Integrating Engineering into the K-8 Classroom: A Method of Identifying and Developing Strong Spatial Skills

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Integrating Engineering into the K-8 Classroom:

A Method of Identifying and Developing Strong Spatial Skills

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Historically, giftedness has been seen as a generic, innate, intellectual quality of an individual that allows one to be successful in reasoning in all domains (e.g., Robinson, Zigler, & Gallagher, 2000). Contrary to this view, recent research suggests that giftedness is domain-specific and malleable (e.g., Subotnik, Olszewski-Kubilius, & Worrell, 2011; Bloom, 1985) and that it must be developed and sustained by way of training and interventions in domain-specific skills (e.g., Lubinski, 2010). In this chapter, we address identifying and developing talent in kindergarten to eighth grade (K-8) students for one specific domain, engineering.

The field of gifted education has devoted a great deal of research and discussion to issues surrounding the identification of academic talent in children (Johnsen, 2011). Issues that have garnered the most attention include the efficacy of the various methods of identification (IQ tests, achievement tests, nonverbal tests, and creativity tests; Lohman, 2005a; Lohman & Lakin, 2008); the use of assessments to identify academic talent equitably among racially and socio-economically diverse groups of students (Lohman, 2005b); and the predictive validity of various identification tools for forms of adult achievement (Subotnik Olszewski-Kubilius, & Worrell, 2011)—all with the goal of generating best practices for educators. Today, schools still rely heavily on measures of general intelligence and overall achievement to identify giftedness, and consequently, many talented students could be overlooked (NAGC, 2015).

However, more recent research demonstrates the efficacy of viewing talent as situated within specific domains of practice. This “talent development” perspective comes with an emphasis on identifying specific skillsets that are related to achievement within particular domains (see Subotnik et al., 2011; Lubinski, 2010). Research about domain-relevant skills is more substantial and typical in athletics (Elferink-Gemser, Kannekens, Lyons, Tromp, & Visscher, 2010) and the performing arts (Subotnik & Jarvin, 2005) but has also been
demonstrated for some academic fields, such as STEM (science, technology, engineering, and math) fields (Park, Lubinski, & Benbow, 2007). Subotnik et al. (2011), provide a more thorough discussion of domain-specific skills. Promoters of the talent development framework assert that a domain-specific perspective of giftedness will result in the identification of more students with talents, as well as a more successful effort at promoting domain expertise (Subotnik, Olszewski-Kubilius, & Worrell, 2011).

Substantial evidence exists that abilities can be enhanced (Herrnstein, Nickerson, deSanchez, & Swets, 1986; Sternberg, 1988; Uttal et al., 2013) and that high abilities within a domain are necessary but not sufficient for generating expertise or exceptional productivity. Without opportunities to learn from skilled instructors and develop psychosocial skills, such as persistence, domain-specific skills may develop too slowly or even counterproductively (Subotnik & Jarvin, 2005). For example, in engineering, learning to interpret blueprints incorrectly can lead to constructing poor quality structures. In many domains, training and instruction from a young age is important for an individual to reach an exceptional level in adulthood (Subotnik et al., 2011).

A recent goal of the United States is to develop America’s future scientists, technologists, engineers, and mathematicians, in order to be competitive in a growing global economy (Friedman, 2005; Jolly, 2009). One way to reach this goal is to introduce all STEM disciplines (not just the math and science traditionally taught in K-8 classrooms) early on in students’ education. Engineering, a distinct STEM domain, is one whose principles and concepts can be easily adapted for elementary and middle school students and for different ability levels. Furthermore, engaging in engineering activities develops skills necessary to succeed in the discipline and important for success in the other STEM domains—e.g., spatial skills (e.g., Shea,
Lubinski, & Benbow, 2001). The adaptability of the lessons and the fostering of skills critical to future STEM success makes engineering an ideal discipline to integrate into the K-8 curriculum (e.g., Museum of Science, 2015; Samuels & Seymour, 2015).

Therefore, we will first discuss some of the advantages of introducing all students, gifted and those not identified, to engineering early on. Second, we will talk about a specific set of skills that are important for engineering, spatial skills, and how they can be assessed in students. Third, we will discuss how engineering can be integrated into the K-8 curriculum and how lessons can be adapted to challenge students of different ability levels. And finally, we will consider the value of adding spatial skills to the traditional measures used to identify academically talented students.

