Virtual Reality application to improve spatial ability of engineering students

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ABSTRACT

We propose using Immersive Virtual Reality activities to improve the spatial ability of engineering students based on the study of solid geometry.

The work group is selected randomly from among all the students registered for the 1st term course Graphic Expression and Computer-Aided Design (GECAD) at the Barcelona College of Industrial Engineering (EUETIB).

A total of 60 participants completed three activities (6 h) in VR, using head-mounted display (HMD) glasses. Another group of students (30) made up the control group, which carried out only the learning activities that were common to all students, in a SolidWorks 3D non-immersive solid modeling software environment.

Spatial abilities are assessed using the Differential Aptitude Test: Spatial Relations Subset (DAT:SR) and the Purdue Spatial Visualization Test: Rotations (PSVT:R). Previous studies have demonstrated a close correlation between successful comprehension of the Graphic Engineering course contents and high scores on the DAT:SR test. The greatest correlation was found between the DAT:SR pre-test and the solid geometry exam (test and 3D modeling exercises).

We propose measuring spatial abilities before and after the classroom activities and looking for correlations between the spatial perception tests (DAT:SR and PSVT:R) and academic results in solid geometry. Furthermore, we also wish to determine the students' opinion with regard to the proposed activities.

This would permit us to recommend and incorporate the use of VR in order to improve spatial abilities, in particular for those students with lower levels of spatial abilities, as measured by a DAT:SR or PSVT:R.

Keywords

Spatial ability · Virtual reality (VR) · Teaching engineering · Head-mounted display (HMD).

1. INTRODUCTION

Our aim here is to apply Virtual Reality (VR) to learning processes in CAD, and to those contents related to space geometry.

According to [Hel92] VR uses hardware and software to create a sensation of immersion, navigation and manipulation.

VR is divided into three main categories: text-based, desktop and immersive VR.

Text-based networked VR is associated with environments in which communication takes place via texts. This type of VR has commonly been used in education and training [Pso95].

Desktop VR is an extension of interactive multimedia applications that incorporate three-dimensional images, but without being considered immersive.

Immersive VR is the application considered in this work. It consists of a combination of hardware, software and concepts that enable the user to interact with a computer-generated three-dimensional world [LA94].

There are different ways in which VR technology can aid learning.

VR is widely used in rehabilitation and surgical training [NGA+13].

Evidence exists [Bor16], [AAH+11], [LZXL05] that, when applied appropriately, VR can offer an effective means of improving certain skills. One example is the effective coordination of sensory motor skills using flight simulators for pilot training.

Some of the most interesting applications are those that enable students to visualize abstract concepts, such as chemical bonds [CTN15] or those that enable them to visit environments and interact with events or objects that would not otherwise be available due to restrictions imposed by distance, time or safety [Jav99].

[Win93] defines a conceptual framework for educational VR applications, and states that:

1. Immersive VR provides non-symbolic first-person experiences that are specifically designed to help students learn content.
2. These experiences cannot be obtained in any other way in formal education.
3. This type of experience constitutes a large part of our everyday interaction with the world around us, even though schools tend to promote symbolic third-person experiences.
4. Constructivism offers a theory upon which to develop educational VR applications.
5. The convergence of the theories of knowledge construction with VR technology permits promoting hands-on learning in virtual worlds, by making it possible to display information in a different way, and materialize abstract ideas that until now have been very difficult to represent.

[WHH+97] identifies the main contributions of VR as immersion, interaction or participation and motivation.

Pantelidis states that VR provides new ways and methods of visualization, is based on interaction and promotes active participation [PV10].

VR changes the way in which a student interacts with contents, as compared to traditional learning processes. Participants who interact with the virtual environment see immediate results, encouraging them to continue to interact with it, thus increasing their motivation.

[WM98] compared VR learning of an assembly procedure to other traditional media, such as paper and video. They obtained better long-term learning results with VR.

[SK03] compared the perception and understanding of spatial volumes using 2D, non-immersive VR (on a computer screen) and immersive 3D VR head-mounted environments. The students in an immersive VR environment attained a better understanding of volume and its components in three dimensions. Furthermore, the more complex the volume is, the better it is perceived using HMD.

