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Pictorial Visual Rotation Ability of Engineering Design Graphics Students

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Abstract

The ability to rotate visual mental images is a complex cognitive skill. It requires the building of graphical libraries of information through short or long term memory systems and the subsequent retrieval and manipulation of these towards a specified goal. The development of mental rotation skill is of critical importance within engineering design graphics. It promotes the ability to comprehend complex engineering drawings, communicate design ideas through freehand sketching, and develop CAD modeling strategies. Considering this, exploratory development research was conducted in efforts to investigate student ability levels measured by parallel pictorial items of an existing geometric mental rotation measure. Images of rotated general consumer objects were captured and composed in a corresponding format to that of the Purdue Spatial Visualization Test: Visualization of Rotations. An expert review panel from engineering/technical graphics was convened to analyze consistency of format, rotation, and solutions of the corresponding pictorial items instrument. A group of post-secondary Engineering Design Graphics students were randomly administered the Purdue Spatial Visualization Test: Visualization of Rotations where the remainder of the group was administered the pictorial item instrument. The developed pictorial instrument represented orientation familiarity, while geometric forms in the Purdue Spatial Visualization Test: Visualization of Rotations represented unfamiliar structures. Comparative analyses were conducted and differences identified pertaining to student abilities in mental rotation of geometric forms and pictorial visual rotation abilities. Summary statistics, frequency analyses, and hypothesis testing uncovered that student mental rotation abilities of geometric forms collectively exceed that of pictorial rotation ability.

Introduction

Contemporary curriculum policy and planning largely focuses on the development and promotion of numeracy, literacy and articulacy skills (Mosely et al, 1999). However, research has identified the importance of graphicacy across the education system in developing well-balanced human citizens (Danos, 2001; Fry, 1981). *"Graphics"* are the representation of visual images with the purpose of communicating some information. Representations differ vastly in their purpose, mode of creation, and in their level of abstraction (Grignon, 2000). They can be in the mind (internal) or they can be physically perceivable (external).

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The ability to mentally rotate and manipulate geometry is of fundamental importance in terms of being able to graphically communicate. Keen spatial skill is a strong indicator of achievement and attainment in science, technology, engineering, and mathematics fields (Uttal et al, 2013). These abilities are significant for an assortment of reasons, including “effective education in the science, technology, engineering, and mathematics (STEM) disciplines” (Uttal et al, p. 352). Predominantly, previous academic studies concentrated on spatial ability but did not offer attention to the circumstances under which spatial skill was developed or the transfer of those abilities to untrained areas (Miller & Halpern, 2013; Marunic & Glazar 2013). Within STEM education, however, engineering design graphics literature has a concentrated focus of exploratory and experimental research pertaining to spatial and visual skill development, paired with efforts to enhance mental rotation abilities for students. In a 2000 study, Branoff highlighted a criticism of traditional mental rotation measures in their use of “isometric projections for the display of three-dimensional objects”, (p. 15) as well as further introducing the concept of object familiarity and unfamiliarity as an influential variable within visualization measurement. The influence and/or diagnostic impact that object familiarity has on mental rotation measure is largely undetermined.

Spatial Skills Overview

Visuo-spatial skills are of fundamental importance for successfully overcoming and solving many problems in everyday life. The ability to generate, remember, retrieve and manipulate spatial relations in visual imagery (Lohman, 1994) is a complex cognitive skill which is of particular interest to researchers within the STEM education community and beyond (Sorby, 2009, Wai et al., 2009). For decades, several longitudinal studies (Super & Bachrach, 1957) have investigated the nature of spatial ability as a psychological attribute in young adolescents. These studies found that spatial ability was a prominent attribute among adolescents who subsequently were successful in achieving advanced educational credentials and employment in STEM disciplines. An eleven year longitudinal study entitled Project TALENT by Wai et al. (2009) further highlights this.
Figure ***1*** shows the proportion of each STEM degree group as a function of spatial ability, where spatial ability scores were categorized on a nine point (stanine) scale with 1 being the lowest scoring category and 9 the highest. These findings clearly show that spatial ability is an important factor in achieving advanced qualifications within STEM disciplines. Forty-five percent of STEM Ph.D. graduates were in stanine 9 on spatial ability eleven years earlier, while ninety percent were in stanine 7 or above.

