational resources.

Conclusions

The research reviewed in this article demonstrates spatial thinking's malleability and its importance in STEM education. Improving spatial thinking can help provide the skills necessary to succeed in STEM fields, yet a specific focus on spatial thinking has been lacking in almost all educational programs. Future research is needed to specify which methods of training will lead to the greatest STEM-related improvements. Like any cognitive skill, spatial thinking can improve if nurtured and supported. Considerable effort has been made toward investigating how to enhance relevant cognitive skills for math, reading, and many other disciplines. Now is the time to add spatial skills to this list.

Recommended Reading

Miller, D. I., & Halpern, D. F. (in press). (See References). A randomized, longitudinal spatial training study investigating transfer to STEM outcomes among highly gifted STEM undergraduates.

National Research Council. (2006). (See References). In-depth recommendations for incorporating spatial thinking in K-12 education, written by a panel of experts in education, psychology, geography, and geoscience.

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator*, *34*, 29–43. A concise summary of literature and recommendations for incorporating spatial thinking in STEM education, with a particular focus on earlier grades in elementary school.

Uttal, D. H., & Cohen, C. A. (2012). (See References). A literature review of correlational studies investigating the relationship between spatial skills and STEM outcomes.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). (See References). A systematic, quantitative review of 206 spatial training studies conducted within the past 25 years.

Acknowledgements

We thank David B. Wilson, Larry Hedges, Loren M. Marulis, and Spyros Konstantopoulos for their help in designing and analyzing the meta-analysis. We also thank Greg Ericksson and Kate O'Doherty for assistance in coding and Kseniya Povod and Kate Bailey for assistance with references and proofreading.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

This work was supported by the Spatial Intelligence and Learning Center (National Science Foundation Grants SBE-0541957 and SBE-1041707), the Institute for Education Sciences (U.S. Department of Education Grant R305H020088), and a National Science Foundation Graduate Research Fellowship (Grant DGE-0824162 awarded to D. I. Miller).

References

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn?: A taxonomy for far transfer. *Psychological Bulletin*, *128*, 612–637.

Campbell, S. M., & Collaer, M. L. (2009). Stereotype threat and gender differences in performance on a novel visuospatial task. *Psychology of Women Quarterly*, *33*, 437–444.

Chatterjee, A. (2008). The neural organization of spatial thought and language. *Seminars in Speech and Language*, 29, 226–238.

Chein, J. M., & Morrison, A. B. (2010). Expanding the mind's workspace: Training and transfer effects with a complex working memory span task. *Psychonomic Bulletin & Review*, *17*, 193–199.

Dye, M. W., Green, C. S., & Bavelier, D. (2009). Increasing speed of processing with action video games. *Current Directions in Psychological Science*, *18*, 321–326.

Estes, Z., & Felker, S. (2011). Confidence mediates the sex difference in mental rotation performance. *Archives of Sexual Behavior*, *41*, 557–570.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science*, *18*, 850–855.

Forbus, K., Usher, J., Lovett, A., Lockwood, K., & Wetzel, J. (2011). CogSketch: Sketch understanding for cognitive science research and for education. *Topics in Cognitive Science*, *3*, 648–666.

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: The role of the linear number line. *Developmental Psychology*, *48*, 1229–1241.

Hegarty, M. (2010). Components of spatial intelligence. In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 52, pp. 265–297). San Diego, CA: Academic Press.

Kail, R., & Park, Y. (1992). Global developmental change in processing time. *Merrill-Palmer Quarterly*, *38*, 525–541.

Kastens, K. A., & Ishikawa, T. (2006). Spatial thinking in the geosciences and cognitive sciences: A cross-disciplinary look at the intersection of the two fields. *Geological Society of America Special Paper*, *413*, 53–76.

Kolvoord, R. A., Charles, M., & Purcell, S. (in press). What happens after the professional development: Case studies on implementing GIS in the classroom. In J. MaKinster, N. Tratman, & M. Barnett (Eds.), *Teaching science and* *investigating environmental issues with geospatial technology* (pp. 424–451). New York, NY: Springer.

Linn, M. C., & Eylon, B.-S. (2011). *Science learning and instruction: Taking advantage of technology to promote knowledge integration*. New York, NY: Routledge.

Miller, D. I., & Halpern, D. F. (in press). Can spatial training improve long-term outcomes for gifted STEM undergraduates? *Learning and Individual Differences*. doi:10.1016/j.lindif.2012.03.012.

Moè, A., & Pazzaglia, F. (2006). Following the instructions!: Effects of gender beliefs in mental rotation. *Learning and Individual Differences*, *16*, 369–377.

National Research Council. (2006). *Learning to think spatially*. Washington, DC: The National Academies Press.

Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2012). Spatial anxiety relates to spatial abilities as a function of working memory in children. *Quarterly Journal of Experimental Psychology*, *65*, 474–487.

Sanchez, C. A. (2012). Enhancing visuospatial performance through video game training to increase learning in visuospatial science domains. *Psychonomic Bulletin & Review*, *19*, 58–65.

Sims, V. K., & Mayer, R. E. (2002). Domain specificity of spatial expertise: The case of video game players. *Applied Cognitive Psychology*, *16*, 97–115.

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

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction*, *17*, 219–234.

Stransky, D., Wilcox, L. M., & Dubrowski, A. (2010). Mental rotation: Cross-task training and generalization. *Journal of Experimental Psychology: Applied*, *16*, 349–360.

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*, 996–1013.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM: When, why and how? In B. Ross (Ed.), *Psychology of learning and motivation* (Vol. 57, pp. 148–182). New York, NY: Academic Press.

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*, 352–402.

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*, 817–835.

Wai, J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2010). Accomplishment in science, technology, engineering, and mathematics (STEM) and its relation to STEM educational dose: A 25-year longitudinal study. *Journal of Educational Psychology*, 102, 860–871.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review*, *15*, 763–771.