In summary, there is a great deal of evidence to suggest that VR can be used successfully in learning processes. In many cases, the contribution of methodologies based on VR represents significant improvements in the comprehension of the course contents.

2. SPATIAL VISUALIZATION ABILITY

The ability to visualize space (or simply spatial ability or SA) is the capacity to understand and remember the spatial relationships between objects. More specifically, it is the ability to mentally maneuver two- and three-dimensional shapes [UMT+13].

Moreover, some authors [SS01], [MSB+11], [KJJ14] suggest the importance SA in the engineering design process and propose educational strategies to promote the development of this competence among students. The development of spatial capacity has always formed part of the Graphic Engineering curricula [MB05], [MG13]. One aim of introductory classes in graphic engineering is to increase the spatial capacity of students in order to construct cognitive representations of the geometric shapes and mentally maneuver them. To accomplish this, 2D and 3D representations are regularly used and students do exercises to obtain views, convert 2D into 3D, and vice versa. This makes it possible to obtain graphic representations of technical contents and to acquaint engineering students with the use of design resources. Increasing a student's spatial ability helps him/her better understand the concepts of solid geometry, which in turn, are used to design products, devices and systems.

SA is a complex human capacity that many researchers believe can be identified based on 2 or 3 components. Authors such as [PK82], [PH91] and [RG00], each cited by [MGK+13], identify three components of SA: spatial visualization, spatial orientation and spatial relation.

However, since spatial orientation and spatial visualization have factors in common, many researchers consider that there are really only two basic components of SA: spatial relation and spatial orientation [CG98], [HT11], [Moh08], [PRL+02], as referenced by [MGK+13].

Spatial relation is the capacity to mentally rotate an object around its axes. Spatial orientation is the ability to mentally maneuver or transform the representation of an object in another view.

In previous studies [TAB14], we have found a positive correlation between SA and academic performance in the study of solid geometry. The same is true for chemistry-related contents [MGK+13].

[Eli02] states that SA affects all daily activities, insofar as it refers to the ability to make mental representations and manipulate visual and spatial information. [LK83] divide SA into three subdomains: visualization, which includes complex tasks with numerous steps; spatial relations, which include simple tasks, such as quick mental rotation; and orientation, which includes tasks that involve imagining changes of perspective.

It would seem that the orientation and mental maneuvering abilities generally encompassed in the ability for spatial visualization rely on similar mental processes. [OSR+02] studied how people learn to rotate objects. They compared the configurations of real and virtual objects (using HMD) and found a greater correlation with cognitive-analytic skills than with mental rotation abilities. They obtained the best results with participants who used HMDs, which led them to conclude that immersive VR is an excellent training tool for developing spatial capacity.

3. MEASURE OF SPATIAL ABILITY

From among the wide variety of tests used to measure the spatial visualization ability, we highlight four here that are frequently mentioned in the literature [DKSG06]:

- Differential Aptitude Test: Space Relations (DAT:SR); visualization, paper folding
- Mental Cutting Test (MCT); visualization, object cutting
- Mental Rotation Test (MRT); quick mental rotation
- Purdue Spatial Visualization Test: Rotations (PSVT:R)

The Differential Aptitude Test: Space Relations (DAT:SR) [BSW73] contains 50 items.

The task consists of selecting the correct representation of a 3D object from among four choices depicting the representation of a folded 2D shape. In one study [MGS98], it was found that student scores on the DAT: SR were the most important predictor of success in an engineering graphics course, as compared to three other spatial visualization tests.

The Mental Cutting Test (MCT) [Cee39] contains 25 items. Each question presents a shape that has been cut along a given plane. The objective is to select the resulting cut from among 5 alternatives.

The Mental Rotation Test (MRT), developed by [VK78], is used to assess a person's ability to visualize rotated solid objects. It consists of 20 items. Each question presents a shape with two correct and two incorrect choices. The objective is to identify which two alternatives are rotated images of the shape in question. A clear predecessor of the MRT is the Mental rotation of three dimensional objects by [SM71] used by [HLXB15].

