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Use of Virtual Reality Head-Mounted Displays for Engineering Technology Students and Implications on Spatial Visualization

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Abstract

Results from a number of studies indicate that the use of head-mounted displays can influence spatial visualization ability; however, research provides inconsistent results. Considering this, a quasi-experimental study was conducted to identify the existence of statistically significant effects on rotational view drawing ability due to the impacts of the displays. In particular, the study compared the use of three different types of displays; head-mounted, pc dynamic and 3D printed and whether a significant difference exists towards rotational view drawing ability, among engineering technology students. According to the results of this study it is suggested that the impact of the display type provides no statistically significant differences.

Introduction

Virtual reality (VR) technology dates back to the 1960s and is defined as the “computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors” (Oxford Dictionaries, 2015). Since the 1960s, VR use has evolved in business and industry, as well as in the classroom. Burdea (2004) is one of the first authors who acknowledged issues with teaching virtual reality. He expressed concern for the lack of faculty experts, textbooks, dedicated laboratories, and curriculum content on VR. Through an informal survey, Burdea (2008) found that only 148 universities offered VR studies, however, by 2008 this number increased to 273 universities.

Review of Literature

Spatial Ability

The term spatial ability varies in definition, to include a range of abilities across the years and by different authors. Researchers, for the most part, recognize five elements in particular: spatial perception, spatial visualization, mental rotations, spatial relations, and spatial orientation (Maier, 1994). Spatial skills are a component of aptitude critical to success in engineering, technical, and scientific fields (Martín Gutiérrez, García Domínguez, & González, 2015). In addition, spatial ability has been widely researched in the areas of science, technology, engineering, and mathematics (STEM). Related research determined that retention and student success in engineering education depends largely on highly developed spatial skills. In addition, research has also shown that different instructional methodologies may increase student spatial ability achievement in different disciplines, including engineering and science education (Häfner, Häfner, & Ovtcharova, 2013; Martín-Gutiérrez et al., 2015; Rafi, Anuar-Samsudin, & So-Said, 2008).

Spatial Ability and Virtual Reality

Virtual reality is recognized as a “set of technologies and interfaces which allow one or more users to interact in real time with a computer-generated 3D environment or dynamic world” (Martín Gutiérrez et al., 2015, p. 325). In Rafi, Anuar, Samad, Hayati, and Mahadzir (2005) study of pre-service teachers using virtual reality for spatial ability learning, subjects showed improvement in their mental rotation abilities, as well as a marginal gain in spatial visualization. Traditionally, engineering courses have sought to achieve a near equal amount of mathematical precision and practical applications in a laboratory environment (Tibola, Pereira & Tarouco, 2014).

Lee and Wong (2014) found a significant difference in achievement for those students in a VR-based learning environment than the control group who used PowerPoint slides. In particular, it was determined that low spatial ability learners showed significant gains in spatial ability. Martín Gutiérrez et al. (2015) found that the use of 3D virtual technologies significantly improved spatial skills of the subjects studied. In addition, the results revealed that more than half of the students exposed to the traditional methods (non-3D environments) were not able to pass an Engineering Graphic Design course, while those exposed to the 3D methods showed a 60% pass rate.

Visualization and Virtual Reality

Visualization, a component of spatial abilities, is defined as the “ability to mentally manipulate, rotate, twist, or invert a pictorially presented stimulus object” (McGee, 1979). It is important to note here that research reveals many definitions, but they all reinforce the basic characterization of mentally rotating an object in the mind’s eye or “mental management” of complex shapes (Martín Gutiérrez et al., 2015). Sorby and Baartmans’s (1996) study on a newly implemented semester course that integrated virtual geometric objects, which could be sliced and rotated, revealed successful learning outcomes in spatial visualization. Sorby and Baartmans (2000) found that year after year, students completing this course showed statistically higher graphics grades, as well as an increase in engineering retention.

Chen (2006) found that learners with high and low spatial visualization ability benefited from guided VR treatment (a learning mode that uses a VR-based learning environment with additional navigational aids) and outperformed those with non-guided VR and non-VR treatments. The interactive effect between spatial visualization ability and the learning mode revealed no significance differences. This result further supports the finding that learners benefit from guided VR treatment regardless of spatial visualization ability.