The Importance of Early Engineering Learning

K-8 engineering learning activities have become increasingly popular in recent years, both within school and in out-of-school spaces (e.g., Honey & Kanter, 2013; Martinez & Stager, 2013; NAE & NRC, 2009; NRC, 2012; NSF, 2012; Resnick & Rosenbaum, 2013). In schools, they have become a formal part of the Next Generation Science Standards (NAE & NRC, 2009; Next Generation Lead States, 2013; NRC, 2012), while out-of-school makerspaces, tinkering studios, engineering camps, and after school coding or robotics clubs have grown greatly in popularity (e.g., Honey & Kanter, 2013; Martinez & Stager, 2013; Resnick & Rosenbaum, 2013).

These early engineering learning interventions are beneficial for a number of reasons. First, they spark student interest and provide opportunities to learn about engineering, potentially increasing the number of students interested in and able to pursue careers in engineering and
other STEM disciplines (National Science Board, 2010; Mann et al. 2011). Second, they cultivate skills and habits of mind that are valuable both in engineering and in other domains, including 21st century skills such as collaboration, creativity, self-management, communication, and systems thinking (Hilton, 2010; Katehi, Pearson, & Feder, 2009; Mann et al., 2011). Many within the field of gifted education find that these skills are also attributes of gifted students (Mann et al., 2011). Lastly, they provide a vehicle for teaching and improving spatial skills, a set of skills important in STEM (Uttal & Cohen, 2012) and in everyday reasoning and problem solving (Gauvain, 1993) but which are currently undervalued and underdeveloped in K-8 schooling (e.g., NRC, 2006; Newcombe, Uttal, & Sauter, 2013).

**What are Spatial Skills?**

So what are spatial skills? Traditional definitions of this skillset characterize it as one type of ability. For example, an early definition defines it as the ability to “search the visual field, apprehending the forms, shapes, and positions of objects as visually perceived, forming mental representations of those forms, shapes, and positions, and manipulating such representations ‘mentally’” (Carroll, 1993, p. 304). Though often presented as a unitary construct, there are actually several different kinds of spatial skills (Newcombe & Shipley, 2015; Guilford & Lacey, 1947; McGee, 1979; Thurstone & Thurstone, 1941). Some common spatial skills include skills for navigation (e.g., Weisberg et al., 2014), perspective taking (envisioning the world from a different point of view; e.g., Hegarty & Waller, 2004), and disembedding (identifying a figure within a complex array of other figures; e.g., Witkin et al., 1971).

Not only is there more than one kind of spatial skill, but performance on one skill does not necessarily predict performance on another type of skill. For example, Atit, Shipley, and
Tikoff (2013) showed that the skills used to visualize the rotation of an object are distinct from the skills used to visualize the bending or un-bending of an object. Therefore, a student who may be good at one type of spatial skill may not be good at all spatial tasks.

Furthermore, recent research suggests that spatial skills may be domain specific (Uttal & Cohen, 2012). For example, Jee and colleagues (2009) found that geoscience students outperformed psychology students on cross-sectioning or penetrative thinking tasks involving images of rock formations, but there was no difference between the two groups on a spatially similar task involving layers of fruit or lasagna. Similar patterns have been found in other STEM disciplines, such as chemistry (Stieff, Hegarty, & Dixon, 2010), and dentistry (Hegarty, Keehner, Khooshabeh, & Montello, 2009). As spatial skills can be improved with training and practice (Uttal et al., 2013), this research indicates that perhaps these skills should be developed within the context of a specific domain.

**Spatial Skills and Measures Relevant To Engineering**

As the multiplicity of spatial skills has been recognized, many researchers have focused their efforts on understanding which skills are important for which disciplines (e.g., Atit, Gagnier, & Shipley, 2015; Baartmans & Sorby, 1996; Sorby, 1999; Stieff, 2013). Work in engineering has suggested that there are three major kinds of spatial skills that are important for success in the field: mental rotation, spatial visualization, and two-dimensional (2D) to three-dimensional (3D) mental transformation (e.g., Hegarty, 1992; Hegarty, 2004; Hsi, Linn, & Bell, 1997; Sorby et al., 2013). Mental rotation is the ability to mentally rotate a 2D or 3D figure (Linn & Petersen, 1985; Shepard & Metzler, 1971). Spatial visualization is the ability to piece together objects into more complex configurations or visualize and mentally transform them (Linn &
Petersen, 1985; Newcombe & Shipley, 2015). For example, the ability to mentally fold and unfold an object requires spatial visualization skills (e.g., Harris, Newcombe, & Hirsh-Pasek, 2013; Milivojevic, Johnson, Hamm, & Corballis, 2003). Lastly, 2D to 3D transformation involves visualizing a 2D representation in 3D and vice versa (e.g., Atit, Weisberg, Shipley, & Newcombe, 2016; Sorby, 2009).

