ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

New Orleans JAZZED about Engineering Education

Paper ID #15814

An Analysis of First-Year Engineering Majors' Spatial Skill

Jaclyn Kuspiel Murray, University of Georgia

Jaclyn Kuspiel Murray is currently a research scientist at Georgia Institute of Technology in the department of biomedical engineering. In May of 2016 she graduated with a doctorate of philosophy in science education from The University of Georgia. She earned a bachelor of science in mechanical engineering from Georgia Institute of Technology and a master of science in biomedical engineering from The University of Tennessee Health Science Center and The University of Memphis. After a brief career in biomedical engineering, she taught high school physics in the public school system. She continues to be an active member of the AP Physics community. Her research interests include engineering student spatial and creative development, the nature of engineering, engineering learning environments, and engineering student motivation.

An Analysis of First-Year Engineering Majors' Spatial Ability

Abstract

Previous studies have indicated females do not score as high on spatial skill assessments as males. However, this investigation found females differed from males on only one spatial assessment. In particular, this study examined the spatial skill level of 433 first-year male and female students enrolled within a college of engineering at a large southeastern university. After gathering and analyzing data from a battery of object manipulation spatial assessments, the findings indicated males and females did not score significantly different from one another on five out of six assessments. A Mann-Whitney U test was conducted to determine whether there was a difference in the mean rank score of males and females on the Revised Purdue Spatial Visualization Tests: Visualization of Rotations (Revised PSVT: R) test. Results of that analysis indicated that there was a difference, $\chi^2 = 7.99$, $p < .01$ with males scoring higher than females, with an effect size of Cohen's $d = 0.53$. Males and females were also compared separately across all spatial assessments. A Spearman's rank correlation coefficient matrix was developed to visualize correlations between assessments and gender. Male participants showed significant (mostly) moderate correlations between all tests at the $p < .001$ level. Moreover, female participants suggested different strengths of correlation and significance across all assessments.

Introduction

Investigation into science, technology, engineering, and mathematics (STEM) professional knowledge has gained momentum since funding became available through government agencies and private sources. Spatial skill level is a known predictor of STEM achievement.[1] Currently, K-12 instruction emphasizes both verbal and mathematical skills, but does not afford equitable attention to the spatial domain.[2,3] This investigation sought to understand the object manipulation skill level of first-year engineering students, and to characterize relationships among mental rotations and spatial visualization assessments.

Competence in spatial thinking arises from a broad set of interconnected cognitive skills that require knowledge of space, representation, and reasoning.[4] Spatial skill can be assessed by domain-general or domain-specific means; the difference is context. Although the domain was engineering, the spatial assessment centered on context-free spatial skill. Specifically, aspects of reflection, dimensional transformations, and rotation were assessed. Object manipulation spatial skills are considered fundamental to the field of engineering and includes mental rotations and spatial visualization.[5] "Spatial visualization and [mental rotations] require the ability to mentally manipulate spatial forms from a fixed perspective" (p. 746).[6]

Assessments of mental rotation require individuals to mentally rotate images in space. These images or objects can be two-dimensional (2D) or three-dimensional (3D). Objects rotated in 2D have three degrees of freedom (two translational and one rotational) while those in 3D have six degrees of freedom (three translational and three rotational). Therefore, 3D mental rotation tasks should, in theory, be more difficult than 2D mental rotation tasks.

Spatial visualization entails rotation in addition to other manipulations that may change the shape of an object.[7] This includes changing an object's size by folding, or the concatenation of multiple objects to create a new shape. Also the transformation of an object across dimensions (i.e., 2D to 3D or 3D to 2D) constitutes spatial visualization. In essence, spatial visualization requires higher cognitive skill, compared to mental rotation, because it combines elements of manipulation with rotation.