Virtual Reality head-mounted display (Oculus™)

While virtual reality is not new to educational environments, Oculus™ is just beginning to break barriers, especially in engineering and science education. Due largely to high cost and lack of expertise, Oculus™ technology has been in the background until its recent release into gaming and other popular technologies on the market. Sony and Microsoft have entered the market by developing Xbox live and Sony PlayStation to bring virtual worlds to the home and marketplace (Callaghan, McCusker, Lopez-Losada, Harkin, & Wilson, 2009). The Oculus™ Rift should be released later this year, and Sony plans a project launch date in 2016 for their virtual reality head-mounted display, Project Morpheus. Retail versions of Oculus™ will offer resolutions higher than the typical 1,920 by 1,080 pixels per eye. This technology will soon become a household standard that was unimaginable 30 years ago when similar technology started at $100,000 (Parkin, 2014).

Head-Mounted Displays (HMDs) like Oculus™ allow users to experience full immersion, permitting a realistic 3D setting similar to a physical environment (Beattie, Horan & McKenzie, 2015). Oculus™ technology has only been on the market a short time. It is the most commonly used in education, specifically in computer science, followed by engineering and mathematics (Freina & Ott, 2015). The most relevant research related to this technology has been conducted and published in the United States, followed by Germany. In addition, most of the research on VR and HMDs has been related to higher education or adult training, since immersive VR may hinder the cognitive and physical development of children. VR and HMDs support learner engagement and motivation, as well as a range of learning styles (Freina & Ott, 2015).

Virtual Reality in Engineering Education

With recent evolutions of computer hardware and software, lower associated costs, and an increase in expertise in the field, Virtual Reality has become a more feasible teaching solution in Engineering education, as well as other educational environments and disciplines (Abulrub, Attridge, & Williams, 2011; Häfner, et al., 2013). There is a new generation of computer savvy engineering students entering higher education with the expectation of learning cutting-edge technologies. This requires faculty to understand the needs of these students and to provide programs that offer advanced learning environments with 3D visualization technologies and state-of-the-art curriculums. Virtual environments not only promote learning, they also promote innovation and creativity, which allows students to be engaged and successful in their educational environments. Abulrub et al.'s (2011) study found that using 3D interactive virtual reality visualization systems to prepare engineering students for an authentic experience in industry considerably improves the efficiency of both teaching and training. Furthermore, students are able to apply theoretical knowledge domains to complex real-world problems in an educational environment that has active learning components and enhances student motivation.

Virtual Reality and 3D Modeling

Advanced engineering courses depend on the students' ability to visualize three-dimensional (3D) objects as interconnected parts and as a whole. The dynamic nature of such objects is equally important (Flanders & Kavanagh, 2013). A study by Cohen and Hegarty (2014) reveals interventions using virtual models and interactive animations are effective in training children on simple spatial skills, as well as more complex spatial skills in adults. Yurt and Sünbül's (2012) study showed significantly higher scores for mental rotation in those students assigned to a virtual environment.

Combining VR and 3D graphics provides an environment that can enhance a user's spatial ability. Research suggests the 3D immersive virtual environment is more efficient in training spatial ability and skills than the 2D or 3D non-immersive environments. The evolution of computer software and the decrease in costs has introduced an environment supportive of virtual reality and 3D modeling (Fillatreau et al., 2013).

Research Question and Hypothesis

To enhance the body of knowledge related to VR in the college classroom, the following study was conducted.

The following was the primary research question:

> Does the mode of displaying a rotating 3D geometric shape (PC image, 3D physical model, PC image viewed through a head-mounted display) have an effect on students': a) Spatial visualization ability as measured by the MRT and b) ability to sketch a rotational view drawing?

The following hypotheses will be analyzed in an attempt to find a solution to the research question:

> H_0: There is no effect on students': a) Spatial visualization ability as measured by the MRT and b) ability to sketch a rotational view drawing due to the mode of displaying a rotating 3D geometric shape (PC image, 3D physical model, PC image viewed through a head-mounted display).
>
> H_A: There is an identifiable amount of effect on students': a) Spatial visualization ability as measured by the MRT and b) ability to sketch a rotational view drawing due to the mode of displaying a rotating 3D geometric shape (PC image, 3D physical model, PC image viewed through a head-mounted display).