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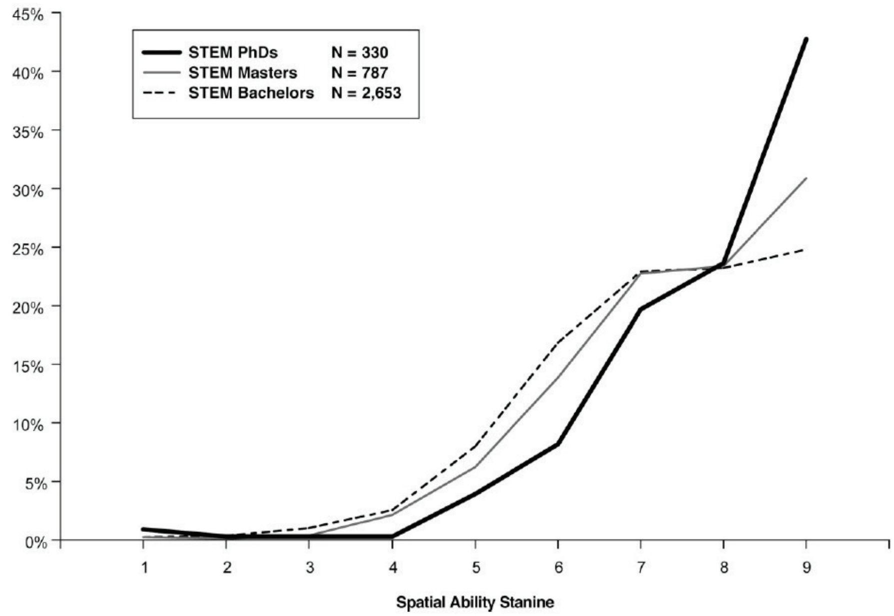

***Figure 1.* Proportion of each STEM degree group as a function of spatial ability (Wai et al, 2009).**

While spatial ability as a psychological, innate attribute is a clear indicator of success within STEM disciplines, it is important to acknowledge that spatial skills can be developed through appropriate and purposeful intervention. Several longitudinal studies by researchers such as Sorby et al. (2009, 1999) have shown that the implementation of a specially designed course aimed at developing spatial skills in first year engineering students had a positive impact on student success in their degree studies, especially for women. Therefore, if pedagogical interventions that focus on spatial skill development have such a positive impact on students, how can spatial ability be validly measured in order to inform the design of these instructional activities?

Measuring Spatial Skills

It is somewhat difficult to establish absolute definitions on what exactly constitutes spatial ability from the existing body of associated research literature. For example, Maier proposed that there are five components that make up spatial skill (Sorby, 1999), while McGee (1979)believed that there are two distinct categories of 3-D spatial skills which include spatial visualization and spatial orientation. Essentially, spatial visualization is the mental movement of an object in space, while spatial orientation involves the mental modification of a viewing direction.

Over several decades of research, many different types of tests have been used in an attempt to establish the psychological attributes of visual cognition. These tests have ranged from Finke’s (1988) experimental tests on visual synthesis in mental imagery, Ekstrom’s (1976) range of cognitive tests that measure attributes such as figural fluency and perceptual speed, and The Differential Aptitude Test; Space Relations (Bennett et

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al., 1973). Contemporary research studies associated with the evaluation of spatial skills have converged on a select number of tests. This includes the Spatial Composite Test: This test was designed and administered by Wai et al. (2009) as part of an 11 year longitudinal study of 400,000 participants who were drawn from a stratified sample of U.S. high schools (Grades 9-12). The Spatial Composite Test was composed of four measures including; three-dimensional spatial visualization, two-dimensional spatial visualization, mechanical reasoning and abstract reasoning. We feel that this test is worth mentioning due to the nature of the longitudinal study, large number of participants, and the findings (some of which were illustrated in Figure *1*).

