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A Cognitive Approach to Spatial Visualization Assessment for First-year Engineering Students

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Abstract

First-year engineering (FYE) students are routinely screened for spatial ability, with the goals of predicting retention in the major and identifying those who need supplementary spatial instruction. Psychometric tests used for such screenings are often domain-general measures that lack diagnostic information to inform remedial instruction. A new approach to spatial screening is to use measures that assess performance on authentic engineering tasks while accounting for the cognitive processes that underlie spatial thinking. We tested the utility of a relatively new spatial visualization test (the Santa Barbara Solids Test; SBST) to characterize individual differences in performance among FYE students with low mental rotation scores. The internal reliability and predictive validity of the SBST were previously demonstrated in sample populations with average spatial skill. One hundred and forty-one FYE students with low mental rotation scores completed the SBST and an engineering drawing task before instruction. We investigated the internal reliability of the SBST, patterns of performance and the validity of the test to predict performance on the drawing task. Through item analysis, we deleted problems that contributed to low internal reliability. Performance means were normally distributed. There were small significant positive correlations between the drawing task and SBST total score and subscales. The SBST shows promise for diagnosing difficulties and strategies demonstrated by students who are challenged by spatial visualization. We suggest applications of the SBST to support remedial spatial instruction.

Introduction

First-year engineering (FYE) students are frequently screened for spatial abilities, with the goals of predicting who will persist in engineering programs and identifying those who might benefit from supplemental spatial instruction (Maeda, Yoon, Kim-Kang, & Imbrie, 2013; Sorby & Baartmans, 2000; Veurink et al., 2009). The remediation of spatial thinking is particularly critical in the first year of an engineering program, as many FYE students enter the university with low spatial ability (Duffy et al., 2015; Garmendia, Guisasola, & Sierra, 2007; Maeda, Yoon, Kim-Kang, & Imbrie, 2013; Nagy-Kandor, 2007; Veurink et al., 2009). Although there is literature demonstrating a male advantage on some spatial tasks, (Baenninger & Newcombe 1989; Bergvall, Sorby, & Worthen, 1994; Voyer, Voyer & Bryden, 1995), a number of studies confirmed that sex differences in performance can be greatly reduced by changing the testing environment, changing testing instructions, and reassuring women about their spatial abilities skills prior to testing (Sorby, 2009; Moe, 2009; Sorby & Veurink, 2010).

Engineering educators typically use *spatial visualizatio*n tests to screen FYE students for spatial ability. The construct of spatial visualization is defined in the psychometric litera-

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ture as the ability to comprehend, encode and transform three-dimensional visuospatial forms in multi-step processes (Carroll, 1993). Component processes of spatial visualization include encoding a three-dimensional stimulus, constructing a visuospatial representation from perceptual input, mentally rotating a three-dimensional image, switching one's view perspective, and comparing a visual stimulus to one in working memory (Carroll, 1993; Hegarty & Waller, 2005).

There is no definitive spatial visualization test. Engineering educators use a variety of assessments, including the Purdue Spatial Visualization Test: R (PSVT:R: Guay, 1976), the Mental Cutting Test (CEEB, 1939) the Revised Minnesota Paper Form Board Test (Pearson, 2011), and the Differential Aptitude Test (DAR; Bennett, Seashore, and Wesman, 1973) to screen FYE students for spatial ability (Maeda, Yoon, Kim-Kang, & Imbrie, 2013). The standard and most widely used assessment of spatial skills in engineering education is the PSVT:R, Several studies provide evidence that there are sex differences in performance on the PSVT:R (Miller & Bertoline 1991; Hsi et al. 1997; Sorby & Baartmans 2000; Humphreys, Lubinski, & Yao 2003; Webb, Lubinski & Benbow 2007; Sorby 2009).

While useful in identifying students who would benefit from remedial spatial instruction, most of the above mentioned tests are limited in their value to support remedial spatial instruction. There are a number of reasons for these limitations. Many standardized spatial tests were developed out of the factor analytic tradition with the goal of measuring skills that likely to predict performance in skilled trades and crafts. Consequently, these traditional psychometric spatial ability tests use domain-general stimuli that bear little resemblance to authentic engineering tasks.

In many spatial tests, 3D objects are represented by pictorial views of axonometric drawings, mostly with isometric projections (Yue, 2007). Isometric projections distort the visible dimensions of the objects. These distortions may contribute to students' misconceptions of the spatial properties of the figures, thus comprising the validity of the tests to measure students' actual spatial abilities (Yue, 2007).

Finally, tests that have historically been used to screen for spatial ability lack subscales to identify difficulties faced by students who are challenged by spatial visualization tasks. While useful in predicting performance in skilled trades, the design of many psychometric spatial tests does not reflect current theories of cognitive processes that account for performance in spatial tasks.

Applying Cognitive Theory to Spatial Assessment: The Santa Barbara Solid Test (SBST)

A new approach to spatial assessment in STEM domains is to measure performance on authentic tasks with instruments that are designed to capture individual differences in

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performance, as understood by cognitive psychology theory. We investigated the utility of a relatively new spatial visualization test (Santa Barbara Solids Test) to identify the challenges and problem-solving strategies of low-spatial FYE students on a task that contributes to performance in many areas of engineering (Duesbury & O'Neill, 1996; Hsi, Linn & Bell,1997; LaJoie, 2003; Ha & Brown, 2017), the ability to represent the two-dimensional cross section of a three-dimensional geometric figure.