Methodology

A quasi-experimental study was selected as a means to perform the comparative analysis of spatial visualization ability during the spring of 2015. The study was conducted in an Engineering Graphics course offered as part of the Engineering Technology program.

The participants from the study are shown in Figure 1. Using a convenience sample, there was a near equal distribution of participants between the three groups.

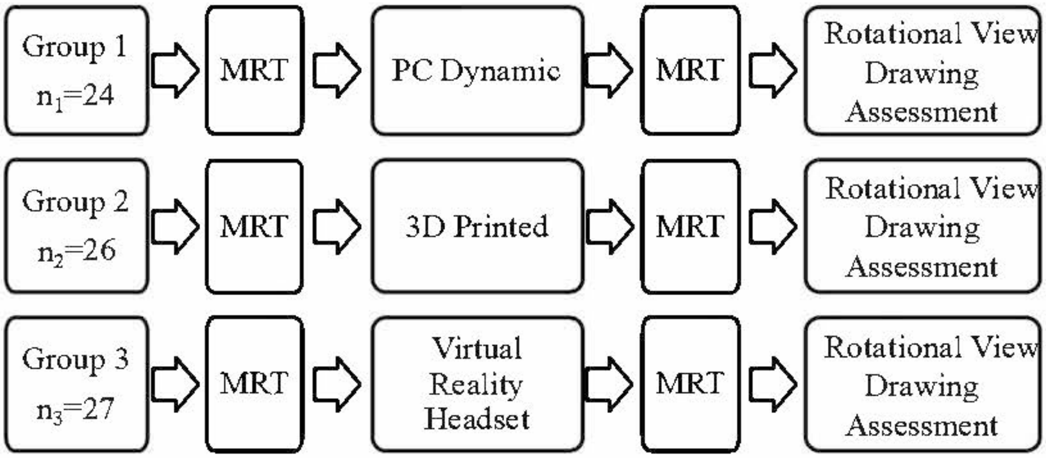

Figure 1. Research design methodology

The engineering graphics course emphasized hands-on practice using 3D AutoCAD software in the computer lab, along with the various methods of editing, manipulation, visualization, and presentation of technical drawings. In addition, the course included the basic principles of engineering drawing/hand sketching, dimensions and tolerance.

The students attended the course during the spring semester of 2015 and using a convenience sample they were divided into three groups. The three groups (*n1*=24, *n2*= 26 and *n3*=27, with an overall population of *N* = 77) were presented with a visual representation of an object (visualization) and were asked to create a rotational view. The first group (*n1*) received a 3D dynamic PC generated heptahedron visualization, self-rotated at 360 degrees at approximately four rounds per minute (slow rotation was used to prevent optical illusion and distortion of the original shape) during the creation of the rotational view (see Figure 2). The second group (*n2*) received a 3D dynamic printed heptahedron visualization, also self-rotated at 360 degrees at approximately four rounds per minute on top of a motorized base (see Figure 3). The third group (*n3*) received a 3D dynamic PC generated heptahedron visualization, viewed through a head-mounted display (Oculus) (see Figure 4), also self-rotated at 360 degrees at approximately four rounds per minute.

In addition, all groups were asked to complete the Mental Rotation Test (MRT) two days prior to completing the rotational view drawing and again right after, in order to identify the level and change of spatial visualization ability, and to show equality between the three groups. The MRT is one of the most commonly used instruments for measuring spatial ability (Caissie, Vigneau, & Bors, 2009). Reliability of the instrument has been found satisfactory; retest correlation was reported at .83 following an interval of one year or more (Vandenberg & Kuse, 1978). The MRT has been used to measure spatial abilities in relation to graphics and design curricula (Contero, Company, Saorin, & Naya 2006; Gorska & Sorby, 2008; Sorby, 2007). MRT consists of 20 items that require the learner to compare two-dimensional drawings and three-dimensional geometric figures. Developed by Vandenberg and Kuse (1978), the MRT assesses spatial visualization and mental rotation components. Each item on the MRT consists of five line drawings, which includes a geometrical target figure (criterion figure) on the left followed by two reproductions of the rotated target, as well as two distractors. The learner is required to indicate which two of the four represented are the actual rotated replicas of the geometrical target figure on the left (Caissie et al., 2009; Gorska & Sorby, 2008). The learner has a time constraint of four minutes for the first ten items, and after a short break, four minutes are given to solve the remaining ten.