The Purdue Spatial Visualization Test: Rotations (PSVT:R) was developed by [Gua77]. It contains 30 items. On this test, students are shown a reference object and then a view of the same object after it has been rotated in space. They are then shown a second object with a set of views and are asked which one matches the same rotation performed on the reference object [MY13].

[DKSG06] analyzed virtual reality (VR) and augmented reality (AR) as tools for use in SA training. In spite of non-conclusive results in terms of the improvement of SA with the tools used, improvements were shown on the four tests (used as pre- and post-tests) among the subjects.

The following tests were given:

- Differential Aptitude Test: Space Relations (DAT:SR); visualization, paper folding
- Mental Cutting Test (MCT); visualization, object cutting
- Mental Rotation Test (MRT); quick mental rotation
- Objective Perspective Test (OPT); orientation, change of perspective

In this study, [DKSG06] describe the limitation of not having a 3D test to measure SA, as traditional paper-based methods do not cover all the skills that come into play when working in a 3D environment.

In an earlier work [TAB14], we developed a model to assess SA in engineering students taking the first-year Graphic Expression and Computer-Aided design course.

In this work, an improvement in SA was observed following the use of 3D solid modeling software. Data from 812 first-year industrial engineering students in three colleges at Barcelona Tech (Universitat Politècnica de Catalunya) were analyzed.

The evolution of the results obtained on the Differential Aptitude Test: Spatial Relations Subset (DAT:SR) and Mental Rotation Test (MRT) were analyzed before and after the content material in computer aided design were studied.

We found the strongest correlation between the DAT pre-test and the solid geometry test. This led to the proposal of this article: to use VR to practice concepts of solid geometry, with the aim of improving academic results. DAT appears to be a good indicator of academic success, as it produced the greatest number of correlations.

On the other hand, MRT does not seem to be a good indicator, as it failed to provide any significant results. No strong correlations were found between the values of MRT and the solid geometry test.

Some data was collected to provide information about other related variables. Such as: age, sex, new/retaking student, engineering branch, route of entrance into the university, working while studying, previous years studying drawing and CAD software, sport practiced by the student, video game player, favourite video game type, internet user, right of left-handed and faculty of engineering.

Other relevant conclusions were:

Regarding the use of CAD software: better results were found for those students who had prior experience with this type of programs.

The data showed a slight improvement in the final DAT:SR score for those students who play sports as compared to those who do not.

Field of engineering: important differences were found among the specialties in which the students were enrolled. In particular, chemistry students obtained low scores.

This enabled us to design remedial educational activities for those students who required them.

4. HEAD-MOUNTED DISPLAY (HMD) APPLICATION

The device displays two almost identical photographs that differ by the point from which the photo is taken. When viewed by each of the eyes separately, the images simulate real vision and the brain composes a three-dimensional relief effect.

HMD devices currently reproduce two images with a slightly different focus on a monitor similar to that of a smartphone. The results cause a high level of immersion, while the movements of the head change the point of view of the receiver, enabling us to simulate movement in the scenario by means of a keyboard or joystick.

An attempt was originally made to use 3D modeling drawings from SolidWorks as the basis to create a version compatible with Oculus Rift, but the results obtained after converting the files were less than satisfactory.

The best resolution was obtained using Cinema4D in *.fbx format and importing it into the Unity game engine, in which the user movement and interaction commands had been programmed.

The scenarios corresponded to subsequent stages in the resolution of a solid geometry exercises. For learning purposes, the transitions between steps were animated following logical drawing processes.

Those animations were created using Unity's Legacy tool.

The symbols for geometric relationships and annotations were created in Photoshop (Figure 1).

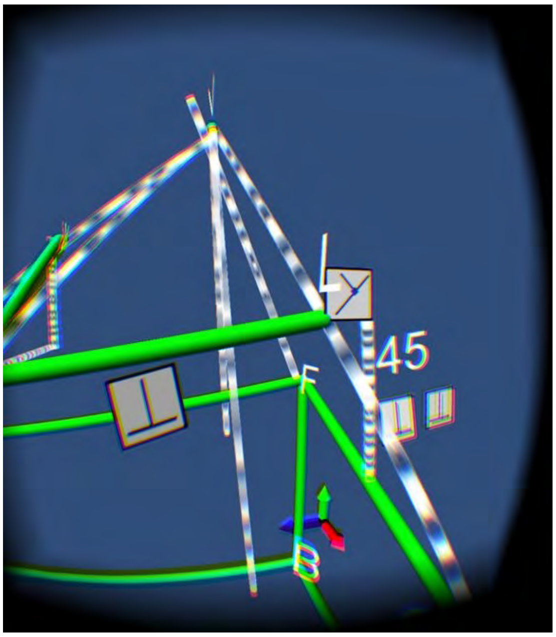

Figure 1. Screenshots from VR exercises.