The 30-item multiple-choice Santa Barbara Solids Test assesses the ability to identify the two-dimensional cross section of a three-dimensional object. The test was designed to reflect cognitive theory that accounts for variability among normal populations in the capacity to mentally form and manipulate visual images (Hegarty & Waller, 2005). Sources of this variability are understood as differences in the capacity of a cognitive system called *visuospatial working memory* to create and transform visuospatial representations (Baddeley, 1992). Visuospatial working memory is one component of Baddeley's *information processing system* of memory, which describes how humans encode, transform and retain new information (1992). Images that have been encoded and processed in visuospatial working memory can subsequently be stored in a system called long-term memory. Images that have been stored in *long-term memory* can subsequently be retrieved and added to new spatial information in visuospatial working memory.

There is experimental evidence for natural variability in the ability to form mental images and to retain visuospatial information while transforming images (Carpenter et al., 1999; Just & Carpenter, 1985; Lohman, 1988). There is also evidence for individual differences in the ability to change one's view perspective of objects or scenes (Hegarty & Waller, 2005; Kozhevnikov & Hegarty; 2001). Individuals who are less able to form and transform visuospatial images, or who lack experience with such transformations, will consequently have a decreased store of visuospatial images available to access from long-term memory.

To capture aspects of performance that might result from normal variation in visuospatial working memory, items in the SBST vary along two hypothesized dimensions of difficulty: geometric structure and orientation of the cutting plane. The first dimension of difficulty is the structural complexity of the test figures, two-dimensional images of three-dimensional solids, rendered with perspective cues and shadows to suggest depth. There are three levels of geometric structure in test figures: simple, joined and embedded figures. Simple figures are primitive cones, cubes, cylinders, prisms and pyramids. Joined figures consist of two simple solids attached at their edges. Embedded figures are composed of one simple solid enmeshed inside another. The use of primitive geometric solids at the lowest level of proposed difficulty is motivated by research that holds that the most elementary recognizable three-dimensional forms are primitive solids (Biederman, 1987; Pani, Jeffries, Shippey & Schwartz, 1996).

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The second dimension of difficulty is the orientation of the cutting plane intersecting the test figure. Mental transformations of objects with axes oblique to the environmental frame of reference are more difficult to perform than mental transformations of objects whose main vertical axes are orthogonal to the environment (Appelle, 1972, Rock, 1973, and Pani, Zhou & Friend, 1997). Thus, the test incorporates two cutting plane orientations: orthogonal (horizontal or vertical) and oblique to the main vertical axis of the test figure.

Fig. 1 shows examples of each geometric structure and each cutting plane. Fig. 1a is a simple figure with an orthogonal (horizontal) cutting plane. Fig. 1b is a joined figure with an orthogonal (vertical) cutting plane. Fig. 1c is an embedded figure with an oblique cutting plane. Each test item shows a criterion figure and four answer choices (Fig. 2).

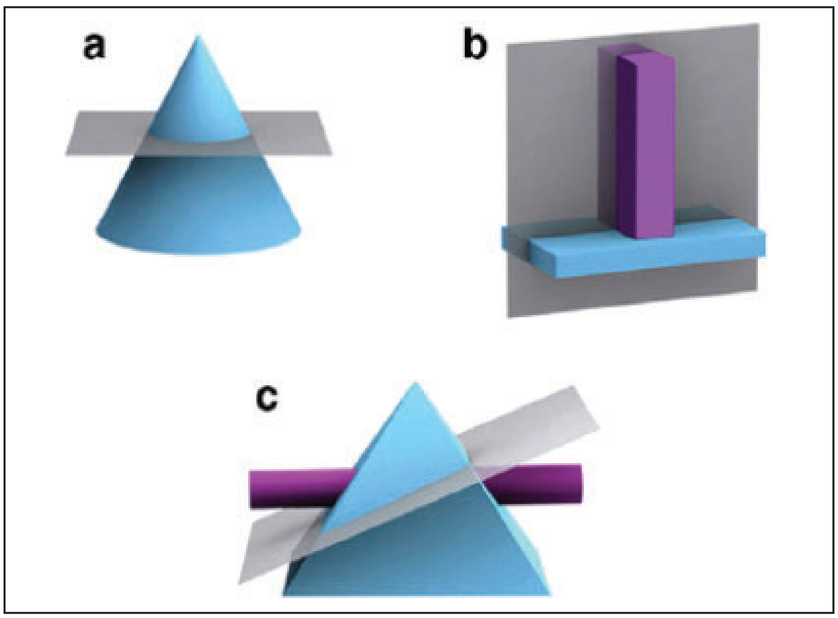

Figure 1. Santa Barbara Solids Test figures varied along two parameters: Geometric structure and orientation of the cutting plane. The above figures are: a) simple figure with an orthogonal cutting plane; b) joined figure with an orthogonal cutting plane; and c) embedded figure with an oblique cutting plane.

The authors of the SBST initially hypothesized that complex (joined and embedded) problems would be more difficult than simple problems because of the added visuospatial working memory resources need to form and transform visual images of in complex objects (Cohen & Hegarty, 2007). However, sample populations of non-engineering science students (Cohen & Hegarty, 2007; 2012) with normal distributions of spatial ability scored significantly higher on complex (joined and embedded) problems than on simple problems, suggesting that SBST subscales were amenable to analytic strategies that did not rely solely on the use of mental imagery. For example, as shown in Fig. 2, the answer choices to embedded problems allow participants to compare the size and location of internal and external structures and to use analytic strategies to eliminate incorrect answers. In contrast, the answer choices to simple problems are single, monochromatic shapes.