Upon completion of the MRT, the course instructor presented the first group (*n1*) with a projection of a PC generated dynamic visualization of the heptahedron and asked them to create a rotational view of it (see Figure 2). The students in the first group (*n1)* were able to approach the visualization and observe from a close range.

For the second group (*n2*), the instructor presented students with a 3D printed dynamic visualization of the heptahedron and asked them to create a rotational view of it (see Figure 3). Students in the second group *(n2)* also had the privilege of close observation.

Group 3 *(n3)* was asked to use the Oculus Virtual Reality head-mounted display to create a rotational view of the dynamic visualization of the heptahedron that was projected inside (see Figure 4).

All groups were given the same amount of time (five minutes) to observe the visualization model. This process took into consideration research that indicates a learner's visualization ability and level of proficiency can easily be determined through sketching and drawing techniques (Contero et al., 2006; Mohler, 1997).

The engineering hand sketch used in this research was a rotational view of the heptahedron. Rotational views are very useful engineering graphics tools, especially for parts that have complex interior geometry, as the sections are used to clarify the interior construction of a part that cannot be clearly described by hidden lines in exterior views (Plantenberg, 2012). The rubric included the following parts: (a) right orientation of axis, (b) use of correct proportion, (c) accurate angle used for isometric perspective, (d) appropriate use of visible lines, and (e) appropriate use of drawing space. The maximum score for the drawing was 6 points (see Figure 5 for rotational views of the Heptahedron).

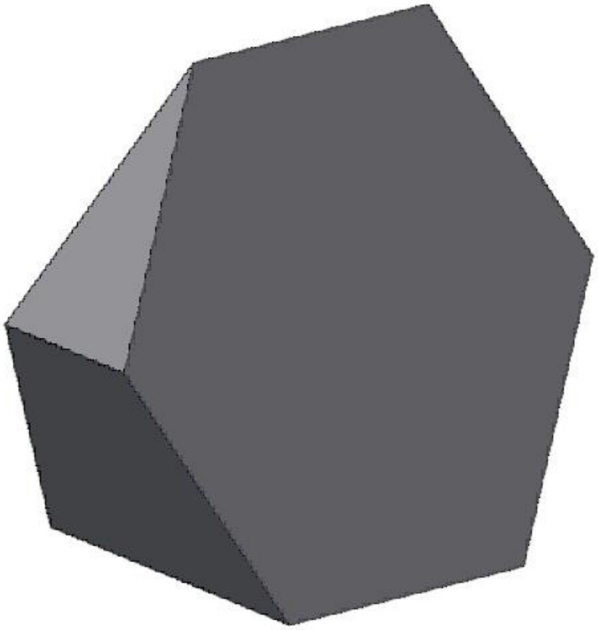

Figure 2. Group 1 was able to view the heptahedron using a 3D PC generated dynamic visualization