5. METHODOLOGY

The investigation focused on the Graphic Expression and Computer-Aided Design (GECAD) course, specifically on the study of the SA developed and the assessment of the academic results in the solid geometry module.

The activities consisted of creating applications to model three-dimensional geometric shapes, introducing the concepts of geometry step by step. Students could interact freely with each scenario and move forward and backward through the sequence of steps.

Interaction takes place through the keyboard and visualization through an HMD headset.

The transitions between different states are created by means of provided animations that progressively build the elements by following the instructions for the exercise.

The concepts of solid geometry incorporated are synthesis, analysis and geometric metrics axioms, such as:

- In order for a straight line to be perpendicular to a plane, it needs only be perpendicular to two non-parallel straight lines found on the plane or parallel to it.
- If the angle between a straight line and a plane is θ, the angle between this straight line and the line perpendicular to the plane is complementary to θ: (90−θ).
- If a straight line has a slope of X%, this means that it has an angle with the horizontal plane of θ=arctg (X/100).

- If the angle between two planes is θ, the angle between two straight lines, each perpendicular to a plane, is the supplementary angle of θ: (180º-θ) (or θ, depending on where it is measured).
- The distance between two straight lines that cross one another is measured on the straight line perpendicular to both that intersects them.

The methodology can be summarized in the following steps:

1. Students in the experimental group and the control group take the Differential Aptitude Test: Space Relations (DAT:SR) and Purdue Spatial Visualization Test: Rotations (PSVT:R) prior to the activities. They also take the survey on controlled variables that can affect SA (1 h).
2. The students individually complete the exercises with the 3D modeling software SolidWorks (10 h). For example, drawing polyhedral shapes considering angles, distances and other geometrical relations between edges and faces.
3. The VR activities consist of the guided reading by the professor of the completed exercise. The professor addresses the concepts of solid geometry used in each step. The students have a few minutes to view the animation showing the construction of the geometric shape, and once the representation is finished, they can move freely throughout the scenario, using the keyboard options (6 h) (Figure 2).
4. Students in the experimental group and the control group take the Differential Aptitude Test: Space Relations (DAT:SR) and Purdue Spatial Visualization Test: Rotations (PSVT:R) after the VR activities. At the end, the groups that have worked in the VR also take the satisfaction survey (1 h). Control and experimental groups were formed randomly from all students enrolled in the course. We usually formed this division when new activities or methodologies are introduced in the course. In some cases, that is not possible because of the need to offer the same learning pursuits to all students without discrimination. In this case, both groups had similar results.
5. All the students are assessed on their knowledge of the solid geometry contents by means of a test and 3D modeling exercises similar to those done in class.
6. Finally, the analysis of the SA test data, the controlled variable surveys and satisfaction surveys and the academic results obtained in the solid geometry module enable us to examine the correlations and the strongest determining factors in order to obtain good academic results and propose VR activities to improve the levels of SA obtained on the tests.

Figure 2. VR sessions.

6. RESULTS

The results of this study are exploratory in nature by the small size of the sample and cannot be generalized to the population as a whole. Because of that, we do not discus here values when comparing experimental and control groups' results. The same can be said about the data collected from other variables.

We urge further work analyzing the influence of other factors on the increase in SA, such as: gender, prior experience with this type of programs, play sports or faculty of engineering.

