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REVIEW ARTICLE

How Much Can Spatial Training Improve STEM Achievement?

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Abstract Spatial training has been indicated as a possible solution for improving Science, Technology, Engineering, and Mathematics (STEM) achievement and degree attainment. Advocates for this approach have noted that the correlation between spatial ability and several measures of STEM achievement suggests that spatial training should focus on improving students' spatial ability. Although spatial ability can be improved with targeted training, few studies have examined specifically the relation between spatial training and STEM achievement. In this brief report, we review the evidence to date for the effectiveness of spatial training. We argue that spatial training offers one of the many promising avenues for increasing student success in STEM fields, but research studies that show such training causally improve retention, achievement, and degree attainment remain outstanding.

Keywords Spatial ability · STEM education

Despite an increased demand for mathematicians, engineers, and scientists in the United States workforce, and the need for a mathematically and scientifically literate citizenry, the majority of Science, Technology, Engineering, and Mathematics (STEM) students continue to achieve at or below basic proficiency levels. In particular, national trends indicate that U.S. students face significant challenges meeting national, state, and local STEM content standards (National Center for Educational Statistics 2012). Likewise, studies at the postsecondary level similarly demonstrate that STEM college students often fail to achieve a basic understanding of fundamental STEM content prior to graduation (e.g., Bao et al. 2009; Chittleborough and Treagust 2007; Smith and Knight 2012). Although dropout rates in STEM undergraduate degree programs are comparable to non-STEM fields, fewer students than needed are electing

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to pursue STEM degrees and STEM careers (Daempfle 2003; National Science Foundation 2009; White et al. 2006).

The underlying mechanisms responsible for America’s difficulty producing STEM graduates are the subject of much debate: environmental factors that include teacher preparation, curriculum design, and assessment practices have all been targeted for reform. Recently, several researchers have shown an increased interest in the role of individual and group differences in cognitive abilities on STEM achievement and degree attainment. In particular, spatial abilities (e.g., spatial visualization, mental rotation, perspective taking, etc.) have received significant attention, and there are many ongoing studies that are investigating whether low spatial skills explain why some students struggle to succeed in specific STEM courses or drop out of STEM career pathways. As increasing evidence for the role of spatial ability in STEM problem solving and practice accumulates, the belief that spatial training will improve STEM achievement and increase access to STEM degree programs and careers is becoming more widespread among teachers, researchers, and the public (Knapp 2011; Lubinski 2010; National Research Council 2006; Park et al. 2010). Clearly, spatial abilities can be improved with training, and multiple interventions that vary in duration and curriculum have yielded improvement (e.g., Uttal et al. 2013a, b; Wright et al. 2008). Yet, the effect of spatial training on an individual student’s success in STEM remains unknown. Here, we argue that the evidence that spatial training can improve STEM achievement is still quite preliminary and propose that novel research programs are needed to demonstrate the effectiveness of spatial training.

Why Should Spatial Training Improve STEM Achievement?

The rationale for spatial training interventions begins as follows: STEM problem solving relies primarily on spatial thinking; therefore, success in STEM relies primarily on a student’s spatial ability. There is some merit to this argument as STEM problem solving quite often requires students to reason about spatial information. For example, math students routinely quantify geometric relationships in three-dimensional solids, and geology students characteristically describe how land masses move over centuries. Examples of spatial reasoning such as these abound across STEM disciplines including chemistry (Stieff 2011), astronomy (Rudmann 2002), physics (Kozhevnikov et al. 2007), computer science (Jones and Burnett 2008), and mechanical engineering (Sorby 2001). Given the nature of STEM problem solving, a student’s achievement in STEM ostensibly rests on how capable they are at solving problems that involve reasoning about spatial information. As the argument goes, it stands to reason that interventions that improve an individual student’s spatial ability should translate to increased STEM achievement and degree attainment for that student.