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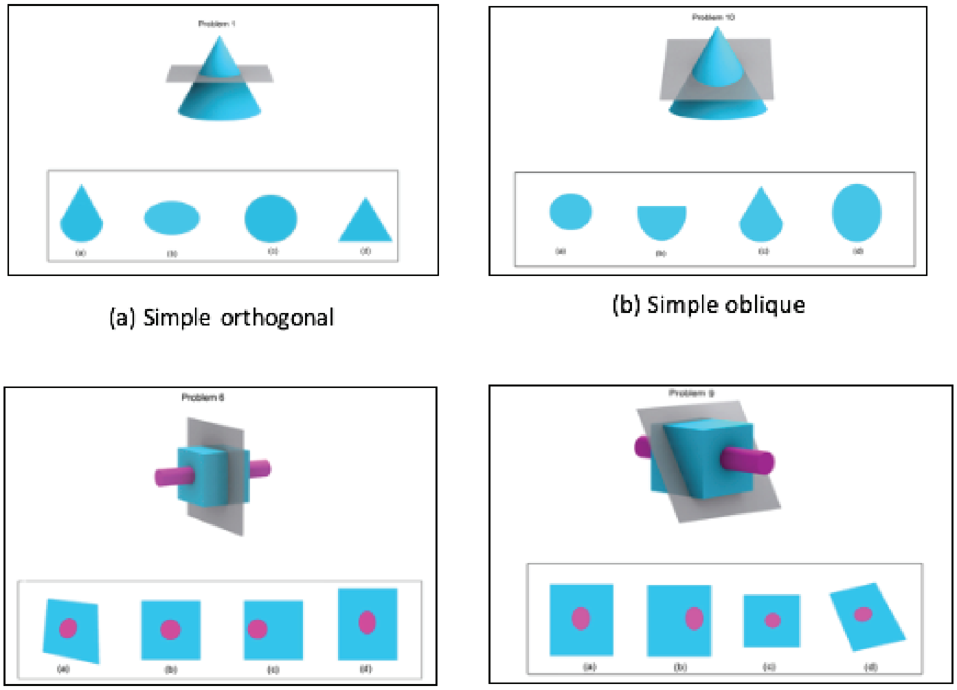

(a) Simple orthogonal (b) Simple oblique

(c) Embedded orthogonal (d) Embedded oblique

Figure 2. Four categories of problems on the Santa Barbara Solids Test. The participant is asked to identify the two-dimensional shape that would result when the criterion figure is sliced by the indicated cutting plane. Correct answers are: 1(a) Simple orthogonal: answer c; 1(b) Simple oblique: answer d; 1(c) Embedded orthogonal: answer b; 1(d) Embedded oblique: answer a.

The interpretation that participants can use non-imagistic strategies on spatial visualization test problems is consistent with literature describing a continuum of strategy use, ranging from purely imagistic to analytic strategies, both within and between individual (Gluck & Fitting, 2003; Hegarty, 2010). In their review of spatial strategy use on mental rotation and other psychometric spatial tests, Gluck & Fitting (2003), found that purely imagistic strategies were associated with robust working memory capacity, and that the use of analytic strategies increased with the complexity of test items. Emphasizing the importance of adaptive spatial thinking in STEM domains, Hegarty (2010) described the ability to flexibly switch between purely imagistic and analytic strategies as a valuable component of spatial thinking.

The internal reliability of the SBST, as measured by Cronbach's alpha, was previously demonstrated in (Cohen & Hegarty, 2007; 2012), and for a sample population of sophomore civil, mechanical and aeronautical engineering students enrolled in mechanics of materials classes at five U. S. colleges and universities (Ha & Brown, 2017). As

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there were no floor and ceiling effects in these samples, the difficulty of the SBST was deemed to be appropriate for undergraduate non-engineering students with normal distribution of spatial skill and for engineering undergraduates.

The SBST shared moderate significant positive correlations with an aggregate spatial visualization measure in Cohen & Hegarty (2007; 2012). Its validity in predicting performance on the Mechanics of Materials Concept Inventory (MMCI) was demonstrated in Ha & Brown (2017). The MMCI assesses the ability to visualize and analyze the distribution of stress loads on cross sections of inclined planes (Richardson, Steif, Morgan, & Dantzler, 2003). For civil engineering students, the SBST accounted for 53% of the variance in performance on the MMCI and up to 31% of the same variance for mechanical and aerospace engineering students (Ha & Brown 2017).

Given the evidence that the SBST was an appropriate and predictive tool for measuring the spatial abilities of liberal arts and engineering undergraduates, we investigated the benefits of using the test to characterize the performance of students previously identified with low mental rotation scores, as measured on the PSVT: R. Our first research goal was to determine if the difficulty level of the SBST was appropriate for a population of undergraduate engineering students with below average spatial abilities. The second research goal was to investigate the utility of the test in identifying difficulties and strategies demonstrated by this population. After reporting our results, we consider the implications of our findings and suggest how the SBST might be used to inform remedial spatial visualization instruction.

Present Study

Method

Participants

One hundred and forty-one FYE students (males= 79; females= 62) participated in the study. All had previously scored 18 or less on a pre-semester PSVT: R screening, placing them the lower 60% of a distribution of 1,651 incoming freshmen at a large public university. All students had voluntarily enrolled in an introduction to spatial visualization class.

Materials

Santa Barbara Solids Test (Cohen & Hegarty, 2012). The Santa Barbara Solids Test (SBST) consists of 30 multiple-choice figures. Three levels of geometric structure and two types of cutting planes are distributed evenly across the 30 figures: simple figures (10 items) are primitive geometric solids: cones, cubes, cylinders, prisms and pyramids. Joined figures (10 items) are two simple solids that are attached at their edges or faces, but do not intersect, along one face. Embedded figures (10 items) consist of one simple solid enmeshed inside of another. In joined and embedded figures, each simple solid is

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a distinct color. Fifteen of the test items are bisected by plane that is orthogonal (parallel to or at a 90 degree angle) the figure's main vertical axis, and 15 figures are bisected by an oblique cutting plane. There was no time limit. Participants took 5-8 minutes to complete the test.