With this in mind, we would like to highlight the following findings in the experimental group:

Those students with less spatial ability as measured by a PSVT:R (Table 1) or DAT:SR pre-test (Table 2) are those who show the greatest degree of improvement on the post-tests after having completed the VR activities.

pre-test PSVT (Results)	Degree of improvement (Average)
1st set (0-15)	14,3
2nd set (16-20)	2,2
3rd set (>21)	1,02

Table 1. PSVT results vs degree of improvement.

pre-test DAT (Results)	Degree of improvement (Average)
1st set (0-30)	12,4
2nd set (31-50)	4,9
3rd set (>50)	0,6

Table 2. DAT results vs degree of improvement.

The greatest correlation (R=0.323) was found between the PSVT:R pre-test and the solid geometry exam (Test and 3D modeling exercises (Table 3).

These results corroborate those obtained by [SB00] at Michigan Technological University (MTU) with regard to the interest in using PSVT:R as a predictor of academic results.

Model	R	R Square	Adjusted R	Std. Error
1	,323	,104	,085	2,35307

Table 3. Correlation PSVT:R pre-test vs. solid geometry exam

The experimental group and the control group showed no significant differences.

The evaluation by the students of the incorporation of VR/HMD activities is positive (Table 4). They have the perception that the system is easy to use, enables them to better understand the contents presented and they consider it to be useful. Therefore, in agreement with the findings of [LL12], the use of VR motivates students during their learning process.

The immersion system is easy to use
Strongly disagree 0%
Disagree 0%
Neither agree nor disagree 26%
Agree 63%
Strongly agree 11%
The content provided is easy to understand
Strongly disagree 0%
Disagree 11%
Neither agree nor disagree 58%
Agree 32%
Strongly agree 11%
Immersion system provides useful content
Strongly disagree 0%
Disagree 0%
Neither agree nor disagree 16%
Agree 47%
Strongly agree 37%

Table 4. Satisfaction survey results

7. LIMITATIONS & FUTURE WORKS

Some results obtained from the data analysis are indecisive in terms of the correlation between the VR activities carried out and the improvement in spatial abilities. The activity also failed to have an impact on academic results.

In our opinion, this may be caused by several factors:

1. The small size of the experimental (60) and control (30) groups.
2. The short duration of the VR/HMD activity, which consisted of only two sessions of three hours each. In previous studies, we obtained important increases (8 points) in scores on the Differential Aptitude Test: Spatial Relations Subset (DAT:SR) after holding numerous 3D solid modeling sessions (15 h).
3. The impact of other variables on the learning process, the definition and influence of which should be analyzed in future works.

In any case, the results obtained confirm the interest in using VR to develop SA in engineering students. In future studies, we intend to expand the size of the sample and the diversity of the populations analyzed, in order to make the results more generalizable. In this regard, work is underway to incorporate conventional mobile devices, which when fastened to a simple support structure similar to a pair of glasses and connected to a control device (numeric keypad or joystick) would make it possible to extend the experience to a large number of students at several colleges.

The basic assertion that we would like to test in future work is that students who use the VR show a significant improvement in spatial abilities as compared to those who do not use it.

Another concept related to VR is augmented reality (AR), which uses a combination of the user's physical environment and real-time interactive computer representations [ADD+01], [Bon01], [WTA11].

VR immerses the user in a digital 3D environment where he/she cannot see the real world. Just the opposite, AR enables the user to see the real world, with some virtual objects superimposed on it. AR thus complements reality instead of completely replacing it. Virtual and real objects are perceived in the same space. AR is currently being applied in education and training with good results [GGW+13], [Lee12], [WLC13], [AAP+12].

Both VR and AR environments could be applied to our study, although ultimately the decision was made to use an immersive VR environment due to the abstract nature of the solid geometry course content being taught. One proposal for future work could be to incorporate geometry topics that combine both real and synthetic images. This could be extremely useful for design validation in engineering design courses.

Other additions for future works could be:

The use of Mental Cutting Test (MCT) and the study of its effectiveness in order to improve the model as a predictor of learning outcomes.

The use of 3D tests. Some cases already exist in which immersive 3D tests have been applied, such as the

Virtual Reality Spatial Rotation (VRSR) system [RBN+98], which make it possible to administer the Mental Rotation Test (MRT) [SM71] directly in 3D, providing improvements over the administration of the paper-and-pencil MRT following VRSR training.

