Journal of Women and Minorities in Science and Engineering 25(1): 1–23 (2019)

PREPARING FOR STEM: IMPACT OF SPATIAL VISUALIZATION TRAINING ON MIDDLE SCHOOL MATH PERFORMANCE

***Sheryl A. Sorby*[1,*] *& Norma Veurink*[2]**

[1]*University of Cincinnati, Cincinnati, OH*

[2]*Michigan Technological University, Houghton, MI 49931*

*Address all correspondence to: Sheryl A. Sorby, Department of Engineering Education, 2851 Woodside Dr., ML0074, Cincinnati, OH 45221, E-mail: sheryl.sorby@uc.edu

The ability to visualize in three-dimensions has been shown to be critical to success in engineering and in mathematics. Unfortunately of all cognitive process, spatial visualization exhibits some of the most robust gender difference, favoring males. Poorly developed spatial skills among women and girls could be a hindrance as we strive to diversify engineering. A course for developing 3D spatial skills has been implemented at the university level with promising results. A spatial skills curriculum was implemented in 7th grade mathematics at a low-performing school in rural Colorado. Student outcomes on standardized mathematics tests, including the statewide assessment and a local diagnostic test for 9th grade math placement were examined for student participants as well as for a comparison group. The students who participated in the spatial skills training in 7th grade performed better on both the statewide mathematics assessment as well as on the local placement test for 9th grade mathematics. The improvements in mathematics performance were particularly strong for the girls in the study.

KEY WORDS*:* *spatial cognition, gender differences, SES differences, mathematics achievement, K-12*

1. PURPOSE OF THE STUDY

Numerous reports, articles, and opinion pieces all extol the need for more engineering graduates to fill the need for economic competitiveness in the U.S. as engineers are seen as the drivers to prosperity in this knowledge-based economy. In response, states across the country are implementing efforts to increase their engineering workforce and school districts nationwide are hiring Directors of STEM Education to bolster achievement in science and mathematics. Historically, we have always been hampered in our ability to attract women and minorities to engineering programs. Despite nearly four decades of concerted effort, we have made little progress in achieving goals of increasing the proportion of women and minorities who study engineering. The lack of women and minorities in engineering means that diverse perspectives are not always available to solve the critical problems our society faces. Wai et al. (2009) showed the clear link between STEM degree attainment and strong spatial skills. There is also growing recognition of the importance of spatial thinking for educational and occupational success in STEM fields (particularly engineering); however, several studies have shown the spatial visualization skills of females lag those of males, and those of lower socioeconomic status tend to also have weaker spatial visualization skills. Could weak spatial ability be part of the problem in achieving a diverse engineering profession?

At the post-secondary level, research has shown that engineering students with initially weak spatial visualization skills that receive spatial training not only see an increase in spatial ability, but have higher retention and graduation rates and higher grades in STEM courses commonly taken during a first-year engineering curriculum than students with comparable visualization skills who do not take the spatial training. Based on the success of spatial training at the post-secondary level, could similar results be achieved if spatial training were implemented at the secondary level? In other words, if spatial ability is trainable and the training is implemented early enough in a student's career, could that lead to more students, particularly females and minorities, pursuing engineering degrees? The purpose of this study is to begin to answer that question.

A longitudinal study to track long-term impacts of spatial training on pre-college students was implemented in a Colorado school beginning in the fall of 2011. In this study, a spatial training curriculum was integrated into 7th grade math courses and career-related attitudes and choice of STEM-related high school courses of students who received spatial training are being analyzed to determine if students, particularly females, that take the training ultimately are more likely to take more STEM courses in high school and go on to STEM careers than students not taking the training. This paper presents a partial analysis of the data by comparing math success of students taking spatial visualization training with those not taking the training. Future analysis will look at whether or not the spatial skills intervention improved students' attitudes about STEM careers.

2. RESEARCH QUESTIONS

The research questions addressed in this paper include the following:

- Do students who receive spatial training in 7th grade increase their spatial ability significantly more than those who do not receive the training?
- Do students who receive spatial skills training perform better on standardized math tests compared to those who do not receive the training?
- Do students who receive spatial skills training in 7th grade enroll in higher-level math classes in 9th grade than students who do not receive the spatial training?
- Are there sex differences apparent for any of these factors?

3. BACKGROUND INFORMATION

While women account for almost half of the U.S. workforce, they hold less than 25% of STEM jobs. This has remained largely unchanged over the last decade (2000–2009) even though the percent of female college-educated workers has increased from 46% to 49% during the same time period (Beede et al., 2011). The scarcity of women and minorities in high-paying careers such as engineering further exacerbates problems in the gender and minority wage gaps. The low percentages of women and minorities in engineering also mean that there are few role models and mentors for those who do defy the odds and enroll in engineering programs.

Changes in the demographics of the U.S. population amplify problems associated with not attracting women and minorities to engineering. If we look at the demographic projections for the U.S. into the coming decades, our traditional source of engineers, majority males, is shrinking in relative size to other groups. Between 1990 and 2000, the total population grew at a rate of 13%. However, the minority population grew by 35% while the non-Hispanic white population only grew by 3.4%. The Hispanic population more than doubled between 1980 and 2000, increasing from 14.6 million to 35.3 million. The Pew Hispanic Center (Pew Research Center, 2005) projects that the Hispanic population will reach 60.4 million by 2020. As the complexion of our nation changes, we must attract a more diverse pool of students into engineering in order to meet the need for innovation for coming generations.

3.1 Importance of Spatial Skills in Engineering Success

Spatial visualization skills are becoming increasingly identified as being critical to success in and selection of STEM studies and careers. The National Research Council (2006) and the National Science Board (NSB) (2010) highlight the importance of spatial skills to STEM success. “Preparing the Next Generation of STEM Innovators” recommends that talent searches measure not just verbal and math ability, but also spatial ability (NSB, 2010). In a study that addressed a wide range of disciplines, Wai et al. (2009) analyzed eleven years of longitudinal data from over 400,000 talented high school students. Spatial ability emerged as a consistent and statistically independent predictor of STEM-related career selection and attainment of an advanced STEM degree.

Verdine et al. (2014) looked at children’s ability to correctly build block figures as a test of their spatial visualization skills. They found an early link between spatial skills and mathematical skills for children as young as 3 years old. In another study, Gunderson, et al. (2012) found that preschoolers who performed better on a test of spatial skills were better at mathematics as 8-year-olds, even when controlling for verbal ability. Several studies have shown the link between spatial skills and the ability to solve word problems (e.g., van Garderen, 2006).

In a review article discussing numerous studies in chemistry education, Harle and Towns (2011) describe research through the years demonstrating the need for well-developed spatial skills for success in chemistry, especially, but not limited to, organic chemistry. Several studies have shown a link between spatial skills and introductory engineering courses, including graphics and computer aided design (Sorby, 2000; Branoff, 2014; Veurink and Sorby, 2011). There is evidence that spatial visualization skill predicts course selection and success in physics (Talley, 1973; Kozhevnikov et al., 2007) and spatial skills have been shown to be a predictor of success in geology (Kali and Orion, 1996; Orion et al., 1997). Recent articles link spatial skills to creativity and technical innovation (Kell et al., 2013) and to success in computer programming (Jones and Burnett, 2008). Thus, it is readily apparent that high spatial ability is a requirement for engineering success.