Purdue Spatial Visualization Test: Rotations (PSVT: R; 1976). In the Purdue Spatial Visualizations Test: Rotations (PSVT: R) participants are asked to choose which of four answer choices is rotated in the same direction and to the same degree as a criterion figure. Test figures are black and white line drawings of truncated blocks. Participants have 20 minutes to complete 30 figures. The maximum score is 30. Figure 3 shows a sample problem from the PSVT:R).

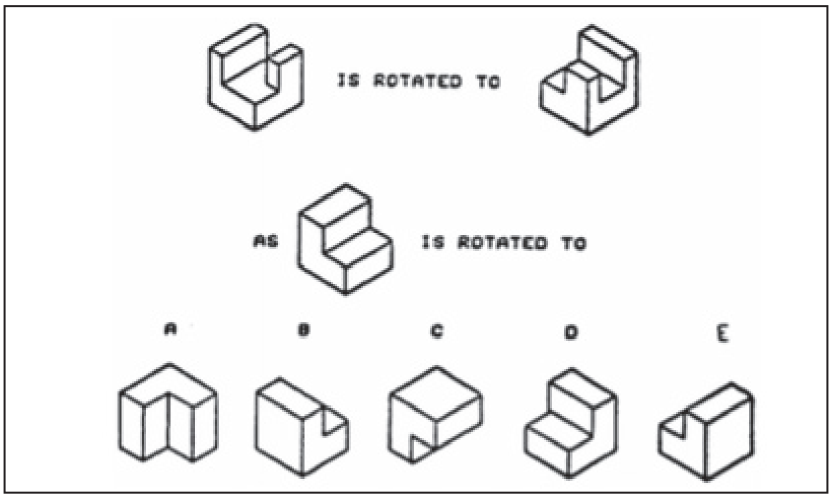

Figure 3. A sample problem from the Purdue Spatial Visualizations Test: Rotations. Participants are asked to choose the multiple-choice option that represents the indicated rotation of a criterion figure.

Sectional Drawings (Srivasavan, Smith & Bairaktarova, 2016). Students completed six drawing problems. As shown in Figs. 4 (a -b), each problem was a black and white drawing, without shading, of a simple, symmetrical mechanical object, with an indicated cutting plane. (Drawing 4b is the correct answer template for this problem. Drawings 4c-4e are three student drawings of this problem.)

The instructions read:

> Draw a two-dimensional sectional view of the object at the indicated cutting plane. To visualize how the section would look, make an imaginary cut through each object and remove the portion of the object between your point of view and the cutting plane line. Arrows at the end of the cutting plane line indicate the direction of the cut. Use hatch marks to indicate cut surfaces of the mechanical object.

Students were given 15-minutes to complete 6 drawing problems.

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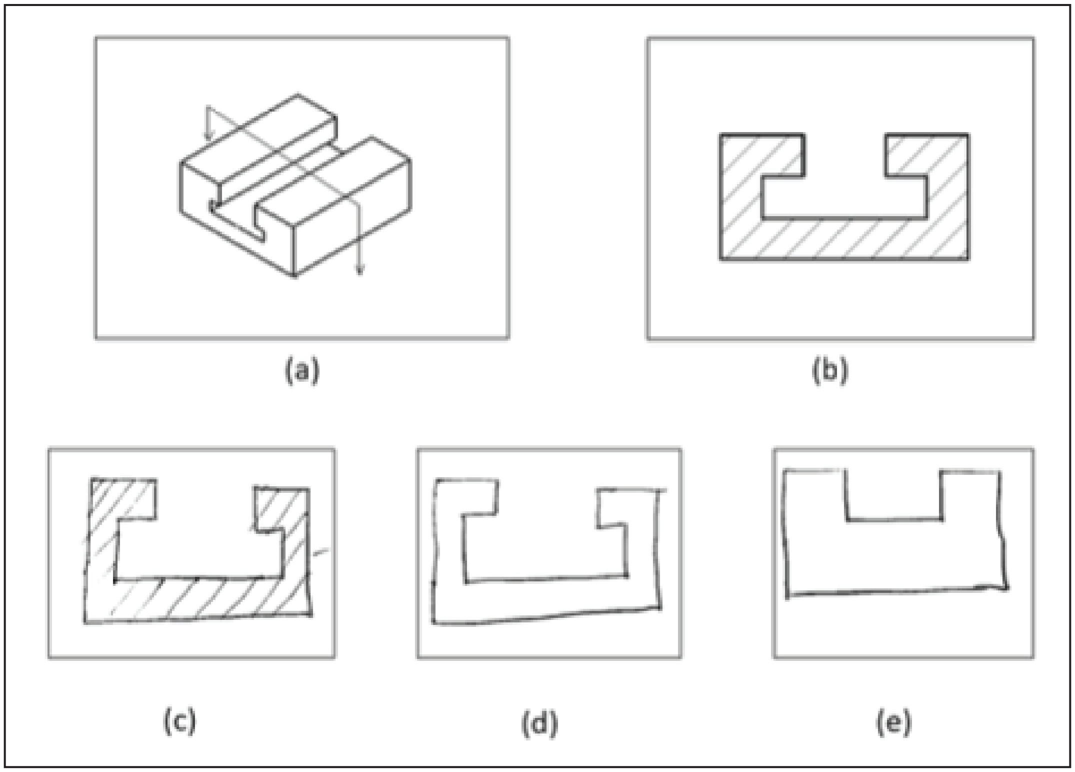

Figure 4. Examples of (a) sectional drawing problem; (b) correct answer template; and (c)-(e) student drawings of the given problem. Drawing (c) earned 5 points; drawing (d) earned 4 points (hatching was absent); and drawing (e) earned 3 points (hatching and structural features of section are absent).