Before an object is ever created, an engineer must be able to visualize the object and draw its plans (Baartmans & Sorby, 1996). Completing this task requires using mental rotation, spatial visualization, and 2D to 3D transformation skills. In engineering, the standard drawing layout typically includes orthographic projections of top, front, right-side, or cross-section views of the object, and also an isometric, or corner view, of the object. In order to draw the different views for an object, the engineer needs to be able to visualize what each side of the object looks like. This requires mental rotation skills and spatial visualization skills (mentally unfolding the object and visualizing the individual pieces). Lastly, in order to build the object, the engineer needs to be able to interpret the 2D drawings of the structure and visualize it in 3D – 2D to 3D mental transformation skills (Baartmans & Sorby, 1996).

Though many assessments have been created to measure these specific spatial thinking skills in adults (e.g., Peters et al., 1995; Ekstrom et al., 1976; Titus & Horsman, 2009), only a few have been created for K-8 students. Tests of mental rotation that have been found to be suitable for children include the chronometric mental rotation test created by Petra Jansen and her colleagues (Lehmann & Jansen, 2012; Kaltner & Jansen, 2014) and the Mental Rotation Subtest from the Chicago Primary Mental Abilities Test (Thurstone & Thurstone, 1941). A test of spatial visualization for children is the Mental Folding Test for Children (Harris, Newcombe, & Hirsh-Pasek, 2013), and a test of 2D to 3D mental transformation is the Diagrammatic
Representations Test (DRT; Frick & Newcombe, 2015). As the small number of spatial tests developed for K-8 students indicates, much more research in this area is required. Yet, these few tests can help us begin to identify students with strong engineering-relevant spatial skills.

**Cultivating Spatial Skills Through Engineering Learning Activities**

Given the strong connection between engineering and spatial skills (e.g., Hsi et al., 1997; Sorby, 1999; Sorby, 2009; Sorby & Baartmans, 2000; Sorby, Casey, Veurink, & Dulaney, 2013; Tseng & Yang, 2011), parents, educators, and researchers should consider how to foster the development of these skills through engineering activities at an early age (e.g., Newcombe, 2010). Research on cognitive development and engineering learning provides insight into how and when we might help students cultivate their spatial skills. For example, object manipulation, in the form of puzzle play or manual rotation, has been shown to improve preschoolers’ spatial transformation or mental rotation skills (Levine, Ratliff, Huttenlocher, & Cannon, 2012; Ping, Ratliff, Hickey, & Levine, 2011). Similarly, engaging young children in talk and gesture about spatial ideas may improve spatial skills (Ping et al., 2011; Pruden, Levine, & Huttenlocher, 2011). To the extent that engineering activities provide opportunities for discussing and manipulating spatial objects and ideas, we might expect these activities to similarly improve learners’ spatial skills.

However, not all engineering learning activities are the same. There are three general categories of engineering learning activities, which vary in terms of both the goals and structure of the engineering task (Ramey & Uttal, submitted). The first are construction kit activities, such as Lego®, K’nex®, or Snap Circuits®, in which students build devices from diagrammatic instructions (Ramey & Uttal, submitted). The second category is engineering design activities.
These are included in many of the school engineering curricula, such as Project Lead the Way and Engineering is Elementary. They encourage students to walk through the steps of the engineering design process (e.g., ask, imagine, plan, create, and improve) to achieve a predetermined goal, given specific material constraints (e.g., Brophy, Klein, Portsmore, & Rogers, 2008; Museum of Science, 2015; Project Lead the Way, 2015). Finally, the third category of activities are tinkering or making activities. These activities are most often seen in makerspaces, maker-clubs, and museum-based tinkering studios. They are modelled after the adult maker movement and are grounded in constructionist principles of learning and the desire to integrate new tools and technologies into design (Papert, 1980; Resnick & Rosenbaum, 2013).

Of the three types of engineering activities, they are the most open-ended and creative, tending to focus around the use of particular tools or skills, instead of predetermined goals or design processes (Martinez & Stager, 2013; Resnick & Rosenbaum, 2013; Vossoughi et al., 2013).

Different activities cultivate different spatial skills. For example, making, tinkering, and engineering design activities all encourage learners to visualize, communicate, and create novel spatial configurations (Ramey & Uttal, submitted). In contrast, construction kits necessitate attention to specific spatial relations between objects and diagrammatic instructions (Ramey & Uttal, submitted). Collaborative engineering learning activities allow learners to use spatial talk and gesture to think through and share spatial ideas, while activities involving design sketching or CAD modeling help students learn to use domain-specific representations to think through spatial ideas.