Freshman, at the post-secondary level, often lack formal spatial instruction necessary to enhance spatial skills, knowledge, and thinking.[8] Empirical evidence suggests STEM professionals eventually acquire high dynamic spatial thinking skills[4,9,10] during early childhood development.[1] Individuals entering college with weak spatial skills are sometimes offered an opportunity to improve skills with a course specifically designed to support spatial development.[11] Studies at the K-12 and post-secondary level suggest components of spatial thinking (skills and knowledge) can be learned. [4,12,13,14,15]

Engineering schools, however, have chosen to assess spatial skills with the Revised Purdue Spatial Visualizations Test: Visualizations of Rotations (Revised PSVT: R)[16], to determine whether or not students should be placed in a spatial development course. The Revised PSVT: R is considered an assessment of mental rotations, but some items require an offset revolution about the z-axis axis in addition to a 3D static rotation. The multiple manipulations can be thought of as a partial revolution (earth revolves around the sun across a season) combined with a rotation (earth rotating about its own axis). The increased number of operations necessary to determine a solution seems to suggest individuals should view the Revised PSVT: R as more difficult than other mental rotations assessments.

This study seeks to answer the question, *how does gender and spatial skill compare across object manipulation assessments?*

Frameworks

Lesions affecting the left side of the brain impair speech and other expressive functions as determined during the 1860s.[17] Nearly a century later, figure and facial recognition deficits were found to be triggered by trauma afflicting the right side of the brain. These discoveries prompted the development of theories of separation— the disjunction between verbal and visual processing.[19] Specifically, Paivio's dual coding theory (DCT)[18] and Baddeley's working memory model (WMM)[19] were established on the premise that verbal and nonverbal processing were distinct and independent from one another.

The following account describes what researchers know about how spatial processing is organized. Figure 1 illustrates the model's components beginning with Baddeley's WMM which delineates two systems (channels): the phonological loop and visuospatial sketchpad. Concurrent processing can occur across, but not within, channels like two lightbulbs connected in parallel. In other words, two tasks can occur simultaneously, only if each task is processed by a different channel. Two tasks cannot occur on the same channel at the same time. They can only occur in series, or one after the other.[20] Dual task studies have provided empirical evidence to support the dissociation between verbal and nonverbal information processing. This is further