Several empirical studies have offered more compelling evidence to support the belief that spatial training interventions will improve STEM achievement. In the past decade, researchers have demonstrated that there is a moderate relationship between spatial ability, STEM achievement, and STEM career choice. Students who perform poorly on spatial ability measures are more likely to struggle in entry-level STEM courses and are less likely to enjoy STEM instruction (Wai et al. 2009, 2010). A longitudinal study of STEM professionals demonstrated that this population has higher spatial abilities than non-STEM professionals (Wai et al. 2009), and a number of small studies have shown that spatial ability correlates with performance in several STEM disciplines (Dabbs et al. 1998; Devon et al. 1998; Kozhevnikov et al. 2007; Lord 1990; Lord and Nicely 1997; Ozdemir 2010; Pribyl and Bodner 1987). Taken together, these findings firmly establish that spatial ability plays an important role in STEM success and have to calls for spatial training interventions as a strategy for improving STEM success (Lubinski 2010; National Research Council 2006; Park et al. 2010). However, we need to examine more closely whether spatial training is causally related to improving desired STEM outcomes.

Any causal argument must specify the logic of causation: how changes in one variable could lead to changes in outcome variables. We note that the causal logic that relates spatial training to STEM outcome has two important links. First, training must improve spatial ability—that is, spatial ability must be malleable, and the proposed interventions must specifically cause improvements in spatial ability. Second, these improvements in spatial thinking must subsequently lead to improvements in the desired STEM outcomes. In the next section, we review the evidence for both of these links in the causal chain from interventions that were designed to improve spatial ability selectively in order to yield improvements in STEM outcomes. To preview, the evidence now is quite clear that interventions do lead to enhanced spatial ability, but the evidence that improving spatial ability leads to improvement in STEM outcomes is tenuous at best.

Does Spatial Training Promote STEM Achievement? A Review

Is Spatial Thinking Malleable? There is now considerable evidence that spatial ability is malleable—that a variety of experiences, ranging from life experiences to specific, intensive training, can improve spatial ability. This literature was recently summarized in a meta-analysis (Uttal et al. 2013a, b) on the effectiveness of spatial training. The meta-analysis included over 200 studies, of which more than half were unpublished (thereby decreasing the chances that the results were affected substantially by publication bias). The authors defined training quite broadly by including studies not only of formal spatial training but also of the influences of taking STEM courses, playing videogames, and even learning to design dresses. The meta-analysis showed that spatial training led to an average improvement of almost 1/2 standard deviation in spatial ability measures. At least in some cases, the effects of the training lasted even after substantial delays and transferred to other spatial tasks. In addition, the meta-analysis identified several moderators, most notably the characteristics of the control groups to which spatial training was compared.

Does Improving Spatial Ability Lead to Improvements in STEM Outcomes? Research has established that spatial ability is malleable, but it is much less clear that improving spatial ability improves STEM outcomes. Unfortunately, few studies have used rigorous methods to generate strong evidence for the causal impact of spatial training on STEM achievement, degree attainment, or career choice. In the past 30 years, we can identify only six studies that have attempted to demonstrate the impact of spatial training interventions on STEM achievement in school or professional settings. Here, we review these findings to determine the level of evidence for the causal claim that spatial ability training can improve STEM achievement.

One of the first attempts to assess the impact of spatial training on STEM achievement occurred in the discipline of chemistry over 30 years ago. Small and Morton (1983) implemented a model-based reasoning program in the context of their undergraduate course to evaluate whether such training could improve students' grades. Training involved completing large numbers of items typically found on spatial ability psychometric instruments in addition to working with molecular modeling kits to relate the spatial problems to disciplinary content. Small and Morton reported that the training improved student performance by approximately three percentage points on disciplinary assessments compared to a matched group of students who did not participate in the training. The effect on the disciplinary assessments was limited as the authors observed improvements only on one classroom assessment with no significant differences between groups' course grade. While the intervention suggests promising benefits of spatial training, the authors failed to assess improvements in spatial ability or control for individual differences in other cognitive abilities thus compromising the inference that it was spatial training exclusively that led to differences between groups.

Interest in the efficacy of spatial training appeared to wane for the next 15 years until Hsi et al. (1997) published a study documenting improved student achievement in an engineering course that included a supplementary spatial training intervention. Building on the earlier findings of Small and Morton (1983), the researchers recruited undergraduate students to participate in a voluntary weekly workshop to practice spatial problem solving. In this intervention, students worked in groups to use a researcher-designed software environment where they manipulated duplo blocks to better learn how to interpret and construct orthographic projections of three-dimensional shapes. Improving upon the early work in this area, the authors assessed participants' spatial ability before and after the training as well as students' grade in the main engineering course. Although the researchers were unable to detect any overall improvement in spatial ability, they did report that sex differences in spatial ability visible pre-intervention were undetectable at the end of the course. Due to selection bias confounding the study, the authors did not report whether the intervention improved achievement in engineering; however, they did note that, unlike previous semesters, no students failed the engineering course during the semester that included the intervention.