3.2 Gender Differences in Spatial Skills

Unfortunately, it is well documented that girls (and women) on average perform worse than boys (and men) on tests which measure spatial ability, particularly tests of horizontality concepts (Liben, 1991) and mental rotation (Linn and Petersen, 1985; Tartre, 1990; Voyer et al., 1995).

There is little agreement regarding why there are gender differences in spatial ability. In research conducted by Casey et al. (1992), they examined the nature versus nurture debate in terms of spatial skills development and found that there is likely an interaction between biological and environmental factors in the development of spatial skills for women.

Research conducted by Ganley et al. (2014) showed that gender differences on tests of spatial ability mediated the difference in standardized test scores for 8th grade physical science and technology/engineering subjects (n = 113). They then examined statewide scores on these tests (n = 73,245) and found large gender differences on items that were highly correlated with mental rotation scores.

3.3 Relationship between Socioeconomic Status and Spatial Skills

In addition to the large body of work documenting gender differences in spatial skills, there is a growing body of evidence that spatial skills vary also by socioeconomic status (SES). Early work by Ben-Chaim et al. (1988) showed a link between SES and spatial skills. In this study, students in 5th through 8th grades at three different schools were given tests of spatial cognition. One school was an inner city school with a relatively large proportion of minority students. A second school was a rural district with predominantly white and middle-class students. A third school was a suburban school which served a community of predominantly white upper middle-class university and state government professionals. Their findings included that there were significant differences in spatial visualization performance by grade (increasing with age), by sex (favoring boys), and by site (increasing with SES).

Levine et al. (2005) conducted a study whereby students were tracked over 2 years across grades 2 and 3, giving them tests of spatial ability at four times over the study period. There were 15 schools in the study and SES was assigned at the school level based on census data. Students from high- and middle-SES groups did not vary significantly from one another; however, both were significantly better than the low-SES students.

Casey et al. (2011) conducted a study looking at the impact of spatial skills on measurement concepts among 4th grade students. The study made the case that measurement is a key mathematical skill with two underlying components—a spatial component and an analytic component. There were several measures used in this study—two spatial visualization tests, a measurement task, a numeric test, a verbal working memory task, and a spatial working memory task. Students from a low-SES school district performed worse on all measures. In addition, spatial skill level predicted success on the measurement task for students from the affluent school, but not for those from the low-SES school. This likely means that the low-SES students were not able to apply a basic cognitive process like spatial visualization to the solution of problems.

In a study by Verdine et al. (2014), researchers looked at children's ability to correctly build block figures as a test of their spatial visualization skills. They found that children from high-SES groups outperformed those from low-SES groups by a significant amount. They did not find gender differences in the block-building tasks—just differences by SES groups.

3.4 Malleability of Spatial Skills

There is an abundance of evidence that spatial skills can be enhanced through practice (Uttal et al., 2013); however, helping students to develop their spatial skills is not typically a part of the formal U.S. educational system. Although spatial thinking has been a part of the national mathematics standards for many years (National Council of Teachers of Mathematics, 2000), it is not always specifically assessed on the high stakes tests in most states and therefore is not always a part of the mathematics curriculum. Despite the clear importance of spatial skills for STEM careers these skills are unlikely to be consistently taught in schools. Ben-Chaim et al. (1988) developed a training program for developing spatial skills. Through this training, students had significant gains after instruction with a similar gain for both the boys and the girls.

An interesting finding from this study is that although all grade levels in the study (5th through 8th grades) gained significantly from the spatial skills instruction, both the boys and girls in the 7th grade gained more than the others. This suggests that seventh grade may be an optimal time for spatial skills training.

In 1993, Sorby developed a post-secondary spatial visualization training course for freshman engineering students. Since the development of the course, several studies have shown the positive impact of the training on student spatial visualization skills, grades in calculus and engineering courses, and retention, particularly of females in engineering (Sorby and Baartmans, 2000; Sorby, 2009; Veurink and Sorby, 2011; Sorby et al., 2013). The curriculum was also used in a pilot study in middle and high school, where it was found that the training was effective in improving the spatial visualization skills of pre-college students (Hungwe et al., 2007).

In the pilot study, the curriculum was implemented in a middle school integrated technology course (primarily students in the 8th grade). Students worked in pairs to complete the various software and workbook modules. In the first implementation (2006), students completed the nine modules with no modification. In the second implementation (2007), additional sketching problems were created in four of the modules. Thus, the 2007 treatment group spent more time on task solving problems in support of spatial skills development. Table 1 includes the pre- and post-test results for the middle school students in this previous pilot study. For this study, students were given four component tests of spatial visualization which were combined into a single score through a principal components analysis.

For the results presented in Table 1, gains for both treatment groups were significantly higher than the gains for the comparison group ($p < 0.01$). In addition, gains for the 2007 treatment group, which had more time on task solving spatial problems than the 2006 treatment group, were significantly higher than the gains for the 2006 treatment group ($p < 0.01$).

4. RESEARCH METHODS

4.1 Study Participants

The study was conducted in a rural Colorado school district, where more than three-quarters of the students are of Hispanic ethnicity and more than 40% are English language learners. At this district, a significant proportion of the students are eligible for free or reduced lunch as well (~80%). The students included in this study are students who were in a 7th grade mathematics class beginning in the fall 2010 semester through the spring 2013 semester. It was decided to implement the spatial training at the 7th grade level based on the findings of Ben-Chaim et al. (1988) that 7th graders gained more from spatial instruction than 5th, 6th, and 8th graders and because a pilot study of the spatial training curriculum had been successfully tested in a middle

TABLE 1: Pre- and post-test results for middle school students

Group	n	Average Pre-test	Average Post-test	Average Gain
Comparison	141	42.0%	46.8%	4.8%
2006 treatment	80	42.0%	54.3%	12.3%
2007 treatment	52	54.0%	71.1%	17.1%

school setting (Hungwe et al., 2007).

In this particular district, there were only two individuals teaching mathematics in the 7th grade, and the study was designed such that one of the two teachers would implement the spatial training the first year of the study (2011–2012), while both teachers would implement the training during the second year of the study (2012–2013). All 7th grade students were to be given spatial tests near the beginning and end of the training to assess their improvement in spatial skills whether or not they received the spatial training. Scores on standardized tests and 9th grade math placement were also to be compared. The null hypothesis was that students with the spatial skills training would perform better than those without (one-tailed analysis). In addition, since gender differences in spatial skills are widely reported in the literature, data were to be compared by gender where appropriate.