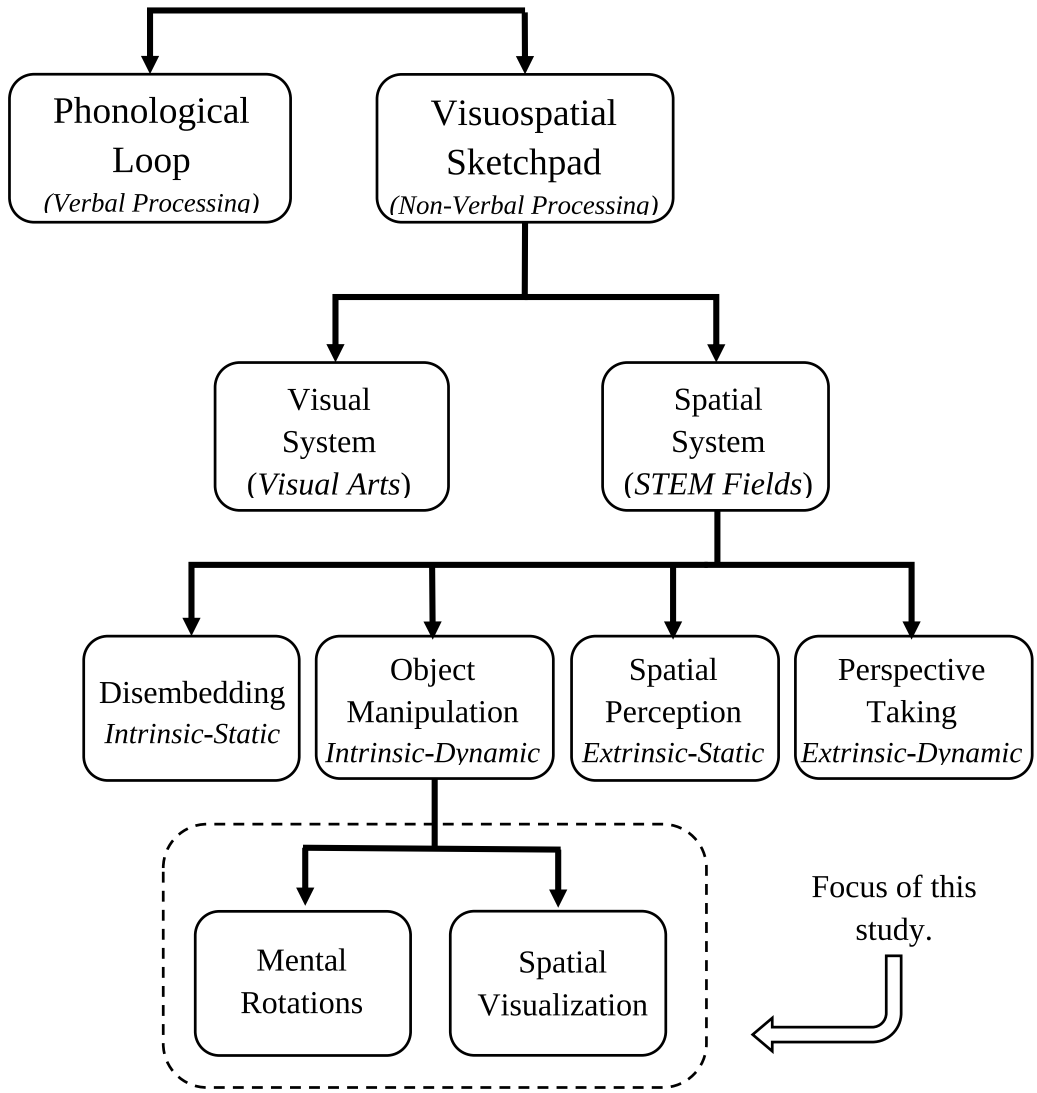

Figure 1. Model of visual-spatial skills.

reinforced by studies utilizing Positron Emission Tomography (PET) scans that assert different regions of the brain are activated by verbal and nonverbal tasks.[21]

According to cognitive psychology and neuroscience research, the sketchpad is composed of two independent components: the visual domain and the spatial domain.[22] The visual domain relates to an object's appearance that processes details about shape, color, texture, etc. within or across an image. Conversely, the spatial domain processes spatial relations in the form of static and dynamic object transformations from either an intrinsic or extrinsic perspective. Essentially, the visuospatial sketchpad is subdivided into two distinct elements just as the phonological loop (verbal) is separate from the visuospatial sketchpad (nonverbal).

Support for this view arises from differences in brain activation regions: ventral (visual domain) and dorsal (spatial domain)— as well as from findings from cognitive psychology. Hegarty and Kozhevnikov[23] determined students, generally, used two strategies when solving word problems. They either produced schematic representations or created pictorial illustrations. Kozhevnikov, Hegarty, and Mayer[24] found a bimodal split among visualizers when visual-spatial ability was assessed. This led to a study to compare how artists and scientists performed on visual-based and spatial-based assessments.[25] Indeed, artists performed significantly better than scientists on a visual-based test (grain resolution) and scientists scored significantly higher on a spatial-based test (paper folding) than artists. This was further solidified by an investigation into abstract representations within the spatial-based domain with think-aloud protocols when participants (visual artists, physicists, and engineers) were asked to interpret kinematics graphs—abstract representations of motion.[25] High spatial visualizers (physicists and engineers) were able to create schematic representations of motion, and low spatial visualizers (visual artists) generated inaccurate pictorial representations. The spatial domain appears to be beneficial to the STEM domain.

Although spatial assessments have been utilized for a long time, the lack of theory has defocused and impeded progress in the area. Some attempt, over the years, has been made to categorize or organize the variety of spatial tests to connect with underlying spatial dichotomies like allocentric vs. egocentric and extrinsic vs. intrinsic. To add to the confusion, terminology overlapped and changed over time. Previously cited literature, in this paper, uses current terminology (as of the beginning of 2016) for the purpose of cohesiveness.

Recently, Uttal et al.[14] developed an organizational system for spatial-based skills.   The categories are represented as a four quadrant typology (See Figure 2). Intrinsic and extrinsic components are positioned along the x-axis with static and dynamic placed on the y-axis. Intrinsic refers to object description either holistically or as the sum of its parts while extrinsic signifies the relationship between objects or to a reference frame.[26] Static denotes an object is fixed against the frame of reference and dynamic indicates an object or its frame of reference is moving. Consequently, the four quadrants are intrinsic-static, intrinsic-dynamic, extrinsic-static, and extrinsic-dynamic. Figure 2 illustrates the four quadrant typology and provides sample spatial assessments as examples of each: Embedded Figures[27], Water-Level[28], Mental Rotations[29], and Perspective-Taking.[17]

This study investigates the intrinsic-dynamic portion of the spatial domain, also known as object manipulation. This segment is assumed to encompass both mental rotation and spatial visualization skills. Researchers[14,30] believe mental rotation and spatial visualization are two separate object manipulations skills. Both skills rely on memory and processing components, however mental rotation tasks require less complex processing than spatial visualization tasks. Three mental rotations and three spatial visualization assessments, as determined by the extant literature, were utilized in this study.