Geometric immersive 3D graphic design software could also be added. [DKSG06] use drawing software that makes it possible to generate 3D models, move around them and modify them in real time. Visualization relies on HMD glasses.

Within the plans for continuing this study is the incorporation of some of these facilities in the near future.

8. CONCLUSIONS

A pilot study was developed using immersive VR to study solid geometry in a 1st term course of engineering. The activities proposed for all students were 3D modeling exercises in Solidworks, and the experimental group completed three activities (6 h) in VR, HMD glasses.

A methodology was applied to assess SA in engineering students previously developed by our research group at Barcelona Tech (Universitat Politècnica de Catalunya). We have incorporated a new evaluation tool in this study: Purdue Spatial Visualization Test: Rotations (PSVT:R). This test appears to be a good indicator of academic success.

Spatial abilities are assessed before and after the classroom activities using the Differential Aptitude Test: Spatial Relations Subset (DAT:SR) and the Purdue Spatial Visualization Test: Rotations (PSVT:R). Despite the fact that all students have improved their results, the greatest degree of improvement on the post-tests was achieved by the students with less initial spatial ability.

The greatest correlation was found between the PSVT:R pre-test and the solid geometry exam (test and 3D modeling exercises). These results corroborate previous studies using PSVT:R as a predictor of academic results.

The evaluation by the students of the incorporation of VR/HMD activities is positive. After the experience, we strong recommend the use of VR in order to improve spatial abilities of engineering, particularly those students showing difficulties in spatial visualization.

9. REFERENCES

[AAH+11] Amin Nur Yunus, F.; Abd Baser, J.; Hadi Masran, S.; Razali, N.; and Rahi, B. (2011). Virtual Reality Simulator Developed Welding Technology Skills. Journal of Modern Education Review, ISSN 2155-7993, USA, Volume 1, No. 1, pp. 57-62

[AAP+12] Aziz, N. A. A.; Aziz, K. A.; Paul, A.; Yusof, A. M.; and Noor, N. S. M. (2012, February). Providing augmented reality based education for students with attention deficit hyperactive disorder via cloud computing: Its advantages. In Advanced Communication Technology (ICACT), 2012. 14th International Conference on Advanced Comunication Technology (pp. 577-581). IEEE

[ADD+01] Azuma, R.; Baillot, Y. R.; Behringer; Feiner, S.; Julier, S.; and MacIntyre, B. (2001). Recent advances in augmented reality. Computer Graphics and Applications, IEEE, vol. 21, pp. 34-47

[Bon01] Bonsor, K. (2001). How Augmented Reality Will Work. http://howstuffworks.com/augmented-reality.htm

[Bor16] Borsci, S. et al (2016). Effectiveness of a multidevice 3D virtual environment application to train car service maintenance procedures. Doi: 10.1007/s10055-015-0281-5

[BSW73] Bennett, G. K.; Seashore, H. G.; and Wesman, A. G. Differential Aptitude Tests, Forms S and T. The Psychological Corporation, New York, 1973

[Cee39] CEEB College Entrance Examination Board. Special. Aptitude Test in Spatial Relations MCT. CEEB, 1939

[CG98] Coleman, S. and Gotch, A. (1998). Spatial perception skills of chemistry students. Journal of Chemical Education, 75, 206-209

[CTN15] Carlisle, D.; Tyson, J. F.; and Nieswandt, M. (2015). Fostering spatial skill acquisition by general chemistry students. Chemistry Education Research and Practice

[DKSG06] Dünser, A.; Kaufmann, H.; Steinbügl, K.; and Glück, J. (2006). Virtual and Augmented Reality as Spatial Ability Training Tools. 7th ACM SIGCHI New Zealand chapter's international conference on Computer-Human Interaction. Pages 125-132

[Eli02] Eliot, J. (2002). About spatial intelligence: I. Perceptual and Motor Skills, 94, 2, 479-486

[GGW+13] Gavish, N.; Gutiérrez, T.; Webel, S.; Rodríguez, J.; Peveri, M.; Bockholt, U.; and Tecchia, F. (2013). Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. Interactive Learning Environments (ahead-of-print), 1-21. DOI: 10.1080/10494820.2013.815221