The design of the study was such that about half the students would receive the spatial training the first year of the study (the experimental group), while the other half did not receive the training the first year (the comparison group). Unfortunately, the school principal, unbeknownst to the researchers, “tracked” the students such that the better students went into our first experimental group and the poorer students went into first our comparison group. However, what is fortunate for us is that they also did this during the previous year, i.e., for the year starting in the fall of 2010. For this reason, we were able to look at historical data for comparison purposes. During the second year of the study, we implemented the spatial skills curriculum in the 7th grade math courses of the teacher who had been the control teacher during the previous year so we now can make comparisons across two teachers and two years of implementation. The first implementation of the spatial skills curriculum at the Colorado district was in Fall 2011; a second implementation took place during the 2012–2013 academic year. It should be noted that across all years of the project to date, teacher 1 taught the more advanced students and teacher 2 taught the less advanced students (as measured by 6th grade standardized mathematics test scores). Table 2 illustrates our experimental design.

4.2 Spatial Training Curriculum and Implementation

In the summers prior to implementation of the spatial skills curriculum, a 7th grade math teacher at the middle school was trained by Sorby in the spatial training curriculum. As part of the training, the teacher was given PowerPoint presentations used in the university spatial training course as well as PDFs of the workbook (Sorby, 2016) to use as potential instructional aids. The teacher was also encouraged to use the software which accompanied the workbook to demonstrate the concepts to the students. The workbook covers ten topics, nine of which were used in the study and are described below.

- *Surfaces and solids of revolution.* Given a 2D shape, students determine which solid objects

TABLE 2: Experimental (EG) and control (CG) groups used in the study

	2010–2011	**2011–2012**	**2012–2013**
Teacher 1	CG1	EG1	
Teacher 2		CG2	EG2

could be formed by revolving the shape about an axis, or given a 3D solid, they determine which 2D shape could be revolved to create the solid.

- *Combining solids.* This module focuses on the identification of objects created by cutting, joining, or intersecting two objects.
- *Isometric sketching.* Students learn how coded plans can be used to define objects constructed of cubes or blocks and are then required to sketch them from several corner views.
- *Orthographic projection of normal surfaces.* In this module, students learn how to construct the top, front, and right views of an object. Hidden features of objects are also discussed.
- *Flat patterns.* Given 2D patterns with and without markings, students determine which 3D solid objects would result from the folding of the pattern.
- *Rotation of objects about a single axis.* Students learn about object rotation and sketch objects as they are rotated about a single axis.
- *Rotation of objects about two or more axes.* Continuing from the lessons learned in the previous module, students now rotate objects about two or more axes and sketch the result of this transformation.
- *Object reflections and planes of symmetry.* Students draw objects reflected across a plane and identify planes of symmetry of objects.
- *Cross sections.* In this module, students imagine a cutting plane passing through an object to determine what the cross section would look like.

Teachers received training in the implementation of the materials, but were given latitude in how they went about implementing the curriculum in their 7th grade math classes. Teacher 1 covered all nine modules described above except the Rotations about Two or More Axes module. Teacher 2 covered all of the nine modules, although in a different order than Teacher 1. Teacher 1 spent between 30 and 45 minutes in class on each module and assigned some of the workbook pages as homework for each module. Teacher 2 spent from 70 to 120 class minutes on the Rotations about a Single Axis, Isometric Sketching, and Orthographic Projections of Normal Surfaces modules, and then spent 30–45 class minutes on the remaining modules. Teacher 2 assigned workbook pages as homework on all but two of the modules.

Another key difference between the two implementations was that Teacher 1 chose to implement the curriculum over a period of approximately 10 weeks at the beginning of the school year and Teacher 2 implemented most of the curriculum over a concentrated period of time at the end of the school year. Since the state standardized testing occurred in March each year in Colorado, this meant that 7th grade standard test results could not be used as part of this analysis, since the 7th grade results for one experimental group would have reflected the impact of the spatial skills training but not for the other experimental group. For this reason, this paper will focus on the impact of the spatial skills training on 8th grade mathematics performance.

4.3 Measures

Six different measures of spatial skill levels were administered to the students in a pre-/postdesign. In general, the pre-tests were given approximately 1–2 weeks prior to the curriculum implementation and the post-test was given 1–2 weeks after the implementation. Students in the comparison group were given the tests of spatial visualization at the same time as the students in the experimental groups.

Two measures were used to determine the impact of the spatial training on students' mathematics performance. The first measure compared scores and pass rates on 6th and 8th grade standardized mathematics tests. The second measure compared the 9th grade math placement of students in the study.

4.3.1 Spatial Skills Measures

The first test of spatial visualization given was the water level task (WLT). The WLT was developed by Piaget and Inhelder in 1956 to assess child development in mastering the concepts of horizontality and verticality and has been used in numerous studies since its development. A six-item version of the test was used for this study. Clark (1999) found the Kuder-Richardson reliability for this version of the test to be 0.82 when used with adults. A sample problem from the WLT is shown in Fig. 1. With this test, students are presented with a tilted glass, are told that the glass is half full of water, and are asked to draw the level of the water on the figure. The correct answer is to draw a horizontal line, regardless of the orientation of the glass itself. In scoring this instrument, students were given one point if the line they drew was within 5° of horizontal and zero points for lines drawn at any other orientation.

In the second test of spatial cognition, 2D rotation (2ROT), students are presented with a figure on the left and asked to mark all of the possible target figures that represent a rotated view of the original figure. Reliability ratings for this instrument were not found in the literature. Some of the target figures are mirror images of the original figure and thus are not correct responses. Figure 2 shows an example problem from the 2ROT test. There were 30 problems in all on this instrument, and students were instructed to identify as many as possible within a 7-minute time limit. Total scores for students were recorded as # correct (marked when they should be marked) minus # incorrect (marked when they should not be correct). If a student score was a negative number, this was recorded as a zero overall on the test.

The third test of spatial cognition was ten items from the Purdue Spatial Visualization Test: Rotations (PSVT:R) (Guay, 1977). This test has an acceptable reliability with middle school students with a Cronbach's alpha of 0.62 (Hungwe et al., 2014). A sample problem from the PSVT:R is shown in Fig. 3. With this test, students are presented with an object on the top line that is shown in both an original and a rotated position. On the second line of the problem, a different object is shown. The objective is to mentally rotate the second object by the same amount as the first object and select the result from the choices given. For the ten problems given, scores were computed as the number correct minus 0.25 times the number incorrect. Overall negative scores were allowed for this portion of the spatial skills test.