Procedure

Participants completed the PSVT: R prior to the first day of instruction. During the first week of class of the semester, they completed the SBST and the Sectional Drawings.

RESULTS

Participants were eliminated from the dataset if their total score on the SBST (as proportion correct) was ≤ .25, which represents chance performance on a four-answer multiple-choice test.

Internal reliability

Satisfactory internal reliability, as measured by Cronbach's alpha, was initially found for the entire test (α=. 69) and orthogonal (α = .74) subscales. Cronbach's alpha for the remaining subscales (simple, joined, embedded and oblique) was at or below α=.43. We conducted item analyses to identify problems that contributed to low reliability, resulting in the removal of five problems (#s 3, 25, 26, 27 and 30) from the scored items. Notably, each of the five removed problems had oblique cutting planes. Two of the removed

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problems (27 and 30) had means lower than chance; three of the five removed problems had standard deviations of .50 and above, indicating high variability. One problem each was removed from the simple and joined subscales, and three problems were removed from the embedded subscale. After removing problems that contributed to low internal reliability, the resulting number of problems by subscale were: orthogonal = 15; oblique = 10, simple = 9, joined = 9, embedded = 7; total score = 25. Cronbach's alpha for the reconstructed scales were: simple (α =.63); joined (α=.62); embedded (α = .64); oblique (α=.65), and total score (α =.82).

Using the remaining 25 problems, we computed descriptive statistics for the SBST, determined the relative difficulty of its scales and subscales, and investigated the validity of the test to predict performance on the sectional drawing task. The results should be interpreted with some caution, as the deletion of five problems from the original test design results in an unequal distribution of problems across scales. Within the orientation of cutting plane scale, there were 15 orthogonal problems and 10 oblique problems. Within the geometric structure scale, there were 9 simple problems, 9 joined problems, and 7 embedded problems.

Descriptive statistics

Table 1 gives descriptive statistics for the SBST (total score and subscales). On average, students answered less slightly more than half of the 30 problems correctly, indicating that this test was challenging for students whose PSVT: R scores were at the lower end of a distribution of FYE engineering students. Subscale means ranged from *M* =.41 (SD= .26) for oblique figures to *M*=.65 (SD = .20) for orthogonal figures.

Table 1
Performance means and standard deviations, Santa Barbara Solids Test (total and subscales) for sample population of low-spatial FYE students enrolled in a remedial spatial visualization class, n = 141

	M	SD	Range
All figures (25 items)	.56	.20	.16 - 0.92
Simple figures (9 items)	.48	.23	.00 - 0.89
Joined figures (9 items)	.58	.21	.00 - 0.89
Embedded figures (7items)	.62	.25	.00 - 1.00
Orthogonal figures (15 items)	.65	.20	.20 - 0.93
Oblique figures (10 items)	.41	.26	.00 - 0.90

The mean PSVT: R score on the, which was administered as a screening measure before beginning of the semester, was .49 (*SD* = .09). The range for the PSVT: R was

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.03-.60. The distribution of PSVT: R scores was negatively skewed (skewness = - 1.54, *SE* = .20). As class enrollment was limited to students with PSVT: R scores of ≤.60, the upper limit of the range and the skew are artifacts of the enrollment policy.

Relations among the subscales and their relation to the PSVT: R

As presented in Table 2, correlations among the five SBST subscales were medium to large (cf., Cohen, 1992) and statistically significant. Using the Bonferroni approach to control for Type I error across the 10 correlations, a p value of less than .005 was required for significance. The correlations indicate that the subscales of the SBST (orthogonal, oblique, simple, joined and embedded) measure a common ability or skill.

Table 2
Bivariate correlations among the subscales of the SBST and the PSVT: R

	Subscales				
	Simple (9 problems)	Joined (9 problems)	Embedded (7 problems)	Orthogonal (15 problems)	Oblique (10 problems)
Joined	.54**				
Embedded	.63**	.56**			
Orthogonal	.76**	.79**	.84**		
Oblique	.80**	.71**	.66**	.67**	
PSVT: R	n.s.	n.s.	n.s.	n.s	n.s

***p*<value is significant at the .01 level

There were no significant correlations between the SBST (total score and subscales) PSVT: R. This contrasts with previous studies (Cohen & Hegarty, 2007; 2012), which reported a significant positive correlation between the SBST and a summary spatial visualization measure that included a mental rotation test. A possible explanation for the absence of a correlation between the SBST and the PSVT:R is the ceiling effect on the PSVT:R (participants had scores of < 18).

Patterns of performance

To determine patterns of performance by subscale, we conducted a 2 (plane) x 3 (geometric structure) within-subjects, repeated measures analysis of variance (ANOVA) on 25 problems of the SBST. Figure. 5 shows relative performance by subscale.