[Gua77] Guay, R. B. (1977). Purdue spatial visualization test: rotations. West Lafayette, IN. Purdue Research Foundation

[Hel92] Helsel, S. (1992). Virtual Reality and Education, Educational Technology, 32(5), pp. 38-42

[HLXB15] Hawes, Z.; LeFevre, J. A.; Xu, C.; and Bruce, C. D. (2015). Mental Rotation With Tangible Three-Dimensional Objects: A New Measure Sensitive to Developmental Differences in 4-to 8-Year-Old Children. Mind, Brain, and Education, 9(1), 10-18

[HT11] Harle, M. and Towns, M. (2011). A review of spatial ability literature, its connection to chemistry, and implications for instruction. Journal of Chemical Education, 88, 351-360. DOI: 10.1021/ed900003n

[Jav99] Javidi, G. (1999). Virtual reality and education, Master Thesis, University of South Florida

[KJJ14] Katsioloudis, P.; Jovanovic, V.; and Jones, M. (2014). A Comparative Analysis of Spatial Visualization Ability and Drafting Models for Industrial and Technology Education Students

[LA94] Loeffler, C. E. and Anderson, T. (eds.) (1994). The Virtual Reality Casebook, New York:Van Nostrand Reinhold

[Lee12] Lee, K. (2012). Augmented reality in education and training. TechTrends, 56(2), 13-21

[LK83] Lohman, D. F. and Kyllonen, P. C. (1983). Individual differences in solution strategy on spatial tasks. Individual differences in cognition. Dillon, D. F. and Schmeck, R. R. (eds.). Academic Press: New York, 105-135

[LL12] Lau, K. W. and Lee, P. Y. (2012). The use of virtual reality for creating unusual environmental stimulation to motivate students to explore creative ideas. Interactive Learning Environments (ahead-of-print), 1-16. DOI: 10.1080/10494820.2012.745426

[LZXL05] Li, L., Zhang, M., Xu, F., Liu, S.(2005). Ert-vr: an immersive virtual reality system for emergency rescue training. Virtual Real. 8(3), 194–197

[MB05] Miller, C. L. and Bertoline, G. R. (2005). Spatial Abilities and Virtual Technologies: Examining the Computer Graphics Learning Environment, iv, pp. 992-997, Ninth International Conference on Information Visualisation (IV '05)

[MG13] Marunic, G. and Glazar, V. (2013). Spatial ability through engineering graphics education. International Journal of Technology and Design Education, 23(3), 703-715

[MGK+13] Merchant, Z.; Goetz, E. T.; Keeney-Kennicutt, W.; Cifuentes, L.; Kwok, O.; and Davis, T. J. (2013). Exploring 3-D virtual reality technology for spatial ability and chemistry achievement. Journal of Computer Assisted Learning, 29, 579-590, John Wiley & Sons Ltd

[MGS98] Medina, A. C.; Gerson, H. B. P.; and Sorby, S. A. (1998). Identifying gender differences in the 3-D visualization skills of engineering students in Brazil and in the United States. Proceedings of the International Conference for Engineering Education 1998, Rio de Janeiro, Brazil

[Moh08] Mohler, J. L. (2008). A review of spatial ability research. Engineering Design Graphics Journal, 72, 19-30

[MSB+11] Metz, S. S.; Sorby, S. A.; Berry, T. S.; Seepersad, C. C.; Dison, A. M.; Allam, Y. S.; and Leach, J. A. (2011). Implementing ENGAGE Strategies to Improve Retention: Focus on Spatial Skills Engineering Schools Discuss Successes and Challenges. American Society for Engineering Education

[MY13] 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.

[NGA+13] Nagendran, M., Gurusamy, K. S., Aggarwal, R., Loizidou, M., & Davidson, B. R. (2013). Virtual reality training for surgical trainees in laparoscopic surgery. Cochrane Database Syst Rev, 8.