Methods

Participants

Participants were purposely sampled using the following criteria: (1) an interest in engineering, (2) enrolled in an introductory AutoCAD™ class, and (3) an ethnically diverse group. All 433 participants (94 females and 339 males) represented typical students enrolled as

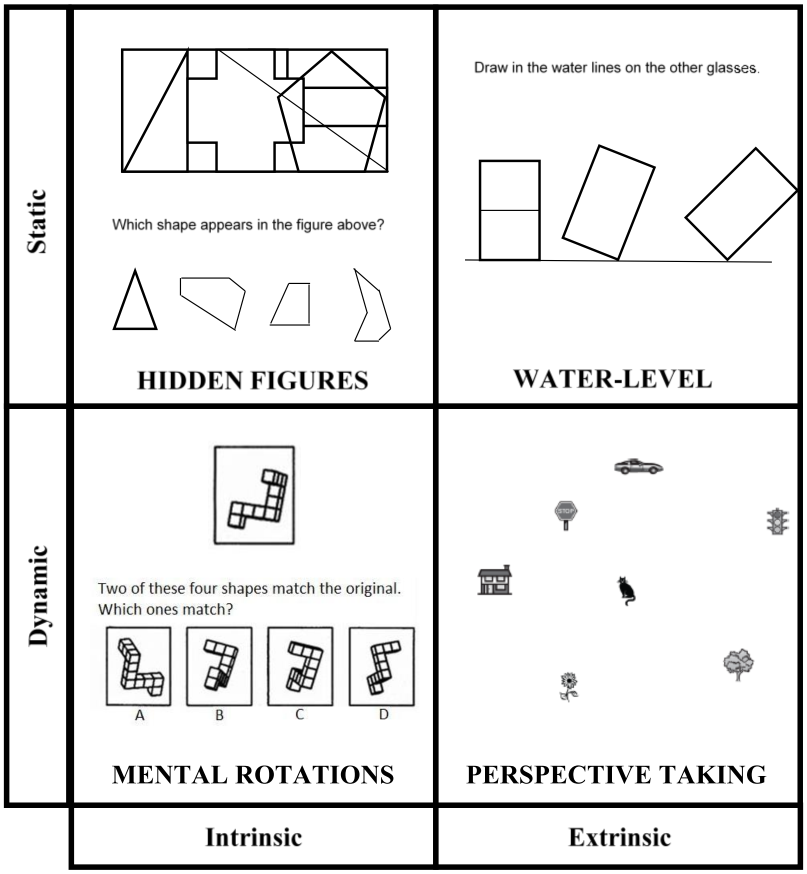

Figure 2. Typology aligned with sample spatial skill assessments. Adapted from Uttal et al. (2013) and Okamoto et al. (2015).

introductory engineering majors at a particular college of engineering at a large southeastern university.

Assessments

Six short spatial assessments were chosen to measure two separate object manipulation skill types: mental rotation and spatial visualization. The mental rotation category included Card Rotations (CR)[31], Cube Comparisons (CC)[31], and the Revised PSVT: R[16]. Form Board (FB), Paper Folding (PF), and Surface Development (SD) formed the spatial visualization set[31]. Cronbach alphas were calculated for each object manipulation assessment to approximate reliability (internal consistency).

The aforementioned assessments were chosen for comparison between the Revised PSVT: R and alternate object manipulation skill assessments. A required score of sixteen on the Revised PSVT: R is often the standard for avoiding placement in a spatial skill development course at colleges of engineering in the United States.

The overall research question in this investigation is, *how does gender and spatial skill level compare across object manipulation assessments?* Two sub-questions reflect specific aspects of the general question:

1. Do assessments of spatial skill level correlate with one another? If so, are the correlations significant?
2. What specific gender differences exist among first-year engineering students' spatial skill level?