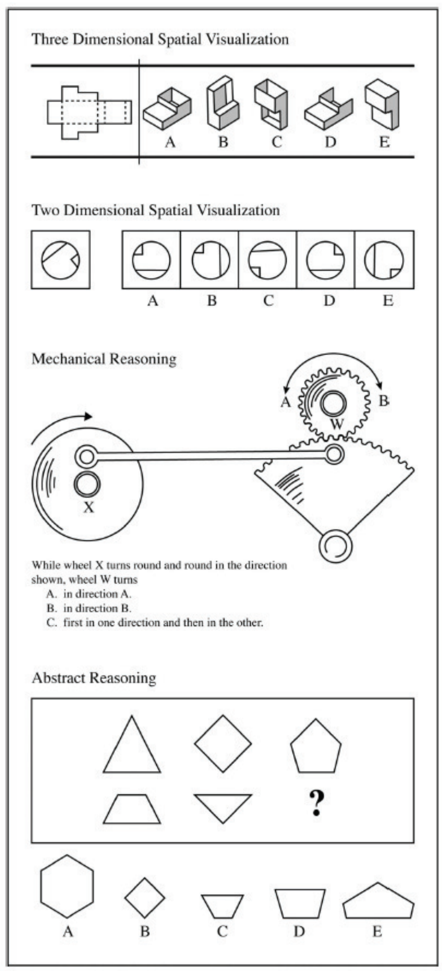

Figure 2. **Spatial Composite Test developed and administered by Wai et al. (2009).**

The Mental Rotation Test is another test for evaluating spatial skills. This test was initially developed by Shepard and Metzler (1971), and its purpose is to evaluate participants' ability to determine whether two pairs of perspective line drawings of objects were congruent or not. Each object is composed of ten solid cubes attached face to face to form a rigid structure with three right-angled bends. The test is widely used as a measure of the spatial visualization factor and has been adapted and redrawn by researchers such as Vandenberg and Kuse (1978) and Peters et al. (1995). Figure 3 shows an example of two questions from Vandenberg and Kuse (1978). Each question consists of a criterion figure, two correct alternatives, and two incorrect configurations which are referred to as distractors.

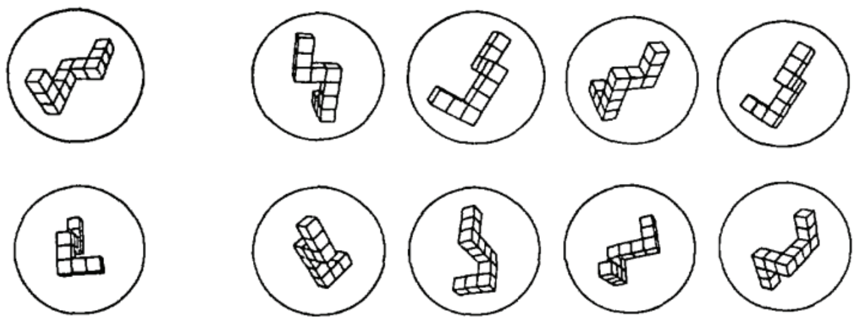

Figure 3. **Examples of Mental Rotation Test questions from Vandenberg and Kuse (1978).**

The fourth test for evaluating spatial skills is the Mental Cutting Test (MCT). The test was originally developed for university entrance examinations in the USA. The MCT measures the ability to recognize the spatial form of an object that has been cut by an imaginary plane (Sorby, 1999, Nemeth, 2007). It is composed of 25 problems consisting of relatively complicated and sometimes truncated solids. The criterion solids are all presented in a perspective drawing. Students are required to choose the correct resultant cross-section from five given alternatives, which are presented in an orthogonally. A sample question from the MCT test is shown in Figure 4 where the correct answer is 2.

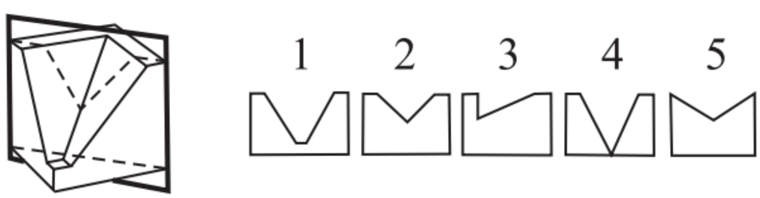

Figure 4. **Sample question from the Mental Rotation Test (CEEB, 1939).**

Finally, the Purdue Spatial Visualization Test – Visualization of Rotations (PSVT:R) is possibly the most widely used measure of spatial visualization ability across the STEM domain. Developed by Guay (1977), this paper based test consists of 30 unfamiliar objects. The test-taker is provided with a sample rotation and is then required to rotate the target object by the same amount. A sample question from the test is shown in Figure 5 where the correct answer is B.