We conducted a 2 (orthogonal, oblique) x 3 (simple, joined, embedded) repeated measures within-subjects analysis of variance (ANOVA) to determine the contribution of orientation of the cutting plane and geometric structure to performance on the SBST. There was a significant main effect of cutting plane orientation, F (1, 140) = 225.80 p<.001, partial eta-squared = .62. Performance was significantly higher on orthogonal

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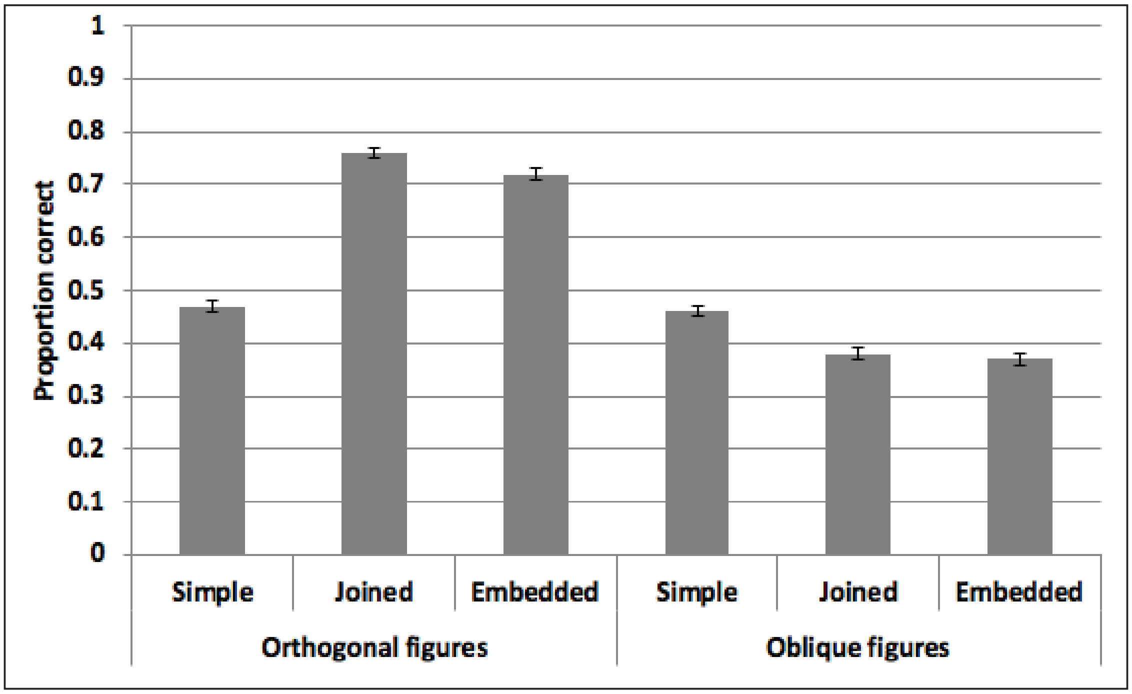

Figure 5. Mean performance on SBST (n=141), showing interactions of geometric structure (orthogonal, oblique) with cutting plane (simple, joined, embedded). Error bars represent +/- one standard error.

figures (M = .65, SD =.20) compared to oblique figures (M = .40, SD =.24). Participants scored significantly higher on joined orthogonal problems, compared to joined oblique problems, t (140) = 18.13, p<.001 and on embedded orthogonal compared to embedded oblique problems, t(140) = 15.87, p<.001. There was no significant difference between the means of simple orthogonal and simple oblique problems. The comparative difficulty of oblique compared to orthogonal figures is similar to that seen with undergraduate non-engineering students (Cohen & Hegarty, 2007; 2012).

There was a significant main effect of structure, F (2, 139) = 13.56, p<.001, partial eta-squared = .01. Across orientation of cutting plane, the highest performance was on embedded (M=.62, SD = .25), followed by joined (M=.58, SD = .21) and simple figures (M =.48, SD = .23). The means of embedded figures were significant higher than that of joined figures, t (140) = 2.25, p = .03, which, in turn, were significantly higher than the means of simple figures, t(140) = 5.71, p<.001. These results suggest that the extra spatial information available in complex figures (joined and embedded), conveyed an advantage, compared to the singular monochromatic shapes lacking internal detail in simple figures. Furthermore, the significantly higher means on embedded, compared to joined problems, suggests that visual information describing the relative size and location of internal vs. external structures in embedded figures conveyed a greater advantage than the visual cues describing the size and location of adjacent structures in joined figures.

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There was a significant interaction between plane and structure, *F* (2, 280) = 60.42, *p*<.001, partial eta-squared = .30. For orthogonal figures, highest performance was on joined figures (*M* =.76, *SD* =.32) , followed by embedded figures (*M* = .72, *SD* =.33) and simple figures (*M* = .48, *SD* =.26). There was no significant difference between the means of joined orthogonal and joined embedded figures, which were combined into an aggregate variable (complex orthogonal). The results of a t-test showed that the means of complex orthogonal figures were significantly higher than the means of simple orthogonal figures, *t* (140) = 16.01, *p*<.001.

For oblique figures, the pattern differed. For oblique figures, highest performance was on simple figures (*M* = .46, *SD* = .22), followed by joined oblique (*M* =.38, *SD* =. 16) and embedded oblique (M = .37, SD =.18) figures. There was no significant difference between the means of joined oblique and embedded oblique figures, which were combined into an aggregate variable (complex oblique). The results of a t-test showed that the means of simple oblique figures were significantly higher than the means of complex oblique figures, *t* (140) = 2.36, *p* <.01. This pattern was similar to that seen in Cohen & Hegarty (2012), but differed from those seen in Ha & Brown (2017), in which there was no significant difference between the means of orthogonal and oblique problems, and a significant advantage on joined problems and simple problems, compared to embedded problems.

Relationship between the SBST and Sectional Drawings score

Two mechanical engineering graduate students independently scored each student's set of six sectional drawings on a scale of 1-5, using the coding scheme shown in Table 3 (Srivasavan et al., 2016). See Fig. 4 for examples of a sectional drawing, the answer template, and three student drawings. Based on the rubric in Table 3, drawing (c) earned 5 points, drawing (d) earned 4 points (one point was deducted for missing hatching); and drawing (e) earned 3 points (one point each was deducted for missing hatching and missing structural features).