The fourth component of the spatial skills test was the Paper-Folding Task (PFT) (ETS, 1962) as shown in Fig. 4. Fleishman and Dusek (1971) reported a Pearson product-moment test-retest correlation of 0.84 with adults for this test which indicates the test has reasonably high reliability. This test has been used with and deemed appropriate for middle school studies by other researchers (Caskey, 2009). With this test, a series of figures shows how a piece of paper is folded. In the final figure in the series, a hole is shown punching through the folded paper. The student then imagines what the piece of paper would look like if the paper were unfolded and se-

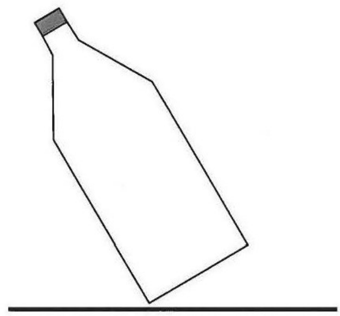

FIG. 1: Sample problem from the water level task

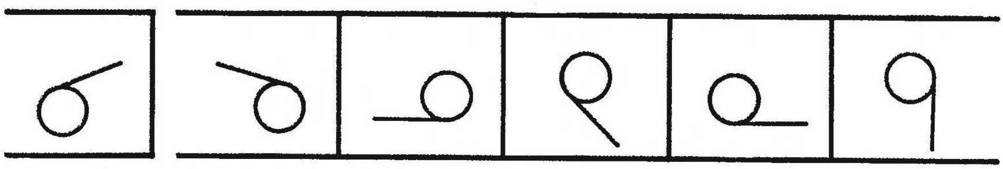

FIG. 2: Sample problem from the 2D rotation test (correct choices are #2 and #5)

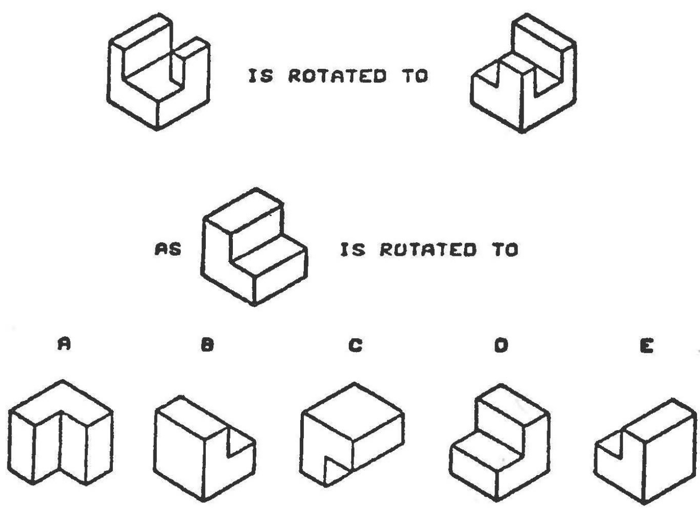

FIG. 3: Sample problem from PSVT:R (correct answer is D)

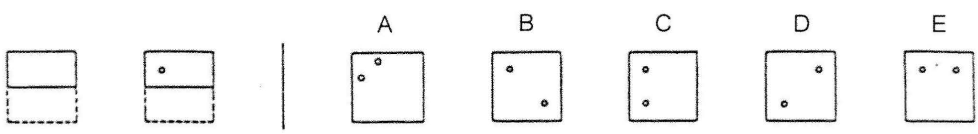

FIG. 4: Sample problem from the paper-folding task (correct answer is C)

lects the correct image from the choices given. There were 20 problems on the PFT, and students were instructed to complete as many as they could within 6 minutes. For the 20 problems given, scores were computed as the number correct minus 0.25 times the number incorrect. Overall negative scores were allowed for this portion of the spatial skills test.

The fifth component of the spatial skills test consisted of ten modified items from the Lappan test (Lappan, 1981). The items were modified by making them compliant with the standards used in the spatial skills curriculum. This test has an acceptable reliability with middle school students with a Cronbach's alpha of 0.64 (Hungwe et al., 2014). A sample item from the modified Lappan test is shown in Fig. 5. This test examines the ability of the students to visualize between 2D and 3D representations of objects. In some cases, students are presented with an isometric view of an object (3D view) and asked to select a given 2D representation (orthographic projection) of the same object. In other problems, students are presented with 2D views of an object and asked to identify what the 3D view of the object would be. For the ten problems given, scores were computed as the number correct minus 0.25 times the number incorrect. Overall negative scores were allowed for this portion of the spatial skills test.

The final test of spatial cognition given to the students was ten items from the Mental Cutting Test (MCT) (CEEB, 1939). This test has an acceptable reliability with middle school students with a Cronbach's alpha of 0.65 (Hungwe et al., 2014). With this test, an object and an imaginary cutting plane are shown on the left. Students are asked to visualize what the cross section would look like that was the result of intersecting the object with the given plane. For the ten problems given, scores were computed as the number correct minus 0.25 times the number incorrect. Overall negative scores were allowed for this portion of the spatial skills test. It should be noted that three of these tests, the PSVT:R, modified Lappan, and MCT, were used in the previous pilot study conducted by Sorby and three tests, WLT, PFT, and 2ROT, were not used in the previous study. A sample problem from the MCT is shown in Fig. 6.

5. RESULTS

As a measure of whether the experimental and control groups were comparable to one another with regards to mathematics preparation, we looked at scores the students earned on their 6th grade stan-

2. You are given a picture of a building drawn from the FRONT-RIGHT corner. Find the BACK VIEW.

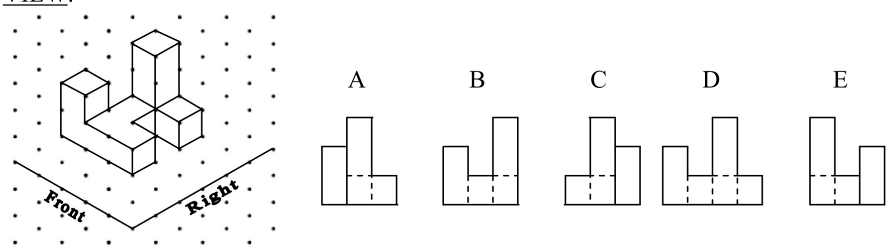

FIG. 5: Sample problem from modified Lappan test (correct answer is C)

dardized math test in the state of Colorado. Table 3 includes the results from this analysis.

From this analysis, it is apparent that the student populations across EG1 and CG1 and across EG2 and CG2 were comparable at the start of the experiment insofar as 6th grade standardized mathematics scores are concerned. It is also clear that the students in EG1/CG1 were significantly more advanced in mathematics 6th grade preparation than were the students in EG2/CG2.

5.1 Improvements in Spatial Skills

Table 4 includes a correlation matrix for the six instruments used in this study. For this analysis,

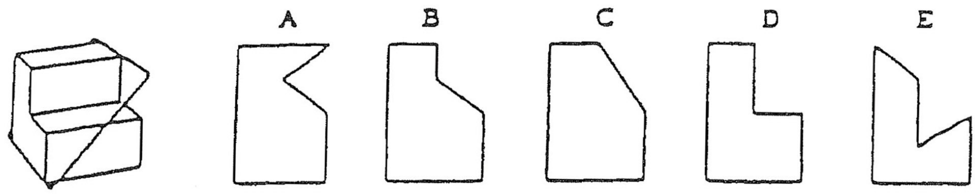

FIG. 6: Sample problem from the MCT (correct answer is D)

TABLE 3: 6th grade math scores for students in the study

	Average 6th Grade Math score	Standard Deviation	n	Significance of Difference
EG1	546.20	66.161	79	p = 0.4736, N. S.
CG1	553.99	64.227	67	
EG2	475.43	71.308	28	p = 0.4875, N. S.
CG2	484.01	51.434	88	

TABLE 4: Pearson's correlation matrix for spatial skills instruments. Pre-test correlations are above the diagonal and post-test correlations are below the diagonal.