Although the mechanism of action remained unknown, the findings from Hsi and colleagues offered compelling evidence that spatial training could improve student achievement in STEM and inspired a concerted effort by faculty in engineering schools to improve retention and degree attainment through spatial training spearheaded by Sheryl Sorby and colleagues. Over a 10-year period Sorby worked to design a self-contained spatial training course for engineering students who achieved below average on standardized measures of spatial ability with the goal of improving their mental rotation, spatial visualization, and perspective taking skills. The fruit of this work was a set of curriculum materials that could be completed in a 10-week course (Sorby 2001). The materials comprise a workbook (Sorby 2011) with hundreds of spatial practice problems that include not only paper folding tasks common to spatial visualization measures but also tasks that involve drawing orthographic projections, reflections, rotations, and cross-sections of three-dimensional solids. These drawing tasks are highly similar to the types of tasks found in drafting or AutoCAD courses offered by colleges in engineering, and share common features with the tasks found on mental rotation and perspective taking spatial ability instruments.

In early 2001, Sorby and colleagues began to conduct a series of related studies to evaluate the effectiveness of the spatial training curriculum for improving students' spatial abilities and their grades in STEM courses with specific attention to introductory engineering courses. The reported results were positive across all studies. In 2009, Sorby reported that students who completed the course using the designed curriculum materials achieved not only better grades in their STEM courses, but also higher overall grade point averages at the end of the semester. Equally important, Sorby demonstrated that participating in the workshop improved participants' spatial ability from pre-to-post. Unlike earlier studies, Sorby's work offered the first evidence to support the claim that spatial training interventions that demonstrated improvements in spatial ability could, in turn, improve STEM achievement. More recently, Sorby and colleagues have provided additional evidence of the causal effects of the intervention on STEM achievement, using a regression discontinuity approach (Sorby et al. 2013). The researchers extrapolated the achievement of students in a control group and compared it to students completing the spatial training curriculum. Importantly, the research design took advantage of an "experiment in nature," in that the spatial skills training course became mandatory for all students at the research site, which helps to assess directly the influences of self-selection in the earlier studies. The results confirmed prior findings: low spatial students who participated in the intervention performed better than the predicted scores of high spatial students in the comparison group. The intervention participants performed better on both measures of spatial ability and showed minor improvements in their calculus grades. The effect size of the intervention was small and students' spatial ability accounted for less than 1 % of the variance in their grades; however, this recent work offers the most compelling evidence to date that spatial training can improve STEM achievement.

Although most of the research on the effects of spatial training interventions has been limited to schools of engineering, one study in college physics has yielded some promising results indicating that spatial ability can be improved in the context of normal college STEM instruction and that this improvement can lead to improvements in STEM achievement. Miller and Halpern (2013) randomly assigned physics students to participate in a supplemental spatial training workshop that used the Sorby curriculum throughout a semester. As in the engineering courses, Halpern and Miller reported that students who completed the intervention achieved significant and moderate improvements in spatial ability (Eta2=0.08) at the end of the semester. As in the engineering studies, the researchers found a weak effect of the intervention on STEM course grades. Students showed small improvements (d=0.32) on a limited number of achievement assessments related to Newtonian mechanics with no significant improvements on other assessments or in other courses. Additionally, the authors used a delayed test design to assess the enduring effects of the intervention. No lasting effects were found: all gains (spatial ability and STEM achievement) made by the spatial training participants were lost within 6 months.