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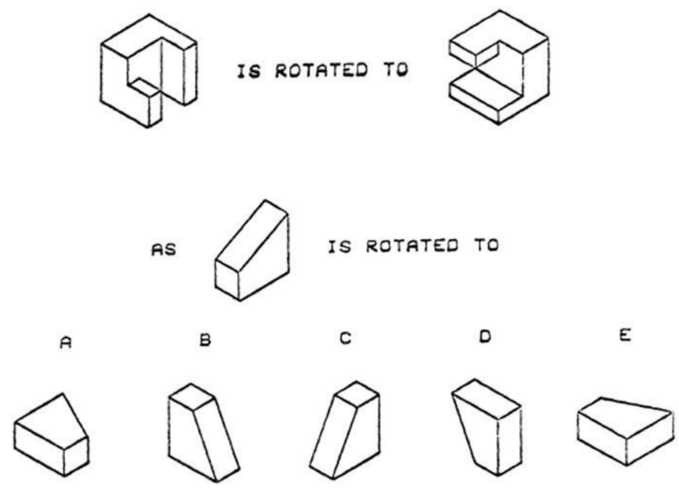

Figure 5. **Sample question from the Purdue Spatial Visualization Test – Rotations (PSVT:R) (Guay, 1977).**

Cognition and Object Familiarity

Visual representations used in spatial tests are generally line drawings of rigid, regular geometric solids which are sometimes sliced, truncated or compounded with other geometric solids. The objects generally consist of a number of flat surfaces with clearly identifiable vertices and no concavities. Research in cognitive psychology suggests that test-takers would probably form an image of the target geometry in the visuo-spatial sketchpad (Baddeley, 1998) of short term memory and subsequently manipulate the image in accordance with the test instructions. The cognitive literature also suggests that test-takers would probably engage a mixture of low-level, intermediate, and high-level processes to initially make sense of the image presented and interpret interrelations within the geometries (Stillings, 1995).

Following from this, it is worth describing how human beings interpret visual images of familiar objects. Human beings are capable of encoding all sorts of information in long term memory. Depending on the level of initial processing, chunks of information can be easily retrieved and are very clear while other information can be difficult to remember and can be vague in nature. In terms of graphical imagery, representations are encoded in long term memory through events such as haptic manipulation of objects over a long period of time.

Stillings (1995) described how identification of objects brings with it highly detailed information and an intimate understanding of their parts. The literature concerning visual cognition suggests that different memory systems are used when processing visual representations. Therefore, it is logical to ask the following question: Would there be an effect on scores in spatial tests if familiar everyday imagery (of which test takers would have a general knowledge) replaced the typical abstract representations of regular geometries present in existing tests? This will form the focus of the next section of this paper.

Research Questions

To further explore object familiarity, a study was formed to examine paired engineering design graphics student mental rotation outcomes using traditional geometric form instrumentation and pictorial-based instrumentation of identical constructs. There was one principal research question guiding this mental rotation study: Does object familiarity provide for greater visual rotation attainment? This question was investigated through an exploratory development research study conducted in efforts to investigate student ability levels measured by parallel pictorial items of an existing geometric mental rotation measure.

Methodology

To begin, the research team met and formalized the investigational query, where they subsequently formulated a proposed research method. The full research protocol was generated and submitted for and received Institutional Review Board approval. A single instructor of 102 students in an initial technology teacher education program at the University of Limerick, Ireland, served as proctor for participants for this exploratory development study. Particular focus in this undergraduate program is in the development of core graphical competencies including graphical communication skills, understanding of geometric principles, and spatial visualization skills.

The study constituted two sections of introductory course offerings affiliated with engineering design graphics concepts and applications. The instructor/proctor randomly determined which instrument would be administered to which section. The Purdue Spatial Visualization test Visualization of Rotations (PSVT-VOR) was administered to the 52 course participants in Section 001, while the Pictorial Visual Rotation Test (VRT) was administered to the 50 course participants in Section 002.