	WLT	PFT	2ROT	PSVT:R	Lappan	MCT
WLT	1	.3378	.4007	.1867	.1629	.2375
PFT	.3323	1	.4730	.4226	.2959	.3903
2ROT	.2593	.5230	1	.3927	.2639	.4223
PSVT:R	.2975	.5216	.5474	1	.3189	.2672
Lappan	.3035	.6201	.5215	.5256	1	.2944
MCT	.1959	.4516	.5340	.4957	.5274	1

Pearson's correlation was used. For the data presented in Table 4, correlations between pre-test scores are shown above the diagonal and correlations for post-test scores are shown below the diagonal. From the data presented in Table 4, it appears that correlations for the WLT are weak for both the pre- and the post-tests. It also appears that correlations for the post-test scores are generally higher than they are for the pre-test scores.

Table 5 includes correlation data between pre- and post-test scores on the same instrument. For this analysis, it appears that the correlation coefficients are all ~0.5 with the exception of the 2ROT instrument where the correlation is 0.7367, indicating that for this instrument, the pre-test score is a good predictor of the post-test score.

Table 6 includes the results from pre- and post-testing with the spatial skills instruments disaggregated by gender. In this table, ***bold italics*** signifies statistical significance ($p < 0.05$) and underline signifies marginal statistical significance ($0.05 < p < 0.1$). It should be noted that no data are available for pre-/post-testing with CG1. For this analysis only paired data were used. If a student score on either the pre- or the post-test was missing, that student's data were eliminated for that particular instrument. From the data presented in this table, it appears that the students in the experimental groups generally experienced higher gains when compared to those in the control group.

In addition to the individual test scores examined for the students in this study, a principal components analysis (PCA) was performed on the test results so that weighting factors could be obtained to combine the scores on the six instruments into a single score. For this analysis, only complete cases were used, i.e., meaning that scores were available for all instruments for both the pre- and post-tests. In all, there were 113 complete cases. In addition, since the six instruments had differing possible maximum scores (e.g., maximum score = 70 for the 2ROT instrument and maximum score = 6 for the WLT) scores on each instrument were normalized according to normalized score equal to X-minimum/range. The weights obtained through the PCA were approximately equivalent, meaning that each instrument contributes almost equally to a "spatial factor" for each student, and are given in Table 7.

Normalized test scores were combined through the weightings achieved in the PCA, average pre- and post-test scores for each group were analyzed with the results presented in Table 8. Due to the small sample sizes, data for this analysis are not presented by gender.

TABLE 5: Pearson correlations between pre- and post-test scores

	WLT Pre-	**PFT Pre-**	**2ROT Pre-**	**PSVT:R Pre-**	**Lappan Pre-**	**MCT Pre-**
WLT post-	0.5449					
PFT post-		0.5774				
2ROT post-			0.7367			
PSVT:R post-				0.5797		
Lappan post-					0.4707	
MCT post-						0.4238

TABLE 6: Average pre- and post-test scores for students in three groups. Standard deviations in parentheses.

		EG1		EG2		CG2	
		M	**F**	**M**	**F**	**M**	**F**
WLT	Avg. pre-	2.00 (1.67)	1.51 (1.39)	1.63 (1.82)	1.00 (1.14)	0.88 (1.04)	1.45 (1.25)
	Avg. post-	1.94 (1.56)	2.11 (1.66)	2.00 (1.63)	1.61 (1.29)	1.38 (1.56)	1.63 (1.15)
	Avg. gain	–0.06 (1.39)	***0.59 (1.76)***	0.37 (1.45)	0.61 (1.72)	***0.50 (1.11)***	0.18 (1.04)
	n	34	37	16	18	34	38
PFT	Avg. pre-	5.79 (3.36)	6.07 (5.11)	4.24 (2.92)	4.71 (3.68)	4.23 (3.67)	4.17 (3.70)
	Avg. post-	7.83 (3.94)	8.49 (4.83)	6.08 (4.42)	6.16 (4.98)	5.67 (3.53)	5.35 (4.11)
	Avg. gain	***2.14 (2.58)***	***2.43 (3.04)***	1.85 (4.05)	1.46 (3.89)	***1.44 (3.71)***	1.17 (4.47)
	n	29	34	18	17	33	36
2DROT	Avg. pre-	26.36 (16.50)	22.51 (14.96)	19.88 (15.73)	12.13 (11.94)	19.26 (17.59)	11.34 (12.07)
	Avg. post-	30.15 (20.98)	32.03 (19.22)	32.56 (20.48)	19.75 (13.56)	23.46 (20.63)	16.77 (16.17)
	Avg. gain	3.79 (13.99)	***9.51 (12.97)***	***12.69 (12.32)***	***7.63 (13.76)***	4.20 (12.65)	***5.43 (12.04)***
	n	33	37	16	16	35	35
PSVT:R	Avg. pre-	1.76 (2.92)	2.34 (2.03)	0.70 (2.29)	0.70 (2.19)	0.15 (2.45)	-0.67 (1.79)
	Avg. post-	1.87 (2.60)	2.70 (3.04)	1.73 (3.04)	0.63 (2.50)	0.85 (2.48)	0.125 (2.43)
	Avg. gain	0.11 (2.31)	0.36 (2.34)	1.03 (3.73)	–0.08 (2.68)	0.70 (2.37)	0.80 (2.47)
	n	33	31	15	16	33	32
Lappan	Avg. pre-	1.69 (2.45)	1.25 (2.60)	–0.84 (1.35)	–0.13 (2.45)	–0.67 (1.97)	0.10 (2.16)
	Avg. post-	2.64 (2.64)	2.92 (2.70)	0.46 (2.30)	–0.36 (2.13)	–0.29 (1.85)	–1.04 (0.90)
	Avg. gain	0.94 (3.27)	***1.67 (2.71)***	***1.31 (2.57)***	–0.24 (2.07)	0.38 (2.50)	–1.14 (2.35)
	n	18	15	18	18	13	12

TABLE 6: *(Continued)*

MCT	pAvg. Pre-	0.66 (2.08)	0.51 (1.82)	0.29 (1.46)	0.21 (1.73)	–0.02 (1.84)	–0.36 (1.39)
	Avg. post-	1.81 (2.14)	1.70 (2.53)	1.94 (2.16)	1.39 (1.86)	0.20 (1.58)	0.18 (1.77)
	Avg. gain	***0.94 (1.96)***	***1.18 (2.31)***	***1.65 (2.22)***	***1.18 (2.25)***	0.22 (2.14)	0.54 (1.83)
	n	27	28	13	18	32	34

As it can be seen from the data presented in Table 8, both groups of students who were provided with spatial skills training experienced gains on the combined spatial skills test. Gain scores for the two experimental groups were nearly identical. The students in the comparison group, who were not exposed to the training, did not experience a significant gain in spatial skills over the same time period. It is also interesting to note from these data the wide disparity in spatial skills levels between EG1 and EG2/CG2 at the pre-test level. This further reinforces the difference between the two cohorts of students with EG1 composed of the better-prepared students and EG2/CG2 composed of the lesser-prepared students. Although the spatial skills training did not close the gap between the two groups, the students in the lesser-prepared group did benefit from the training.