Procedure

Data was collected across three consecutive semesters, not including the summer session. The same set of assessments, in the same order, were given to all students during normally scheduled class time for class credit. Some students arrived late to class and missed the first set of assessments, and a few chose not to participate in other assessments. This accounts for some of the variation in total number of participants for each test comparison. Those students who provided consent, per the university's internal review board policies, were included as participants in the study.

The CR test was removed from the third semester set of assessments. Instead, participants completed two additional assessments, unrelated to the current study, after the aforementioned order of assessments. Class time constraints limited the number of assessments administered per session.

Analysis

Both Excel™ and JMP®[32] were utilized for all quantitative analysis, except when Excel was limited in functionality. Upon graphing the data collectively, and by gender, it was determined the data was not normally distributed. Therefore, Spearman's rank correlation was run to determine the relationship between each object manipulation assessment by gender. A Mann-Whitney U test was performed to determine level of significance between the medians of each spatial test across gender. Mean rank, sum or ranks, Chi-square values, and significance were calculated. The chi-square distribution was used as an approximation and Cohen's *d* represented the effect size.

Results

Table 1 displays Cronbach's alpha values for each object manipulation skill assessment utilized in this investigation. Values above .8 are acceptable because they fall within the "very good to excellent range" for internal consistency (reliability). The items within each assessment are uniform in measuring the same entity.

Table 1.
Cronbach's α for Each Spatial Assessment

CR	CC	FB	PF	SD	Revised PSVT: R
0.99	0.85	0.91	0.83	0.93	0.89

Table 2.
Mann-Whitney U-test Results Across Gender

	N	Median Rank	Sum of Ranks	Test		
				c^2	*p*	*d*
CR						
Male	203	66.3	8326	0.01	.92	0.0072
Female	61	66.3	26919			
CC						
Male	330	61.9	69748	0.015	.9	0.022
Female	94	57.1	19928			
Revised PSVT: R						
Male	129	60	10255.5	7.99	.0047	0.53
Female	29	50	2305			
FB						
Male	325	50	68741	0.406	.53	0.062
Female	92	50	18830			
PF						
Male	334	70	71262	3.6	.059	0.19
Female	94	60	20116			
SD						
Male	338	65	72792	0.57	.33	0.065
Female	94	63.3	20304			

Assessment mean rank, sum of ranks, Chi-square values, significance levels, and effect sizes (Cohen's *d*) are shown for each object manipulation skill in Table 2. Only the results from the Revised PSVT: R spatial assessment suggested gender difference. The Cohen's *d* value (0.53), as shown with an asterisk in Table 2, is consistent with findings from recently published meta-analysis data (Cohen's $d = 0.57$).[33]

Table 3 displays the Spearman's rank correlation coefficients for each test comparison. The asterisks, next to each coefficient, indicate the level of significance as noted below the table. All male Spearman's rank correlation coefficients were statistically significant at the $p < .001$ level. Most Spearman's rank correlation coefficients were at the moderate level with a few exceptions (CC-FB, CR-FB, CR-PF, and CC-Revised PSVT: R) at the weak level. Those with weak correlations were comparisons between mental rotations assessments (CR, CC, and Revised PSVT: R) and spatial visualization (FB, PF, and SD). Male data suggested that the Revised PSVT: R data was significantly moderately correlated to spatial visualization skill level. However, the CC-Revised PSVT: R (mental rotations) relationship indicated a weak correlation.

Female data suggested a distinction between spatial visualization and mental rotations spatial skill level. Correlations between FB, PF, and SD (spatial visualization) are weak to moderate, but significant. In addition, the CR-CC (mental rotations) significant correlation is weak. When spatial visualization and mental rotations spatial skill level were compared, there were no significant correlations. The Revised PSVT: R has no significant correlations with

Table 3.
Spearman's Rank Correlation Matrix of Spatial Assessment Scores for Males and Females

Measure	1	2	3	4	5	6
Males						
1. CR						
2. CC	.50**					
3. Revised PSVT: R	-	.33***				
4. FB	.38***	.25***	.45***			
5. PF	.39***	.44***	.45***	.41***		
6. SD	.42***	.43***	.54***	.43***	.60***	
Females						
1. CR						
2. CC	.30*					
3. Revised PSVT: R	-	.13				
4. FB	.16	-.03	.48**			
5. PF	.28*	.2	.48	.26*		
6. SD	.01	.15	.47**	.35***	.42***	

Note: **p < .05, **p < .01, ***p < .001*

"mental rotations", however FB and SD (spatial visualization) were significantly moderately correlated with the Revised PSVT: R. PF-Revised PSVT: R is moderately correlated, but not significant ($p = .063$).