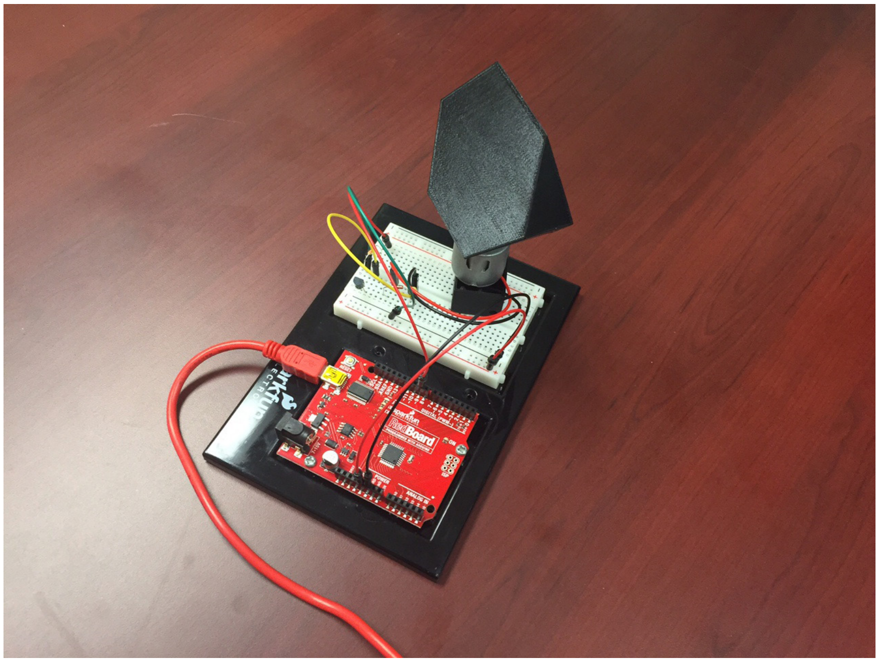

Figure 3. Group 2 was able to view the heptahedron using a 3D printed dynamic visualization

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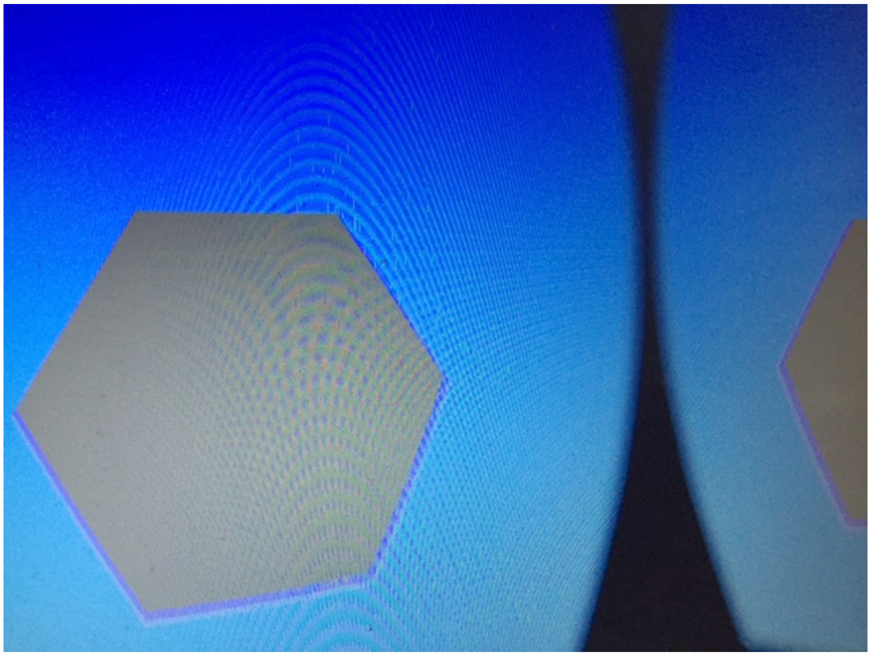

Figure 4. Group 3 was able to view the heptahedron using the Oculus Virtual Reality head-mounted display