The most recent study of spatial training was conducted with young children learning mathematics. Cheng and Mix (2014) have showed that spatial training can improve mathematics learning in 6- to 8-year-olds. In the study, children were randomly assigned either to a spatial training or to a control group. The spatial training group practiced a mental rotation task that had been developed for young children (Ehrlich et al. 2006). The control group completed crossword puzzles. Mental rotation training led to significant improvement on a test of addition and subtraction, but the control group did not improve. In addition, an analysis on the kinds of arithmetic problems that were most affected by the spatial training sheds light on why the training led to improvement. The effect of spatial training was the greatest on *missing term problems*, such as 2+ ______=6. Prior research has shown that children of this age often misinterpret the equal sign and add the numerals before and after the equal sign; thus, they might answer "8" for this problem (e.g., McNeil and Alibali 2005). Cheng and Mix suggested that the spatial training may have helped children to perform the necessary transformations (e.g., mentally moving the 2 and subtracting it from the 6) that support finding answers to these kinds of problems. From this review, we can see that the evidence to date only partially supports the claim that spatial training (with the goal of improving spatial ability) can improve student achievement in STEM fields. While it is clear that such training *can* lead to improvements, the small effect of each of these interventions suggests that spatial training alone is unlikely to raise STEM scores substantially. Certainly, no evidence yet exists that show spatial training will yield increased numbers of scientists, mathematicians, and engineers in the U.S. workforce. Nevertheless, it is important to note that each intervention has achieved *an effect* in authentic classroom contexts where environmental and situational factors are known to have strong impacts on the respective outcome variables.

Establishing the Effectiveness of Spatial Training

While the existing evidence for the effectiveness of spatial training is sparse, no study has shown that spatial training is less effective or ineffective relative to business-as-usual methods. Given the small, but positive effects observed when spatial training interventions are appended or embedded in STEM classrooms, we believe that new research efforts are needed to provide robust evidence for the impact of spatial training. Building on the work of researchers, such as Sorby, Halpern, and Miller, rigorous studies are needed to establish a causal effect of spatial training intervention on STEM outcome measures. Tightly controlled randomized-controlled trials offer the best route to generate evidence for or against such a causal claim. We also believe that new techniques involving learning analytics offer much promise for establishing a relationship between spatial training, spatial ability, and STEM achievement.

As we noted above, most of the quasi-experimental studies that have attempted to show the effectiveness of spatial training have suffered from serious threats to internal validity, which compromises the interpretation of the findings. Most importantly, future attempts must carefully address issues with self-selection and existing group differences in their study designs. Future designs should include random assignment and adequate individual differences covariates that permit us to isolate the impact of spatial training on STEM achievement separate from improvements in general reasoning, strategy acquisition, working memory, motivation, or time on task. New efforts must also strive to move beyond simple evaluations of effectiveness: we need clear evidence that demonstrates why spatial training is effective. Assuming that spatial training improves STEM achievement selectively by improving spatial ability, new efforts must be careful to assess changes in spatial ability that result from spatial training interventions. Interventions, such as that of Hsi et al., which yield improvements in STEM achievement without concurrent improvements in spatial ability raise serious theoretical problems that require attention. Lastly, these experiments must occur in natural contexts to establish the effectiveness of spatial training in real classrooms and to provide ecologically valid predictions for expected outcomes. While such studies are logistically challenging, they are not impossible as evident in recent studies of educational interventions (e.g., Bradshaw et al. 2009; Raver et al. 2008) We also note that in the cases where random assignment is impossible, studies that employ active controls with matched groups offer a reasonable alternative.

Researchers may also want to consider alternate approaches to understanding the influences of spatial ability and spatial training on STEM learning. Although experimental and quasi-experimental approaches can shed light on *whether* spatial training is effective, they typically do allow sufficient inference about *why or how* such interventions are effective. In addition, these studies typically provide relatively little information about individual differences. Newer approaches that emphasize the analysis of individual patterns of learning may prove to be particularly helpful in addressing these questions. Detailed, large-scale studies of learning patterns for a particular STEM course, and the relation of spatial ability or spatial training to these patterns, may simultaneously lead to greater theoretical insight and more specific practical applications.