Discussion and Implications

This study examined the spatial skill level of students interested in the engineering disciplines. In particular, intrinsic-dynamic (object manipulation) skills were assessed among first-year students enrolled in a college of engineering at a large southeastern university. Researchers[14,30] suggest that intrinsic-dynamic skills are divided into two independent categories: mental rotation and spatial visualization.

The Revised PSVT: R was the only assessment to indicate a significant difference between genders and the results were very similar to a meta-analysis performed across previously published data.[33] The effect size (Cohen's *d*) in this investigation was .53 and that of the meta-analysis was .57.

These results support and refute previous studies[24,34] that found males performed better on mental rotations and spatial visualization tests than females. Findings, in this study, show no gender difference for CR, CC, (mental rotations) FB, PF, or SD (spatial visualization) assessments; however, the participant sample was defined as individuals interested in engineering. Possibly, students drawn to engineering have strengths consistent with those utilized by the engineering community of practice (ECoP)[35]. For example, those who enter the visual arts tend to be able to sketch, paint, or have a sense of color. Participating in activities that align with a commensurate skill set may make it easier to join, acclimate, and attain a sense of belonging to the group.

The Revised PSVT: R correlated more closely, for both males and females, with assessments of spatial visualization (FB, PF, and SD)[31] than mental rotation— the category most associated with the Revised PSVT: R according the extant literature. Mental rotation and spatial visualization are believed to require two steps: memory and processing[36]. The memory component, mediated by spatial short term memory (STM)[37], allows individuals to temporarily store images. In the case of the Revised PSVT: R assessment, visual details of the chiseled cube must be maintained while the brain processes, by the spatial working memory (SWM)[37], how to rotate the image to be in agreement with the specified visual-spatial analogy.

As previously stated, mental rotation requires an individual to mentally rotate an image, whether in 2D or 3D space. The Revised PSVT: R raises mental rotation to another level with the addition of a secondary maneuver, coupled with an analogy of a set of spatial manipulations represented by another cube. Conceivably, mental rotation in its most complex state converges on the processes that underlie spatial visualization. One might ask, could mental rotations be a lower level skill, or perhaps subsumed by spatial visualization?

Alternatively, if mental rotation and spatial visualization are indeed two separate constructs, the Revised PSVT: R could tap into both mental rotation and spatial visualization skill level. The CC-Revised PSVT: R correlations were $r = .13$ and $r = .33$***, respectively, for females and males. Both groups (males and females) performed well and similarly on the CC assessment. However, males scored significantly higher on the Revised PSVT: R than females. Both male and female engineering students were able to carry out mental rotation and spatial visualization tasks separately. However, females had difficulty with the Revised PSVT: R. It is possible that females may find it difficult to process higher order tasks that require both mental rotation and spatial visualization processing either simultaneously or in tandem within the same task. This possibility could account for the statistically significant weak and moderate correlations across all male test comparisons and the inconsistent nature of female data.

Is it possible that the visual properties of the object are detailed enough to warrant visual system processing? Could both visual and spatial systems be necessary to correctly answer Revised PSVT: R items?[38] See Figure 1 for the placement of the visual system on the model of visual-spatial skills. The visual system is more closely aligned with visual artists' skills because details are important when representing objects. The spatial system is related to the space between objects and their relation to one another. Perhaps the detail contained within the objects of the Revised PSVT: R require skills from the visual system. Or conversely, visual processes are being used and taking up space within working memory that limit spatial processing. Kaufman[36] suggests a difference may exist is the capacity of working memory among gender. Males tend to experience more spatial activities than females because of an early interest in activities that enhance spatial skills. This experience may have expanded working memory capacity to process spatial tasks.