5.2 Standardized Mathematics Test Performance

In Colorado the Colorado Student Assessment Program (CSAP) standardized test in mathematics was administered every year of the project (in 2014, the state adopted a different standardized testing scheme). Students receive a numerical score for mathematics as well as an indication of how well they are doing by grade level. The categories for student performance are A = Advanced, P = Proficient, PP = Partially Proficient, and U = Unsatisfactory. Table 9 includes data from CSAP testing for EG1 and CG1 (the better prepared students) by gender. The data shown represent paired data for gains between 8th grade and 6th grade (i.e., 8th grade mathematics score minus 6th grade mathematics score). Also included are gain scores for the geometry subscale of the CSAP mathematics test.

From the data presented in Table 9, it appears that the spatial skills training had a positive impact on gains in mathematics scores for the students in the study, particularly for the girls.

For the students in EG1/CG1, we also examined the proportion of students who passed their statewide math assessments in 6th and 8th grades. For this analysis, students who were categorized as either A (Advanced) or P (Proficient) were included in the passing group and students who were categorized as PP (Partially Proficient) or U (Unsatisfactory) were included in the failing group. Table 10 presents the results from this analysis.

Table 11 includes similar data for the geometry subscore of the mathematics assessment. For the geometry subscore, P+ indicates proficient or above and BP indicates Below Proficient.

For the data presented in Tables 10 and 11, there is evidence to suggest that the spatial skills training was a key to girls' success in passing the statewide mathematics assessment, likely at least partially due to improvements in geometry performance for the girls in EG1. There was no difference between the pass rates for the 8th grade boys between the two groups; however, it

TABLE 7: Weights obtained through principal component analysis

	WLT	**PFT**	**2ROT**	**PSVT:R**	**Lappan**	**MCT**
Pre-test	0.3489	0.4514	0.4556	0.4269	0.3563	0.3971
Post-test	0.2878	0.4398	0.4115	0.4460	0.4467	0.3948

TABLE 8: Average normalized test scores on combined spatial instrument expressed as a percentage of the total. Standard deviations in parentheses

	EG1 n = 19	EG2 n = 24	CG2 n = 16
Average pre-test	**47.22%** (0.148)	**26.92%** (0.115)	**24.46%** (0.129)
Average post-test	57.24% (0.175)	**36.06%** (0.165)	**24.53%** (0.133)
Average gain	**10.02%** (0.111)	**9.14%** (0.111)	**0.07%** (0.092)
Significance of gain*	0.001	0.001	0.991

TABLE 9: Average gains on standardized mathematics tests for EG1/CG1

	Females				**Males**			
	Mathematics Overall		**Geometry**		**Mathematics Overall**		**Geometry**	
	EG1	**CG1**	**EG1**	**CG1**	**EG1**	**CG1**	**EG1**	**CG1**
Average gain	31.33	12.53	35.81	8.07	33.66	17.11	21.91	31.70
Standard deviation	30.37	23.94	83.88	62.75	36.70	31.27	111.22	88.34
n	36	30	36	30	32	27	32	27
Significance of difference	p = 0.0039		p = 0.0699		p = 0.0352		N. S.	

should be noted that the boys in CG1 appeared to have a large drop-off in pass rates between 6th and 8th grades, both in their overall mathematics scores as well as in their geometry scores; males in EG1 did not experience this drop-off.

The data for EG2/CG2 follow similar trends as those presented for EG1/CG1; however, in most cases for these groups, statistical significance cannot be inferred. For example, Table 12 includes mathematics and geometry gain scores for EG2/CG2.

Although the trends in gain scores are similar to those obtained with EG1/CG1 (i.e., students in EG2 demonstrating larger gains than students in CG2), they are not statistically significant, due to smaller sample sizes and larger standard deviations among test-takers.

Pass rates were also compared between EG2 and CG2. No significant differences were found; however, an interesting trend was observed for these groups of students when examining the proportion of students who scored an outright U (unsatisfactory) on the mathematics test. These data are presented in Table 13.

For both the boys and the girls in EG2, Unsatisfactory rates decreased; for girls the rate decreased by nearly half. Further, for the boys and the girls in CG2, the Unsatisfactory rates increased; for girls the rate more than doubled.

TABLE 10: Pass rates for CSAP mathematics test in 6th and 8th grades for EG1/CG1

	Females				**Males**			
	EG1		**CG1**		**EG1**		**CG1**	
	6th Grade	8th Grade	6th Grade	8th Grade	6th Grade	8th Grade	6th Grade	8th Grade
A/P	34	29	25	15	26	20	26	17
PP/U	8	7	10	17	15	13	6	11
% A/P	80.95	80.55	71.43	46.88	63.41	60.61	81.25	60.71
Significance of difference in 8th grade	p = 0.0019				N. S.			

TABLE 11: Pass rates for CSAP geometry subscore of the mathematics test in 6th and 8th grades for EG1/CG1

	Females				**Males**			
	EG1		**CG1**		**EG1**		**CG1**	
	6th Grade	8th Grade	6th Grade	8th Grade	6th Grade	8th Grade	6th Grade	8th Grade
P+	31	29	25	17	28	23	23	17
BP	11	7	10	15	13	10	9	11
% P+	73.81	80.55	71.43	53.13	68.29	69.70	71.88	60.71
Significance of difference in 8th grade	p = 0.0080				N. S.			

TABLE 12: Average gains on standardized mathematics tests for EG2/CG2

	Females				Males			
	Mathematics Overall		Geometry		Mathematics Overall		Geometry	
	EG2	CG2	EG2	CG2	EG2	CG2	EG2	CG2
Average gain	59.25	57.33	66.00	51.74	70.5	47.00	104.69	70.89
Standard deviation	29.37	22.22	90.54	82.28	51.15	49.39	120.09	140.57
n	16	42	16	42	16	35	16	35
Significance of difference	N. S.		N. S.		p = 0.0627		N. S.	

5.3 High School Math Course-taking

For this part of the analysis, we looked at high school mathematics course participation. (It should be noted that in this school, 9th grade science requirements are common for all students, so there is no variation in science course-taking across the two groups.) At this particular school, 7th grade math is common. In 8th grade, there is honors math and regular math, with the difference being that honors math is more challenging for the students, but essentially the same topics are covered in the two courses. At the end of 8th grade, students complete a diagnostic test. Based primarily on the results from this test, but also on their scores on the high stakes tests and the 8th grade teacher assessment of the individuals, they are typically placed into 9th grade math in one of six different courses:

1. Basic Math
2. Algebra I
3. Honors Algebra I
4. Geometry
5. Honors Geometry
6. Algebra II

It should be noted that the 8th grade teachers who were making the recommendations for 9th grade math placement were not part of the study and did not know which students were in the experimental or control groups.