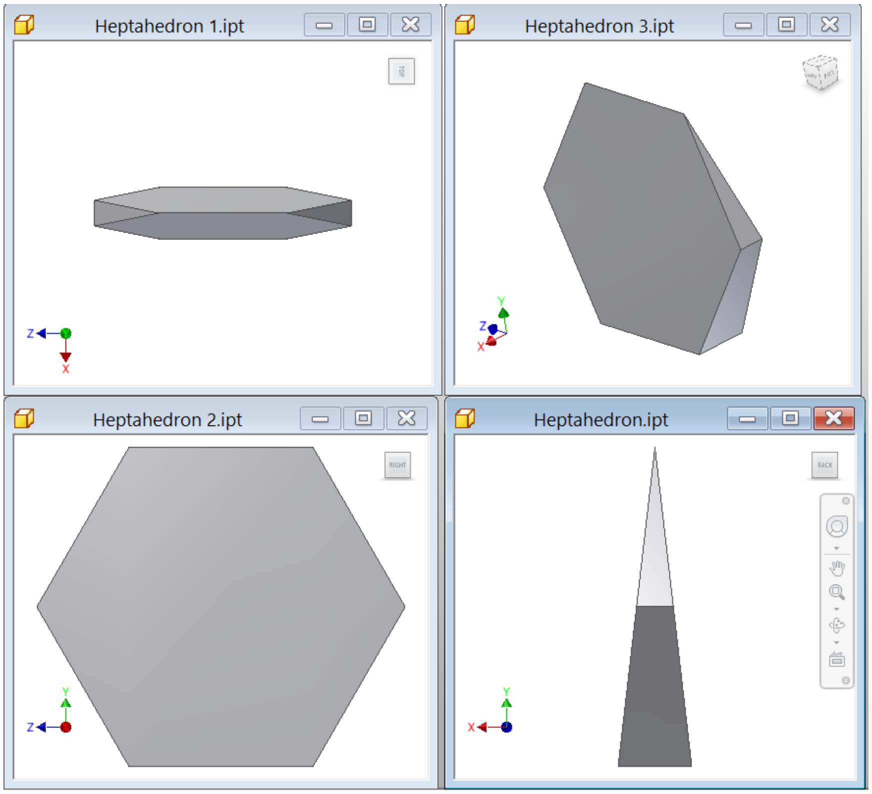

Figure 5. Rotational views of the heptahedron model

Data Analysis

Analysis of MRT Scores

The first method of data collection involved the completion of the MRT instrument before (to show existing level of spatial ability) and after the treatment to show different spatial ability levels between the three different groups. The researchers graded the MRT instrument, as described in the guidelines by the MRT creators. A standard paper-pencil MRT was conducted, in which the subjects were instructed to choose the correct rotational view from the ones presented. The maximum score that could be received on the MRT was 20. As it can be seen in Table 2 for the pre-test, n1 had a mean of 18.792, n2 had a mean of 18.462, and n3 had a mean of 18.815. As far as the post-test n1 had a mean of 19.698, n2 had a mean of 19.042, and n3 had a mean of 19.348 (see Table 1).

Due to the relatively low numbers of the participants and the fact that we did not have random samples, a non-parametric Kruskal-Wallis test was run to compare the mean scores for significant differences, as it relates to spatial skills among the three groups. The result of the Kruskal-Wallis test, as shown in Table 2, was not significant X^2= 1.341, $p < 0.321$.

Table 1
MRT Descriptive Results

						95% Confidence Interval for Mean	
Models	N	Mean pre-test	Mean post-test	SD pre-post	SE pre-post	Lower Bound pre-post	Upper Bound pre-post
PC Dynamic	24	18.792	19.698	3.7181	.7590	18.222	19.362
3D Printed Dynamic	26	18.462	19.042	3.9011	.7651	18.886	18.237
Oculus	27	18.815	19.348	6.1958	1.1924	18.564	19.266
Total	77	18.356	19.362	4.8054	.5476	18.557	18.955

Table 2
MRT pre and post-test Kruskal-Wallis H test Analysis

Models	N	DF	Mean Rank	X^2	P-value
PC Dynamic	24	2	18.80	1.341	.321
3D Printed Dynamic	26		19.82		
Oculus	27		18.26		
Total	77				

Analysis of Drawing

The second method of data collection involved the creation of a rotational view drawing. As shown in Table 3, the group that used the 3D printed Model (*n* =26), had a mean observation score of 5.154. The groups that used the PC computer generated model (*n=24*) or the Virtual Reality head-mounted display (*n* = 26) had lower scores of 4.667 and 4.296, respectively (see Table 3). A Kruskal-Wallis test was run to compare the mean scores for significant differences among the three groups. The result of the Kruskal-Wallis test, as shown in Table 4, was significant: X^2= 1.121, $p < 0.0049$. The data was dissected further through the use of a post hoc *Steel-Dwass* test. As it can be seen in Table 5, the post hoc analysis shows a statistically significant difference between the 3D printed vs. PC generated dynamic model ($p < 0.032$, $d = 0.4571$, Z=2.3420) and the 3D printed vs. Oculus ($p = 0.001$, $d = 0.8417$, Z=2.0815).