How are individuals creating interventions to know which skills students possess: mental rotation, spatial visualization, neither, both, etc., when the Revised PSVT: R is the sole assessment used to determine object manipulation spatial skill level? Does a low score on the Revised PSVT: R imply a student has difficulty with spatial short term memory, spatial working memory, or both? Diagnosing this with the current available resources is problematic. Perhaps a low score on the Revised PSVT: R should be followed by an assessment of lower level processing tasks to determine individual student difficulties.

Summary

Six assessments of mental rotations and spatial visualization revealed a significant difference between gender on the Revised PSVT: R assessment only. This is consistent with previous findings.[33] When participant data was separated by gender and compared across assessments a Spearman's rank correlation test uncovered significantly moderate and strong correlations among mental rotations and spatial visualization assessments for male participants. Data collected from female participants indicated significant weak to moderate correlations between the Revised PSVT: R assessment and other assessments of spatial visualization, except between PF and the Revised PSVT: R.

Limitations

There are two main limitations of this study: no CR-Revised PSVT: R comparison data was collected and other spatial tests could have been administered. CR and Revised PSVT: R data could not be collected at the same time due to time constraints driven by the fifty-minute class period. Other tests could have been utilized; however, at the expense of decreased sample size for each comparison. Since the female population in engineering courses is generally smaller than the male population, this was not an appropriate option.

Further Studies

The Revised PSVT: R is not the only complex mental rotations assessment. A comparison between the Revised PSVT: R[16] and Vandenberg and Kuse's[29] Mental Rotations Test could prove informative. Kaufman[36] determined that the Mental Rotations Test had a unique variance associated with it that did not directly connect with memory storage of an image. Investigation into higher-level forms of what are currently defined as mental rotations tests may disentangle the underlying processes associated with solving assessment items. Are these actually tests of mental rotation, assessments of mental rotation and spatial visualization, or neither? Is there a visual component within the spatial component? Does spatial short term memory and/or spatial working memory have anything to do with it?

Engineering education literature has focused on mental rotation skills as important to the field, but it is important to ask the question, what about other spatial skills? Engineering is a diverse field of study. Does domain specificity play a role in the types of spatial skills necessary for each particular field? Does a chemical engineer rely on the same kinds of spatial skills as an industrial engineer? As interdisciplinary engineering (biomedical, biological, environmental, etc.), fields emerge, in what ways do those fields rely on spatial skills? What spatial skills might be included in a core set of skills common to all engineering fields?

In addition, do measures of spatial skill level relate to abstract representations? Current tests of spatial skill level are concrete. The visualizations are of real tangible objects from different orientations. Process diagrams, however, are schematics— abstractions of tangible objects and processes. Perhaps assessing experts from each engineering domain could inform the types of spatial skills necessary for different engineering fields. For example, an engineer who predominately works with computer aided design software to design fixtures probably uses a different set of spatial skills than does a process or quality control engineer.

References

1. 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.
2. Kell, H. J., & Lubinski, D. (2013). Spatial ability: A neglected talent in educational and occupational settings. *Roeper Review, 35*(4), 219-230.
3. Newcombe, N. S., Uttal, D. H., & Sauter, M. (2013). Spatial development. *Oxford Handbook of Developmental Psychology, 1*, 564-590.
4. National Research Council (NRC). (2006). Learning to think spatially: GIS as a support system in the K-12 curriculum. *Committee on the Support for the Thinking Spatially, National Research Council, Publisher: The National Academies Press, URL: http://books. nap. edu/catalog. php*.
5. Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education, 31*(3), 459-480.
6. Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition, 29*(5), 745-756.
7. French, J. W., Harman, H. H., & Dermen, D. (1976). *Manual for kit of factor referenced cognitive tests*. Princeton, NJ: Educational Testing Service.
8. Deno, J. A. (1995). The Relationship of previous experiences to spatial visualization ability. *Engineering Design Graphics Journal, 59*(3), 5-17.
9. National Science Foundation (US). (2010). *Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital*. National Science Foundation.
10. Okamoto, Kotsopoulous, McGarvey, & Hallowell (2015). The development of spatial reasoning in young children. In *Spatial Reasoning in the Early years: Principles, Assertions, and Speculations* (pp. 15 - 28). Routledge.
11. 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.
12. Yurt, E., & Sunbul, A. M. (2012). Effect of modeling-based activities developed using virtual environments and concrete objects on spatial thinking and mental rotation skills. *Educational Sciences: Theory and Practice, 12*(3), 1987-1992.
13. Cakmak, S., Isiksal, M., & Koc, Y. (2014). Investigating effect of origami-based instruction on elementary students' spatial skills and perceptions. *The Journal of Educational Research, 107*(1), 59-68.
14. 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.