Figures 7–10 show the 9th grade math placement for the students in all groups. (Numbers are expressed as percentages of the overall.)

For the girls in EG1 and for both genders in EG2, we see a shift upwards in 9th grade math placement. To test this, we looked at two things. For the first analysis, we assigned a number to the 9th grade math placement for the students: 1 = Basic Math, 2 = Algebra, 3 = Honors Algebra, 4 = Geometry, 5 = Honors Geometry, and 6 = Algebra II. Tables 14 and 15 include the results from this analysis:

It appears that the difference in 9th grade math placement is significant for the girls in EG1,

TABLE 13: Unsatisfactory rates for CSAP mathematics test in 6th and 8th grades for EG2/CG2

	Females				Males			
	EG2		CG2		EG2		CG2	
	6th Grade	8th Grade	6th Grade	8th Grade	6th Grade	8th Grade	6th Grade	8th Grade
U	8	4	5	11	6	5	13	15
n	20	17	50	48	20	19	41	38
% U	40.0	23.5	10.0	22.9	30.0	26.3	31.7	39.5

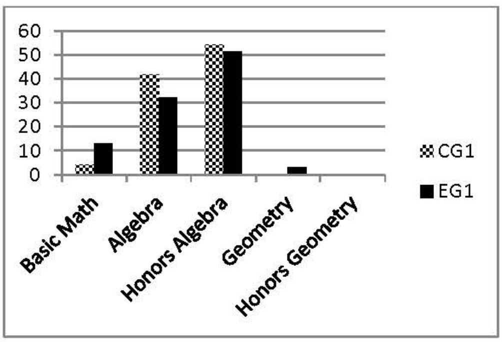

FIG. 7: 9th grade math placement for males in group 1

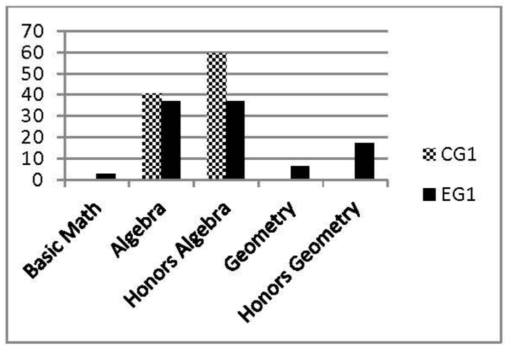

FIG. 8: 9th grade math placement for females in group 1

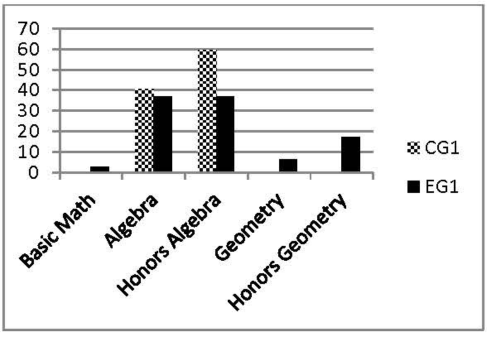

FIG. 9: 9th grade math placement for males in group 2

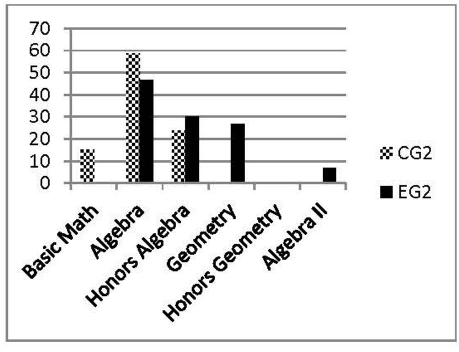

FIG. 10: 9th grade math placement for females in group 2

and is highly significant for both genders in EG2. Since the students in EG2 started significantly "behind" based on their 6th grade standardized mathematics scores, it appears that the spatial skills training is even more important for these students. Of note is that the spatial skills training appeared to bring these lower performing girls (EG2) up to the level of the higher performing girls (EG1) (3.00 vs. 2.97) and nearly so for the boys (2.29 vs. 2.45).

Another test of significance was performed. For this test, we looked at the proportion of the students who ended up taking either Geometry, Honors Geometry, or Algebra II in 9th grade. It is likely that if a student completes Geometry or Algebra II in 9th grade, s/he is much more likely to go into a STEM field. Tables 16 and 17 contain the data from this analysis.

It appears that the girls are much more likely to place into Geometry or higher in 9th grade if they have gone through the spatial skills training. For EG2, the boys were marginally more likely to go into Geometry. Although this is not an indicator of how well they actually will perform in that geometry course and whether or not they continue down a STEM path in future years, it is an indicator of how well they performed in 8th grade mathematics. Ensuring success for students in 8th grade mathematics is a large piece of the puzzle in increasing the number of students, particularly girls, who pursue engineering.

TABLE 14: Average 9th grade math placement for EG1/CG1

	Females		**Males**	
	CG1	**EG1**	**CG1**	**EG1**
Average math placement	2.59	2.97	2.50	2.45
Standard deviation	0.50	1.12	0.59	0.77
n	32	35	24	31
Significance of difference	p = 0.043		N. S.	

TABLE 15: Average 9th grade math placement for EG2/CG2

	Females		**Males**	
	CG2	**EG2**	**CG2**	**EG2**
Average math placement	2.15	3.00	1.63	2.29
Standard deviation	0.759	1.195	0.646	0.686
n	46	15	35	17
Significance of difference	p = 0.001		p = 0.0007	

TABLE 16: Proportion of students placing into geometry or higher for EG1/CG1

	Females		Males	
	CG1	**EG1**	**CG1**	**EG1**
Placed in Geometry	0	2	0	1
Placed in Honors Geometry	0	6	0	0
Proportion in Geometry	0%	22.9%	0%	3.2%
n	32	35	24	31
Significance of difference	p = 0.0020		N. S.	