Cohen's kappa, a measure inter-rater reliability for the scoring was (α = 0.89), indicating satisfactory reliability. The mean sectional drawing score (as proportion of total points received across 6 drawings) was .51, SD=.13 (range =.20 -.98). There were no significant differences in the sectional drawing score by sex.

Table 3
Coding scheme for sectional drawings

Criteria	Points
Student attempted to draw the section.	1
Outline of sectional shape is correct	1
Cutting plane perspective is correct	1
Hatch marks are correct	1
Other structural features are correct	1
Total	5

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We found small significant positive correlation between the drawing score and total score of the SBST, r = .25, p<.01. There were also significant positive correlations between the Drawing Score and the simple (r =.31, p<.01), embedded, (r =.22, p<.05, orthogonal (r =.21, p<.05), and oblique (r = .26, p<.01) subscales. These significant positive correlations, though modest, suggest an association between test subscales and the skills required to visualize and draw sections of mechanical objects.

Discussion

In summary, we determined that the SBST is an appropriate and useful tool for characterizing the spatial visualization challenges and strategies demonstrated by FYE students whose mental rotation scores were in the lower 60% of a distribution of their peers. The 30-item multiple-choice test assesses the ability to identify the two-dimensional cross section of a three-dimensional object. Previous studies with non-engineering undergraduate students demonstrated significant positive correlations between the SBST and an aggregate spatial visualization measure (Cohen & Hegarty, 2007; 2012).

As measured by Cronbach's alpha, the internal reliability of the SBST for this sample was initially below acceptable levels. After deleting five problems that contributed to low internal reliability, we determined that the remaining 25 problems exhibited satisfactory internal reliability for the total score, and for each subscale of the test (orthogonal, oblique, simple, joined and embedded).

The SBST was challenging for this sample of FYE students with low mental rotation scores. The total (M= .56, SD = .20) and subscale scores across 25 problems were lower proportionally than the means seen in samples of undergraduate science students and sophomore engineering students (Figure 6) on the 30-problem version of the test. There was no floor effect in our sample, and the means of students' total and subscale performance provides latitude for measuring gains after instruction. We conclude that this test represents an appropriate level of difficulty for FYE students previously identified has having low spatial ability.

We found small significant positive correlations between the sectional drawing score and the total score of the SBST. We also found significant positive correlations between the sectional drawing score and four of the five test subscales. These correlations, although modest, add to previous evidence (Ha & Brown, 2017) supporting the SBST's validity to predict performance on authentic engineering tasks. The sectional drawings were completed during the first week of the remedial spatial visualization class, before students received instruction in orthogonal and sectional views that would contribute to their understanding of the task. We hypothesize that the shared variance in these measures reflects a range of skills, including imagistic and analytic strategies.

We did not find significant correlations between the sectional drawing score and the PSVT:R. These results contrast with those of Branoff and Dobelis (2013) who found in

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a sample of n =34 students a significant positive correlation between the PSVT:R and a modeling task (p = .50, α = .000). Branoff and Dobelis also found a significant positive correlation between modeling task and the MCT, (p =.70, α = .003) and a significant positive correlation between the PSVT:R and the MCT (p = .49, α = .003). Their modeling task was far more complex than ours, as it required participants to use 3D software to model a machine part from an multi-view assembly drawings accompanied by a list of parts. Additionally, their population (n = 34) was considerably smaller than ours (n = 141) and represented a different population: primarily male, junior-level students who were enrolled in a constraint-based modeling course.