Different types of engineering learning activities also have different affordances for catering to gifted students. Of the different types of engineering activities, tinkering or making activities are perhaps the best suited to gifted learners, because they afford the most creativity
and self-direction. These activities tend to both necessitate and cultivate the types of skills gifted students have, such as systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations (Duke University Talent Identification Program, 2008; Katehi et al., 2009; Mann et al. 2011).

However, through differentiated instruction, the other two types of engineering learning activities may also have their place in gifted education. For example, typical construction kits come with diagrammatic instructions drawn in 3D perspective, because they tend to be the easiest to understand and work from. However, as previously discussed, when professional engineers or architects make or work from construction diagrams (i.e., blueprints), they tend to work from 2D orthographic projections. Translating these types of diagrams into 3D objects requires more complex spatial reasoning. Thus, one way to differentiate instruction for construction kits would be to present spatially talented students with more complex, orthographic diagrams to work from. Taking this a step further, instructors might consider having gifted students design their own structures using construction kit materials and then draw blueprints of their designs, so that another student could replicate them.

Finally, within engineering design activities, educators might consider either pushing gifted students’ creativity, by removing some of the task constraints, or challenging their reasoning skills, by adding additional constraints. For example, one common engineering design activity is making and adjusting blades for a wind turbine, using cardboard or balsawood, so that the turbine can lift a certain number of weights or generate a certain amount of electricity. Unfortunately, using only cardboard or balsawood and a premade turbine base, students are limited to flat blades and a conventional turbine structure. Removing material constraints, and allowing students to, for example, 3D-print curved 3D blades or design their own turbine base
would allow for greater design creativity. Conversely, increasing the number of weights the

turbine has to lift or limiting the number of blades students can use creates a more challenging
reasoning problem.

Identifying Students with Strong Spatial Skills

Traditionally, spatial skills are not assessed when identifying gifted students. Generally,
programs for academically talented students assess only verbal and quantitative abilities (e.g.,
Benbow & Lubinski, 1996; Benbow & Stanley, 1996). Students with a quantitative tilt (i.e.,
stronger quantitative skills than verbal skills) gravitate towards STEM disciplines and are more
likely to pursue STEM careers as adults (e.g., Achter, Lubinski, Benbow, & Eftekharisanjani,
1999; Lubinski, Webb, Morelock, & Benbow, 2001). Research has shown that including an
assessment of spatial skills, in addition to quantitative and verbal measures, reveals more
students that pursue STEM fields in the future than do quantitative skills alone (e.g., Shea, et al.,
2001; Wai, Lubinski, & Benbow, 2009). Thus, assessing for exceptional spatial skills in younger
students could earlier reveal which students could truly benefit from engaging in more
challenging STEM activities.

Conclusion

Given the evidence supporting the relationship between strong spatial skills and success
in STEM disciplines (e.g., Wai, et al., 2009; Lubinski, 2010) and the current need to develop
STEM talent in the United States (e.g., Committee on Integrated STEM Education, NAE, &
NRC, 2014), it is critical that spatial skill assessments be added to identification batteries for
gifted and talented students. Recognizing students with this specific kind of talent could help
unveil the next generation of STEM professionals. However, spatial talent assessment does not
need to be limited to spatial tests. It can also include curricular activities, such as engineering activities, that both cultivate and help identify spatial talent. Using activities to identify talent is especially important for students from low income or diverse cultural backgrounds who have potential but may, for various reasons, be less likely to demonstrate it on tests.

Additionally, teachers should offer activities and curricula that require and develop spatial skills. Noticing students who could be spatially talented and adjusting lesson plans to make sure that they are challenged can help cultivate the skills and interest necessary to pursue STEM domains later on. Moreover, it could increase motivation in school overall.

Lastly, developing spatial skills should not just be a focus for students who show advanced ability or interest in the area, but they should be fostered and developed in all students. Because spatial skills are malleable (Uttal et al., 2013), those students who do not show a propensity early on can develop stronger skills with more exposure and practice. Integrating engineering concepts and activities into the curriculum provides teachers with a vehicle for engaging students of different ability levels, a method for improving this skillset and a means to identify children with exceptional skills or interest. Therefore, we recommend introducing engineering early in the K-8 curriculum as it can benefit both spatially talented students and students with weaker spatial skills.
References


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# Resources for Educators, Parents, and Students

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