The PSVT-VOR employed in the present study is one element of the Purdue Spatial Visualization test battery (PSVT) (Guay, 1977). The test measured students' ability to mentally rotate geometric objects depicted in drawing in three-dimension space. A standard time limit of 20 minutes was given for the test, which consisted of 30 items of increasing difficulty (Branoff, 2000). The directions of the PSVT-VOR test instructed the students to study how the key object in the top line of the question is rotated, and from among the five response options select the one that corresponds to the rotation of the depicted key object (Bodner & Guay, 1997). The PSVT battery provides a valid measure of cognitive abilities (Bodner & Guay, 1997).

The second instrument relied on rotational sequences of acquainted consumer/household objects to construct a metric for object familiarity (see Figure 6 for PSVT-VOR and PSVT comparison). Images of these objects were captured in parallel

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format to the established PSVT item sequences and response choices. A single key object was identified, just as was developed for the PSVT instrument. An expert review panel of post-secondary educators, that were members of the Engineering Design Graphics Division of the American Society for Engineering Education, was convened to analyze consistency of format, rotation, and solutions of the corresponding pictorial items instrument. A call for panel participation was posted on the Engineering Design Graphics Division Listserv where participants self-identified background and expertise in visualization and PVST-VOR. There were a total of four reviewers volunteering to assist in the review process. Feedback was obtained and incorporated based on diagnostic usability, image clarity, rotational accuracy, and uniformity in terms of PSVT metric consistency.

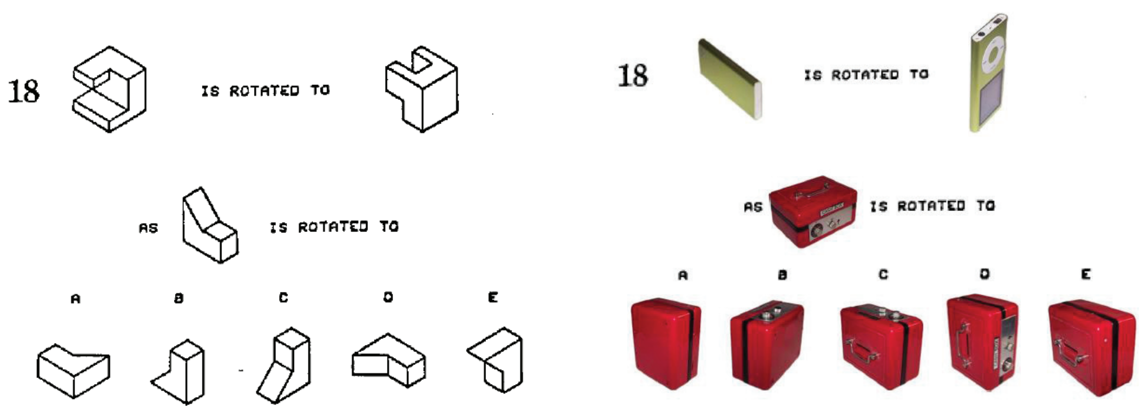

Figure 6. **PSVT-VOR and Pictorial VRT item comparison.**

The developed Pictorial VRT represented orientation familiarity, while geometric forms in the PSVT-VOR represented unfamiliar structures. Comparative analyses were conducted and differences identified pertaining to student abilities in mental rotation of geometric forms and pictorial visual rotation abilities.

Findings

Table 1 shows the summary statistics of the two visual rotation metrics. The average Pictorial VRT score (19.36 of a possible 30) for the 50 participants is lower than the average of PSVT-VOR scores (23.21 of a possible 30) for the other 52 participants. The variance (20.684) and standard deviation (4.548) of Pictorial VRT scores are low in comparison to the variance (22.837) and standard deviation (4.779) of PSVT-VOR scores indicating a slightly smaller spread of Pictorial VRT scores. The standard error (0.643) of Pictorial VRT scores is lower than that of Purdue SVRT indicating a smaller fluctuation in score values from participant to participant for the Pictorial VRT. The medians of both tests exhibit minimal deviance from the means respectively suggesting a somewhat symmetrical score distribution for both tests. The same range on both tests reiterates the comparable degree of difference in variability of participants between the

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two tests. Figure 7 and Figure 8 represent the number of occurrences for PSVT-VOR scores and Pictorial VRT scores.