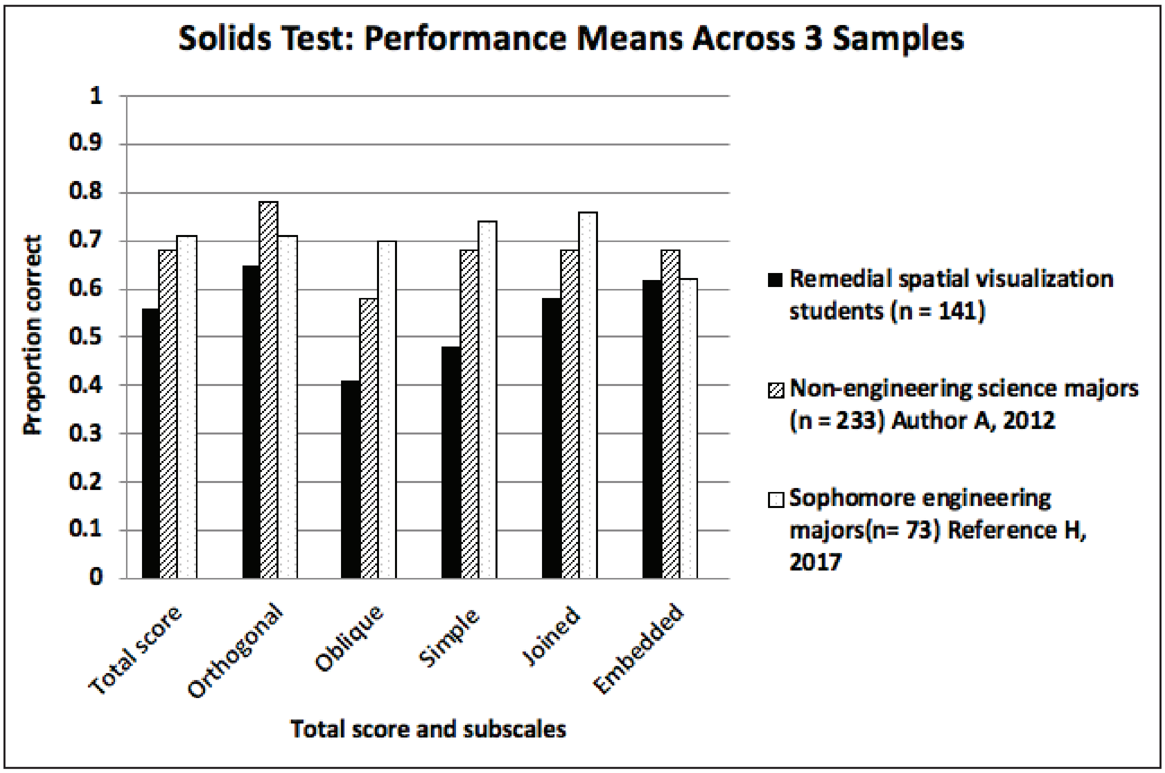

Figure 6. Mean performance on the SBST for three populations: remedial spatial visualization, non-engineering science majors and sophomore engineering (mechanics of materials) students. For the remedial spatial visualization students, scores reflect performance on 25 problems. Scores for the non-engineering and engineering students reflect performance on 30 problems.

Patterns of performance among the subscales of the SBST revealed both similarities and differences to patterns seen among non-engineering undergraduates. As in (Cohen & Hegarty, 2007; 2012), the means of oblique figures were significantly lower than the means of orthogonal figures, across geometric complexity (see Fig. 6). This result is also consistent with literature that predicts difficulty among participants of average spa-

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tial skill in the interpretation of oblique sections (Appelle, 1972, Rock, 1973, and Pani, Zhou & Friend, 1997). It is notable that Ha & Brown (2017), reported that sophomore engineering students performed equally on orthogonal and oblique problems.

Simple orthogonal figures were significantly more difficult than complex orthogonal figures (joined and embedded), a pattern also seen with participants with average spatial skill. As simple figures offer no visual clues, such as relative sizes and placement of interior and exterior shapes, that can be leveraged in analytic strategies, we interpret the relative difficulty of simple, compared to complex, orthogonal problems as evidence of participants' challenge in forming and manipulating visual images. We therefore suggest that performance on the simple scale of the SBST can be interpreted as a reflection of competency in forming and manipulating visual images. This diagnostic information could be applied to remedial spatial visualization instruction by providing to students with low scores on the simple scale more experience manipulating physical or virtual simple geometric solids and observing the shapes of their orthogonal and oblique sections.

In addition to diagnosing challenges in creating and manipulating visual images, the relative difficulty of simple orthogonal, compared to complex orthogonal, problems suggests that participants were successful in using analytic strategies to solve complex orthogonal, but not oblique, problems. Examples of analytic strategies that are commonly applied to spatial visualization test problems are *task decomposition*, rule-based reasoning, and feature matching (Hegarty, 2010). Task decomposition refers to the process of mentally subdividing a complex visuospatial array into separate components in order to reduce demands on visuospatial memory. *Rule-based reasoning* refers to the application of heuristics to the solution of spatial problems. *Feature matching* refers to the comparison of visible features, such as angles, shapes, colors and spatial relationships (e.g. above, below, adjacent, etc.) to determine congruency, or matches, between among whole objects and their parts.

Although the present study does not provide information about *which* strategies participants used on complex orthogonal figures, we hypothesize that SBST answer choices are amenable to analytic strategies. For example, a participant could decompose each answer choice in Fig. 2c into two shapes and evaluate each shape separately. Individuals with memories of previous experience sectioning cubes and cylinders could retrieve that information and predict that the outside shape of Fig. 2c would be a square, and the inside shape would be a circle. The participant could use feature matching to compare the distance between the intersections of the cylinder with the cube in the test figure with the relative placement of the circle inside the square in the answer choices.

Our participants had lower means on complex, compared to simple, oblique problems (Fig. 4), suggesting that they were unable to use either imagistic or analytic strategies on complex oblique figures. This pattern is consistent with that seen in sample popula-

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tions with average spatial skill (Cohen & Hegarty, 2007; 2012). Given that oblique sections are challenging for participants with average spatial skill, and that the ability to use visual imagery is associated with more robust visuospatial working memory, this result is not surprising. We recommend that future studies investigate the benefits of providing explicit instruction in spatial strategies to students.

Our participants anecdotally reported finding some test figures ambiguous in their depiction of three-dimensional space. Ambiguity regarding the spatial extent of the test figures could have contributed the high variability and lack of internal consistency of the oblique test figures. We plan to investigate the perceived ambiguity of test figure and to redraw deleted problems for future test administrations. (Anecdotal information regarding the possible ambiguity of test figures was not collected or reported in previous studies).

Regardless of the artfulness of lighting, there will always be some ambiguity inherent in representing a three-dimensional problem in two dimensions. The test figures were created in a three-dimensional modeling program using linear perspective cues, lighting and shadows. However, some spatial information remains ambiguous in the two-dimensional representation of a three-dimensional figure. In addition to fixing the ambiguity of problematic items as identified by item analysis, there are other ways to address this problem in future research. Participants could be shown small 3D physical models of figures during test administration. Another possible solution is to adapt the test to an augmented or virtual reality display in which participants are allowed to rotate the figure to observe their shapes in three dimensions.

Conclusions

Spatial reasoning is crucial to success in engineering. The development of a cognitive approach to assess of reasoning early on in engineering coursework and providing remedial training to those students that test low in initial assessments is crucial to students' persistence and success in engineering. Our work demonstrates how a relatively new spatial visualization measure can effectively characterize performance on authentic engineering tasks while accounting for the cognitive processes that underlie spatial thinking. In our study, the SBST showed promise for diagnosing difficulties and strategies demonstrated by students who are challenged by spatial visualization. We suggest applications of the SBST to support remedial spatial training by including in spatial reasoning instruction, strategy learning and achieving fluency with solid geometrical shapes.

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