Independent of research designs, researchers working in this area need to be mindful that we lack clear evidence that spatial training causally improves STEM success and, importantly, they must attend to lessons learned from existing studies. First, spatial training often selectively improves performance on only those tasks that depend heavily on spatial skills as evident in the studies above as well as numerous examples in the gray literature. Researchers must be mindful that the task-specificity of spatial training may not yield generalized gains in retention or achievement if these tasks are not found on domain assessments. As such, when course grades or GPA are used as the sole outcome measures, it is highly unlikely that spatial training will produce a large effect. Second, researchers must consider whether spatial training yields benefits during critical windows of opportunity. For example, spatial training may be more effective in a specific *curricular window*. Studies of young children learning mathematics have shown that relationship between spatial ability and mathematics performance not only varies by task but also varies with age (cf., Mix and Cheng 2012). Similarly, among adults spatial ability is more predictive of novice performance than expert performance and that spatial ability may serve as a gatekeeper early in STEM instruction (Keehner et al. 2004; Uttal and Cohen 2012; Uttal et al. 2013b; Wai et al. 2009). This suggests that spatial training may benefit the largest group of students if it is delivered prior to (or concurrent with) introductory STEM courses. Finally, researchers should consider whether the limited effects of spatial training reported in the studies above is due to the duration of training or a delay in onset. Spatial training interventions, if effective, may require extended training in excess of several months to yield lasting effects, and the impact of such training may not be seen until much later in a student's educational life or developmental trajectory. Additional studies that address not only whether spatial training is effective, but also *what type* of spatial training improves STEM achievement and *when* effects can be detected are particularly needed.

Concluding Remarks

We end our report by affirming the belief that spatial training will lead to improvements in STEM achievement has merit given the evidence to date. Preliminary attempts to demonstrate that spatial training will improve STEM achievement by improving spatial ability have shown that there is potential in such efforts. Clearly, it would be premature to fund large-scale spatial training interventions given the lack of evidence for the effectiveness and efficacy of spatial training. Whether the lack of evidence is due to flawed studies, imperfect interventions, or the limited applicability of spatial ability for STEM learning is unclear, and the true effect of spatial training interventions remains unknown. In our opinion, funding is warranted for new concerted efforts that leverage expertise in psychology, learning sciences, and the STEM disciplines if we are to fully understand the effectiveness of spatial training. So too, new interventions need to explore the appropriate time for intervention, the effect of interventions of different duration, and the long-term outcomes of such training.

We would caution those who would pursue research in this area to be mindful that educational interventions seeking significant, generalized improvements in student outcomes are rarely successful. STEM achievement is measured on a wide range of assessments throughout the curriculum and spatial ability contributes only partly to student success on these assessments. Epistemic, affective, and conceptual difficulties plague even high spatial students and may occlude the impact of the most carefully designed spatial training curriculum. As such, we are mindful that spatial training interventions may never produce large effects on achievement, retention, or degree attainment. Although this may seem discouraging, even a small effect can represent opportunities for large numbers of students who may have otherwise been excluded from STEM careers altogether.

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References

Bao, L., Cai, T., Koenig, K., Fang, K., Han, J., Wang, J., Liu, Q., Ding, L., Cui, L., Luo, Y., Wang, Y., Li, L., & Wu, N. (2009). Learning and scientific reasoning. *Science, 323*, 586–587.

Bradshaw, C. P., Zmuda, J. H., Kellam, S. G., & Ialongo, N. S. (2009). Longitudinal impact of two universal preventive interventions in first grade on educational outcomes in high school. *Journal of Educational Psychology, 101*(4), 926–937.

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

Chittleborough, G., & Treagust, D. F. (2007). The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level. *Chemistry Education Research and Practice*, *8*(3), 274–292.

Dabbs, J. M., Chang, E., Strong, R., & Milun, R. (1998). Spatial ability, navigation strategy, and geographic knowledge among men and women. *Evolution and Human Behavior, 19*, 89–98.

Daempfle, P. A. (2003). An analysis of the high attrition rates among first year college science, math, and engineering majors. *Journal of College Student Retention, 5*(1), 37–52.

Devon, R., Engle, R., & Turner, G. (1998). The effects of spatial visualization skill training on gender and retention in engineering. *Journal of Women and Minorities in Engineering, 4*, 371–380.

Ehrlich, S., Levine, S., & Goldin-Meadow, S. (2006). The importance of gestures in children's spatial reasoning. *Developmental Psychology, 42*, 1259–1268.

Hsi, S., Linn, M. C., & Bell, J. E. (1997). The role of spatial reasoning in engineering and the design of spatial instruction. *Journal of Engineering Education, 86*(2), 151–158.

Jones, S., & Burnett, G. (2008). Spatial ability and learning to program. *Human Technology, 4*(1), 47–61.