[OSR+02] Oman, C.; Shebilske, W. L.; Richards, J. T.; Tubré, T. C.; Beall, A. C.; and Natapoff, A (2002). Three Dimensional Spatial Memory and Learning in Real and Virtual Environments. Spatial Cognition and Computation, 2, 355-372

[PH91] Pellegrino, J. and Hunt, E. (1991). Cognitive models for understanding and assessing spatial abilities. In Rowe, H. (ed.), Intelligence: Reconceptualisation and measurement (pp. 203-225). Melbourne: ACER and Hillsdale, NJ: Lawrence Erlbaum Associates

[PK82] Pellegrino, J. W. and Kail, R. (1982). Process analyses of spatial aptitude. In Sternberg, R. (ed.), Advances in the psychology of human intelligence (vol. 1, pp. 311-366). Hillsdale, NJ: Erlbaum

[PRL+02] Piburn, M.; Reynolds, S.; Leedy, D.; McAuliffe, C.; Birk, J.; and Johnson, J. (2002). The hidden earth: Visualization of geologic features and their subsurface geometry. Paper presented at the National Association for Research in Science Teaching (NARST) annual meetings, April 7-10,2002, New Orleans, Louisiana

[Pso95] Psotka, J. (1995). Immersive Tutoring Systems: Virtual Reality and Education and

Training. Instructional Science 23, pp. 405-431, 1995

[PV10] Pantelidis, Veronica S. (2010). Reasons to Use Virtual Reality in Educationand Training Courses and a Model to Determine When to Use Virtual Reality. Themes in Science and Technology Education. Special Issue, pages 59-70. Klidarithmos Computer Books

[RBN+98] Rizzo, A. A.; Buckwalter, J. G.; Neumann, U.; Kesselman, C.; Thiebaux, M.; Larson, P.; and Van Rooyen, A. (1998). The Virtual Reality Mental Rotation Spatial Skills Project. CyberPsychology and Behavior, 1, 2, 113-120

[RG00] Robichaux, R. R. and Guarino, A. J. (2000). Predictors of visualization: A structural equation model. Annual Meeting of the Mid-South Educational Research Association, Bowling Green, KY

[SB00] Sorby, S. A. and 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

[SK03] Schnabel, M. A. and Kvan, T. (2003). Spatial understanding in immersive virtual environments. International Journal of Architectural Computing, 1, 4, 435-448

[SM71] Shepard, R. N. and Metzler, J. (1971). Mental rotation of three dimensional objects. Science, 171, 972, 701-3

[SS01] Strong, S. and Smith, R. (2001). Spatial visualization: fundamentals and trends in engineering graphics. Journal of Industrial Technology, vol. 18, No. 1

[TAB14] Torner, J.; Alpiste, F.; Brigos, M. (2014) Spatial ability in computer-aided design courses. Computer-aided design and Applications. Vol. 12, num. 1, p. 1-9 DOI: 10.1080/16864360.2014.949572

[UMT+13] Uttal, D. H.; Meadow, N. G.; Tipton, E.; Hand, L. L.; Alden, A. R.; Warren, C.; and Newcombe, N. S. (2013). The malleability of spatial skills: a meta-analysis of training studies. Psychological bulletin, 139(2), 352

[VK78] Vanderberg, S. G. and Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. Perceptual and motor skills. Volume 47, issue , pp. 599-604. DOI: 10.2466/pms.1978.47.2.599

[WHH+97] Winn, W.; Hoffman, H.; Hollander, A.; Osberg, K.; Rose, H.; and Char, P. (1997). The Effect of Student Construction of Virtual Environments on the Performance of High- and Low-Ability Students. Human Interface Technology Laboratory. http://www.hitl.washington.edu/publications/r-97-6/

[Win93] Winn, W. (1993). A conceptual basis for educational applications of virtual reality. HITL Laboratory. http://www.hitl.washington.edu/publications/r-93-9

[WLC13] Wu, H. K.; Lee, S. W. Y.; Chang, H. Y.; and Liang, J. C. (2013). Current status, opportunities and challenges of augmented reality in education. Computers & Education, 62, 41-49

[WM98] Waller, D. and Miller, J. A. Desktop virtual environment trainer provides superior retention of a spatial assembly skill. Poster presented at ACM SIGCHI '98, Los Angeles, CA

[WTA11] Wither, J.; Tsai, Y. T.; and Azuma, R. (2011). Indirect augmented reality. Computers & Graphics, 35(4), 810-822