TABLE 17: Proportion of students placing into geometry or higher for EG2/CG2

	Females		Males	
	CG2	**EG2**	**CG2**	**EG2**
Placed in Geometry	0	0	0	1
Placed in Honors Geometry	1	4	0	0
Placed in Algebra II	0	1	0	0
Proportion in Geometry or higher	2.2%	33.3%	0%	5.9%
n	46	15	35	17
Significance of difference	p = 0.00022		p = 0.07353	

6. CONCLUSIONS

From the results of this study, the potential impact of spatial visualization training at the middle school level on increasing the number of students, particularly females, in engineering careers appears promising. The training resulted in significant gains on tests of spatial cognition. Students taking the training also had higher gains on standardized math tests than those not taking the training. A higher percentage of students who had the training were placed in higher-level 9th grade math courses than students not taking the training, particularly for girls. Improving math performance at the middle school level and placement at the high school level may lead students to take higher-level math courses in high school which in turn better positions them for engineering post-secondary education. Improved performance in math courses could also lead to greater self-efficacy in engineering careers. Greater self-efficacy in engineering careers may have a large impact on female career choices, particularly when engineering careers may be perceived as male dominated due to the low representation of females in those fields.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support for this work from the National Science Foundation through collaborative grants HRD-1159252 (PI: Sorby) and HRD-1036715 (PI: Liben). The opinions expressed here are those of the authors and not of the National Science Foundation. The authors also gratefully acknowledge the assistance of Dr. Scott Streiner who performed some of the statistical analysis for this paper. Finally, the authors are grateful to Mr. Scott Graham who assisted with the data gathering for this study.

REFERENCES

Beede, D., Julian, T., Langdon, D., McKittrick, G., Khan, B., & Doms, M. (2011). Women in STEM: A gender gap to innovation. *ESA Issue Brief #04-11.*

Ben-Chaim, D., Lappan, G., & Houang, R. T. (1988). The effect of instruction on spatial visualization skills of middle school boys and girls. *American Educational Research Journal*, 25(1), 51–71.

Branoff, T. J. (2014). Examining the constraint-based modeling strategies of undergraduate students. In *Proceedings of the 69th Engineering Design Graphics Division Midyear Conference*, Normal, IL, 54–66. Retrieved from http://edgd.asee.org/conferences/proceedings/69th%20Midyear/69th%20Proceedings.pdf.

Casey, B. M., Dearing, E., Vasilyeva, M., Ganley, C. M., & Tine, M. (2011). Spatial and numerical predictors of measurement performance: The moderating effects of community income and gender. *Journal of Educational Psychology*, 103(2), 296–311.

Casey, M. B., Pezaris, E., & Nuttall, R. L. (1992). Spatial ability as a predictor of math achievement: The important of sex and handedness patterns. *Neuropsychologia*, 30(1), 35–45.

Caskey, M. M. (2009). Origami instruction in the middle school mathematics classroom: Its impact on spatial visualization and geometry knowledge of students. *Research in Middle Level Education Online*, 32(7), 1–12.

CEEB. (1939). *Special aptitude test in spatial relations*. Developed by the College Entrance Examination Board, USA.

Clark, S. (1999). Effects of spatial perception level and gender using two and three dimensional graphics. *PAACE Journal of Lifelong Learning*, 8, 53–67.

ETS (1962). *Paper folding test*. Developed by the Educational Testing Service, USA.

Fleishman, J. J., & Dusek, E. R. (1971). Reliability and learning factors associated with cognitive tests. *Psychological Reports*, 29(2), 523–530.

Ganley, C. M., Vasilyeva, M., & Dulaney, A. (2014). Spatial ability mediates the gender difference in middle school students' science performance. *Child Development*, 85(4), 1419–1432.

Guay, R. B. (1977). *Purdue spatial visualization test: Rotations*. West Lafayette, IN, Purdue Research Foundation.

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(5), 1229–1241.

Harle, M., & Towns, M. (2011). A review of spatial ability literature, its connection to chemistry, and implications for instruction. *Journal of Chemical Education*, 88(3), 351–360.

Hungwe, K. N., Sorby, S. A., & Drummer, T. (2007). Preparing K-12 students for engineering studies by improving 3-D spatial skills. *International Journal of Learning*, 14(2), 127–135.

Hungwe, K., Sorby, S. A., Molzan, R., Charlesworth, P., & Wang, M. (2014). Supporting the development of spatial visualization in middle grade and high school students. *Journal of Women and Minorities in Science and Engineering*, 20(4), 379–393.

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

Kali, Y., & Orion, N. (1996). Spatial abilities of high-school students in the perception of geologic structures. *Journal of Research in Science Teaching*, 33(4), 369–391.

Kell, H. J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2013). Creativity and technical innovation: Spatial ability's unique role. *Psychological Science*, 24(9), 1831–1836.

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science*, 31(4), 549–579.

Lappan, G. (1981). *Middle grades mathematics project, spatial visualization test*. East Lansing, MI: Michigan State University.

Levine, S. C., Vasilyeva, M., Lourenco, S. F., Newcombe, N. S., & Huttenlocher, J. (2005). Socioeconomic status modifies the sex difference in spatial skill. *Psychological Science*, 16(11), 841–845.

Liben, L. S. (1991). The Piagetian water-level task: Looking beneath the surface. In R. Vasta (Ed.), *Annals of child development*, (vol. 8, pp. 81–143). London, England: Jessica Kingsley Publishers.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, 56(6), 1479–1498.

National Council of Teachers of Mathematics. (2000). *Principles and standards for school mathematics: An overview*. Reston, VA: National Council of Teachers of Mathematics.

National Research Council. (2006). *Learning to think spatially: GIS as a support system in the K-12 curriculum.* Washington, DC: National Academy Press.

National Science Board (NSB). (2010). *Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital*. Arlington, VA: National Science Foundation.

Orion, N., Ben-Chaim, D., & Kali, Y. (1997). Relationship between earth science education and spatial visualization. *Journal of Geoscience Education.* 45(2), 129–132.

Pew Research Center. (2005). Hispanics: A People in Motion. In *Pew Research Center Hispanic Trends.* Retrieved from http://www.pewhispanic.org/2005/01/24/ii-demographics-2/

Sorby, S. A. (2000). Spatial abilities and their relationship to effective learning of 3D modeling software. *Engineering Design Graphics Journal*, 64(3), 30–35.

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

Sorby, S. A. (2016). *Developing spatial thinking*. Houghton, MI: Higher Education Services.

Sorby, S. A., & Baartmans, B. J. (2000). The development and assessment of a course for enhancing the 3-D spatial visualization skills of first year engineering students. *Journal of Engineering Education*, 89(3), 301–307.

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

Talley, L. H. (1973). The use of three-dimensional visualization as a moderator in the higher cognitive learning of concepts in college level chemistry. *Journal of Research in Science Teaching*, 10(3), 263–269.

Tartre, L. A. (1990). Spatial skills, gender, and mathematics. In E. H. Fennema & G. C. Leder (Eds.), *Mathematics and Gender* (pp. 27–59). New York, NY: Teachers College 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(2), 352–402.

van Garderen, D. (2006). Spatial visualization, visual imagery, and mathematical problem solving of students with varying abilities. *Journal of Learning Disabilities*, 39(6), 496–506.

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

Veurink, N., & Sorby, S. A. (2011, June). Raising the bar? A longitudinal study to determine which students would benefit most from spatial skills training. In *Proceedings of the American Society for Engineering Education Annual Conference*, Vancouver, Canada. Retrieved from: https://peer.asee.org/raising-the-bar-longitudinal-study-to-determine-which-students-would-benefit-most-from-spatial-training.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, 117(2), 250–270.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, 101(4), 817–835.