[15] Uttal, D. H., Meadow, N. G., Hand, L. L., Lewis, A. R., Warren, C., & Newcombe, N. S. (*Under Review*). Training spatial skills: What works, for whom, and for how long.
[16] Yoon, S.Y. (2011). *Psychometric properties of the Revised Purdue Spatial Visualization Tests: Visualization of Rotations (The Revised PSVT: R)* (Doctoral Dissertation). Retrieved from ProQuest Dissertations and Theses. (Order Number: 3480934).
[17] Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*, *32*, 175-191.
[18] Paivio, Allan. (2007). *Mind and its evolution: A dual coding theoretical approach*. Psychology Press.
[19] Baddeley, A. (2007). *Working memory, thought, and action*. Oxford University Press.
[20] Sims, V. K., & Hegarty, M. (1997). Mental animation in the visuospatial sketchpad: Evidence from dual-task studies. *Memory & Cognition*, *25*(3), 321-332.
[21] Salmon, E., Van der Linden, M., Collette, F., Delfiore, G., Maquet, P., Degueldre, C., & Franck, G. (1996). Regional brain activity during working memory tasks. *Brain*, *119*(5), 1617-1625.
[22] Kozhevnikov, M. (2015). Visual-object versus visual-spatial representations: Insights from studying visualization in artists and scientists. In *Studying Visual and Spatial Reasoning for Design Creativity* (pp. 193-204). Springer Netherlands.
[23] Hegarty, M., & Kozhevnikov, M. (1999). Types of visual–spatial representations and mathematical problem solving. *Journal of Educational Psychology*, *91*(4), 684.
[24] Kozhevnikov, M., Hegarty, M., & Mayer, R. E. (2002). Revising the visualizer-verbalizer dimension: Evidence for two types of visualizers. *Cognition and Instruction*, *20*(1), 47-77.
[25] Kozhevnikov, M., Kosslyn, S., & Shephard, J. (2005). Spatial versus object visualizers: A new characterization of visual cognitive style. *Memory & Cognition, 33*(4), 710-726.
[26] Ganis, G & Kievit, R.A. (2015). A New Set of Three-Dimensional Shapes for Investigating Mental Rotation Processes: Validation Data and Stimulus Set. *Journal of Open Psychology Data 3*(1):e3, DOI:http://dx.doi.org/10.5334/jopd.ai
[27] Witkin, H. A., Oltman, P. K., Raskin, E., & Karp, S. A. (1971). *A manual for the group embedded figures test*. Palo Alto, California.
[28] Inhelder, B. (2013). *The early growth of logic in the child: Classification and seriation*. (Vol. 83). Routledge.
[29] Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*(2), 599-604.
[30] Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. In *Studying Visual and Spatial Reasoning for Design Creativity* (pp. 179-192). Springer Netherlands.
[31] Ekstrom, R. B., French, J. W., Harman, H., & Dermen, D. (1976). Kit of factor-referenced cognitive tests (rev. ed.). Princeton, NJ: Educational Testing Service.
[32] JMP®, Version 10. SAS Institute Inc., Cary, NC, 1989-2016.
[33] Maeda, Y., & Yoon, S. Y. (2013). A meta-analysis on gender differences in mental rotation ability measured by the Purdue spatial visualization tests: Visualization of rotations (PSVT: R). *Educational Psychology Review*, *25*(1), 69-94.
[34] Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*, 1479-1498.
[35] Lave, J. & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge, UK: Cambridge University Press.
[36] Kaufman, S. B. (2007). Sex differences in mental rotation and spatial visualization ability: Can they be accounted for by differences in working memory capacity?. *Intelligence, 35*(3), 211-223.
[37] Cowan, N. (2008). What are the differences between long-term, short-term, and working memory?. *Progress in Brain Research*, *169*, 323-338.
[38] Wood, J. N. (2011). When do spatial and visual working memory interact?. *Attention, Perception, & Psychophysics, 73*(2), 420-439.