Table 1
Summary Statistics

Assessment	n	Mean	Variance	Std.Dev.	Std.Err.	Median	Range
PSVT-VOR	52	23.21	22.837	4.779	0.663	24	18
Pictorial VRT	50	19.36	20.684	4.548	0.643	19	18

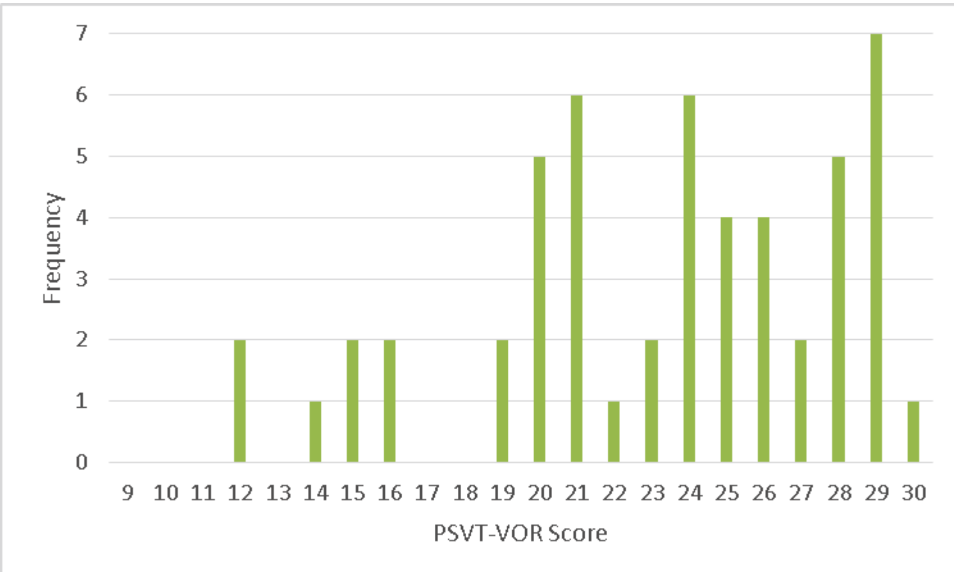

Figure 7. **PSVT-VOR Histogram.**

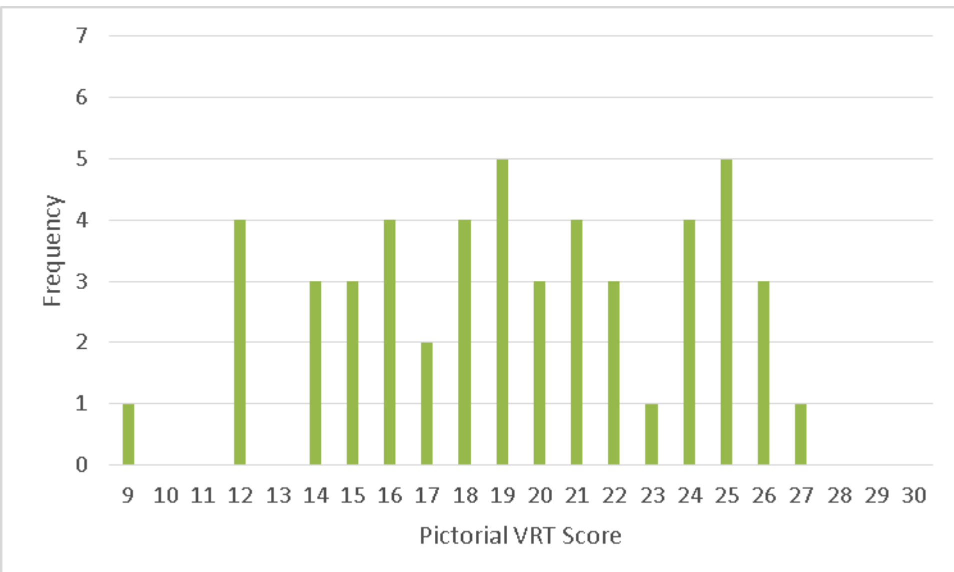

Figure 8. **Pictorial VRT Histogram.**

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The primary hypothesis was non-directional provided the experimental nature of the study and the lack of basis for a directional hypothesis. A single null hypothesis was evaluated: There is no difference in the score distributions of PSVT-VOR and Pictorial VRT. This hypothesis was evaluated in Table 2 using the nonparameric Mann-Whitney U-test. Due to the sampling methodology in that two single groups of students were selected to represent the engineering graphic student population, a Gaussian population cannot be assumed. In this case, a Mann-Whitney U test, which "is often thought of as the nonparametric analogue of the t test for two independent samples"(Howell, 2013, p.668), was adopted to compare the means of the scores from two unpaired groups, Purdue SVRT and Pictorial VRT. The test statistic for the Mann-Whitney U-test was compared to the designated critical value table. The critical alpha value was set at 0.05 for this investigation. The p-value for the test (<0.0001) uncovered that the null hypothesis was rejected. The result suggests that the collective outcome scores of the PSVT-VOR is significantly different than the score of Pictorial VRT. Summary statistics, frequency analyses, and hypothesis testing uncovered that student mental rotation abilities of geometric forms collectively exceed that of ability of pictorial rotation ability.

Table 2
Mann-Whitney U-test

Purdue SVRT (n)	Pictorial VRT (n)	Diff.Est.	Test Stat.	P-value
52	50	0	717.500	<0.0001

Conclusions

This study was conducted with the premise that forms of assessment can be extended or built upon to reflect the needs and values of a discipline. Specifically, the researchers wanted to determine if using actual captures of everyday objects (i.e. Pictorial VRT), would lead to student demonstration of higher proficiency on visual-based tests. As the findings indicate, it was just the opposite; students that participated in this study scored higher using the traditional geometric or isometric drawing test. Prior to the exploratory study, the researchers held the conception that through increased presence of visual cues participants would be assisted in determining proper rotation and orientation. However, little research has been previously conducted in determining the level of surface topology needed to heighten outcomes in the visual rotation of objects.