Table 3
Rotational View Drawing Descriptive Results

					95% Confidence Interval for	
	N	Mean	SD	Std. Error	Lower Bound	Upper Bound
PC Dynamic	24	4.667	.6370	.1300	4.398	4.936
3D Printed	26	5.154	.6748	.1323	4.881	5.426
Oculus	27	4.296	.7753	.1492	3.990	4.603
Total	77	4.701	.7791	.0888	4.524	4.878

Table 4
Rotational View Kruskal-Wallis H test Analysis

Models	N	DF	Mean Rank	X^2	P-value
PC Dynamic	24	2	17.92	1.121	.0049
3D Printed Dynamic	26		19.79		
Oculus	27		16.92		
Total	77				

Table 5
Rotational View Drawing Steel-Dwass test Results

	Visual Aids (1 vs. 2 vs. 3)	Score Mean Diff.	Std. Error	*Z*	*p*
2 vs 1	3D Printed vs. PC Dynamic	0.4751	0.1872	2.3420	0.032*
2 vs 3	3D Printed vs. Oculus	0.8417	0.1982	2.0815	0.001*
3 vs 1	Oculus vs. PC Dynamic	-0.2531	0.1981	1.0381	0.102

* Denotes statistical significance

Discussion

This study was done to determine if there is a difference in spatial visualization ability and the impacts of Virtual Reality head-mounted displays on dynamic visualizations for engineering technology students. In particular, the study compared the use of different visual models: a 3D printed solid dynamic visualization, a 3D computer generated visualization, and a 3D printed dynamic visualization viewed through a Virtual Reality head-mounted display (Oculus). It was found that the use of the Virtual Reality head-mounted display provided no statistically significant higher scores over the other two types of visual models; therefore, the hypothesis that there is significant effect in spatial visualization ability due to the mode of displaying a rotating 3D geometric shape (PC image, 3D physical model, PC image viewed through a head-mounted display) on students': a) Spatial visualization ability as measured by the MRT and b) ability to sketch a rotational view drawing was rejected.

The fact that none of the groups gained any statistically significant advantage from the use of virtual reality head-mounted displays over other conventional types of models could suggest that the geometrical shape used for this study (heptahedron) was not complex enough to promote additional gains that a virtual reality head-mounted display could offer. The use of Virtual Reality (VR) head-mounted displays (HMDs) can also produce temporary deficits of binocular vision (Mon-Williams, Warm, & Rushton, 1993). Numerous reports exist that show adverse visual symptoms following use of VR systems (Regan & Price 1994). Mon-Williams et al. (1993) showed that these symptoms are associated with changes in the visual system. According to Mon-Williams et al. (1993), various causal mechanisms related to headset engineering explain the observed change in heterophoria (the bias that exists in the vergence eye movement system under open-loop conditions) after VR HMD use. According to Mon-Williams et al. (1993), an additional cause of visual stress, which has not been previously identified with regard to Virtual Reality systems, is the change in the vertical gaze angle. Gaze angle (the vertical orientation of the eyes with respect to the head) is changed, so the effort of the extra-ocular muscles is modified (Heuer & Owens, 1989; Heuer, Wischmeyer, Bruwer,

& Romer, 1991). Therefore, it could be suggested that one of the reasons the Virtual Reality head-mounted displays did not provide statistically significant higher scores over the other two types of visual models was that during treatment the students experienced temporary deficits in binocular vision that could result in errors during the rotational view drawing process. An additional reason it could be the fact that the treatment only lasted for a short time and it was not enough to make significant gains in spatial ability.

Interestingly enough, even though it is not statistically significant, during the Kruskal-Wallis test, the Steel-Dwass post hoc test revealed that the groups who received treatment via 3D printed vs. Oculus (p=0.001), followed by the group that received treatment via 3D printed vs. PC dynamic (p=0.032), had significant differences in between. This result could suggest that the virtual reality head-mounted display technology is a new, unfamiliar technology that can favor specific populations based on their level of spatial skills. Hegarty and Waller (2005) suggest that individuals with high spatial abilities benefit from more complex visualizations because they already have effective mental models to process 3D information versus individuals with lower spatial abilities who lack these effective mental models.

Limitations and Future Plans

In order to have a more thorough understanding of the effects on spatial visualization ability of head-mounted displays for engineering technology students, as measured through rotational view drawings, and to understand the implications for student learning, it is imperative to consider further research. Future plans include, but are not limited to:

- repeating the study using a larger population to verify the results.
- repeating the study using a different population such as mathematics education, science education, or technology education students.
- repeating the study by comparing male versus female students.
- repeating the study and extending the time of treatment.

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