Keehner, M., Tendick, F., Meng, M. V., Anwar, H. P., Hegarty, M., Stoller, M. L., & Duh, Q.-Y. (2004). Spatial ability, experience, and skill in laparoscopic surgery. *The American Journal of Surgery, 188*, 71–75.

Knapp, A. (2011). Why schools don't value spatial reasoning. *Forbes*. Retrieved from http://www.forbes.com/sites/alexknapp/2011/12/27/why-dont-schools-value-spatial-reasoning.

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science, 31*, 549–579.

Lord, T. (1990). Enhancing learning in the life sciences through spatial perception. *Innovative Higher Education, 15*(1), 5–16.

Lord, T., & Nicely, G. (1997). Does spatial aptitude influence science-math subject preferences of children? *Journal of Elementary Science Education, 9*(2), 67–81.

Lubinski, D. (2010). Spatial ability and STEM: a sleeping giant for talent identification and development. *Personality and Individual Differences, 49*, 344–351.

McNeil, N. M., & Alibali, M. W. (2005). Why won't you change your mind? Knowledge of operational patterns hinders learning and performance on equations. *Child Development, 76*, 1–17.

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.

Mix, K. S., & Cheng, Y.-L. (2012). The relation between space and math: developmental and educational implications. *Advances in Child Development and Behavior, 42*, 197–243.

National Center for Educational Statistics (2012). *The nation's report card: Science 2011* (NCES 2012–465). Washington, D.C.: Institute of Education Sciences, U.S. Department of Education.

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

National Science Foundation. (2009). *Women, minorities, and persons with disabilities in science and engineering*. Arlington: National Science Foundation.

Ozdemir, G. (2010). Exploring visuospatial thinking in learning about mineralogy: spatial orientation ability and spatial visualization ability. *International Journal of Science and Mathematics Education, 8*(4), 737–759.

Park, G., Lubinski, D. L., & Benbow, C. P. (2010). Recognizing spatial intelligence. *Scientific American*. Retrieved from http://www.scientificamerican.com/article/recognizing-spatial-intel/. Accessed 19 Nov 2014.

Pribyl, J. R., & Bodner, G. M. (1987). Spatial ability and its role in organic chemistry: a study of four organic courses. *Journal of Research in Science Teaching, 24*(3), 229–240.

Raver, C. C., Jones, S. M., Li-Grining, C. P., Metzger, M., Champion, K. M., & Sardin, L. (2008). Improving preschool classroom processes: preliminary findings from a randomized trial implemented in Head Start settings. *Early Childhood Research Quarterly, 23*(1), 10–26.

Rudmann, D. (2002). Solving astronomy problems can be limited by intuited knowledge, spatial ability, or both. Paper presented at the Annual Meeting of the American Educational Research Association. New Orleans, LA.

Small, M. Y., & Morton, M. E. (1983). Spatial visualization training improves performance in organic chemistry. *Journal of College Science Teaching, 13*(1), 41–43.

Smith, M. K., & Knight, J. K. (2012). Using the genetics concept assessment to document presistent conceptual difficulties in undergraduate genetics courses. *Genetics*, *191*(1), 21–32.

Sorby, S. A. (2001). A course in spatial visualization and its impact on the retention of female engineering students. *Journal of Women and Minorities in Science and Engineering, 7*(2), 153–172.

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

Sorby, S. A. (2011). *Developing spatial thinking*. Independence: Cengage.

Sorby, S. A., 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.

Stieff, M. (2011). When is a molecule three-dimensional? A task-specific role for imagistic reasoning in advanced chemistry. *Science Education, 95*(2), 310–336.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: when, why and how. *Psychology of Learning and Motivation, 57*, 147–181.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A., Warren, C., & Newcombe, N. (2013a). The malleability of spatial skills: a meta-analysis of training studies. *Psychological Bulletin, 139*(2), 352–402.

Uttal, D. H., Miller, D. I., & Newcombe, N. S. (2013b). Exploring and enhancing spatial thinking links to achievement in science, technology, engineering, and mathematics? *Current Directions in Psychological Science, 22*(5), 367–373.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: aligning over fifty 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.

White, J. L., Altschuld, J. W., & Lee, Y. (2006). Persistence of interest in science, technology, engineering, and mathematics: a minority retention study. *Journal of Women and Minorities in Science and Engineering, 12*(1), 47–64.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin and Review, 15*(4), 763–771.