Based on the study findings, the authors offer the following recommendations. First, comparative analyses uncovered that students that took part in the study demonstrated existing levels of mental rotation ability proficiency with the geometric forms found in the PSVT-VOR. Early on in the participants' university studies, they learned about projection systems and principles associated with descriptive geometry with particular focus on cubes, rectangular prisms, pyramids, cones, and spheres. However, there is rarely a focus placed on the purposeful rotation and manipulation of everyday objects.

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Perhaps the students are influenced by what they observe in everyday media; for example, they will rarely see an iPhone turned upside down in a television commercial. Also, the participating students completed some spatial visualization instruction previous to this module and some of the developmental tasks would have been similar in nature to the PSVT-VOR. It would be interesting to investigate whether object familiarity and general interest with particular objects had an influence on performance. The second major deduction and recommendation lends itself to the pedagogy that engineering design graphics teachers use in the classroom. It could be that students are directly influenced by the geometric forms commonplace in their coursework and are not as proficient in articulating classroom-based study and exercises to everyday objects. If this were the case, it would argue to enhance transferability of skill through the inclusion of more real-world images throughout engineering design graphics curricula. The final supposition and recommendation is that the role of graphics related background instruction, visual skill development, and the use of computer graphics software needs to be considered and factored in investigations related to visualization and mental rotation.

Further research in the use of alternative visual-based tests with familiar and unfamiliar properties is suggested. Overall, more research is needed in what are best practices for using projection and computer technology to enhance students' learning of visual-based materials, as well as test their visual skills and abilities. Finally, research is needed on how we can more accurately diagnose student visual abilities, knowing that they will most likely use three-dimensional modeling and printing, as well as image processing and simulation, as major components within their careers. An industry-modeled and/or field-based course of study within engineering design graphics has potential to enhance the necessary trajectory for visual skill preparedness for the workplace. This has implicit impacts for the engineering design graphics classroom specific to the development, promotion and assessment of visual cognition and visual synthesis in mental imagery.

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Note

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