EXPLORING VIRTUAL REALITY TO IMPROVE ENGINEERING STUDENTS' SPATIAL ABILITIES. PILOT STUDY

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Abstract

A Virtual Reality pilot study is conducted to improve the spatial ability of engineering students based on solid geometry scenarios.

A total of 20 participants completed three activities (6 h) in an immersive virtual learning environment (IVLE), using head-mounted display (HMD) glasses.

Modeling exercises of three-dimensional geometric shapes are proposed, based on concepts of solid geometry.

The scenarios are built step by step and the students can regulate the progress between stages while observing the geometric components at the scale and in the point of view they wish.

Interaction takes place through the keyboard and visualization through an HMD headset. The transitions between different states are created by means of animations that progressively build the elements by following the instructions for the exercise.

Beyond academic results, the assessment of student improvement is based on spatial abilities tests: the Differential Aptitude Test: Spatial Relations Subset DAT-SR, Purdue Spatial Visualisation Test: Rotations PSVT:R and Mental Cutting Test MCT. Those tests are applied for evaluating different skills: mental folding, mental rotation and section by a plane. The results obtained confirm the interest in using IVLE to develop spatial abilities in engineering students. Substantial increases of 10,9% in DAT:SR, 8,8 % in PSVT:R and 9,5% in MCT between pre- and post-tests were found. Moreover, the students' opinion of IVLE/HMD activities is positive.

This work forms part of the investigation that the LAM-UPC, Barcelona TECH group has been conducting with the aim of enhancing the development of the spatial ability of engineering students.

In summary, a methodology is proposed developing activities in an (IVLE) with 3D modelling software applied in solid geometry, in order to promote the development of spatial abilities (SA). Spatial abilities are measured before and after the classroom activities and looking for correlations between the spatial perception tests (DAT:SR, PSVT:R and MCT) and academic results in solid geometry.

This paper describes the exploratory methodology used.

Keywords: Spatial ability (SA), virtual reality (VR), assessment of student learning, teaching engineering, head-mounted display (HMD), solid geometry.

1 INTRODUCTION

The evaluation of students' skills and the didactic methodologies for improving them are constant concerns of University Engineering Departments. In particular, the LAM-UPC, Barcelona TECH research group pursues a research line on spatial ability and the teaching of "Graphic Expression and Computer-Aided design" [1] .

The importance of spatial ability (SA) in engineering design processes has been analyzed in many studies in which methodologies have been proposed for improving SA competence in students [2-13]. In general, all these studies use systems for measuring SA as well as analyzing contextual variables, competence and academic results to look for correlations that underpin methodologies for the development of SA.

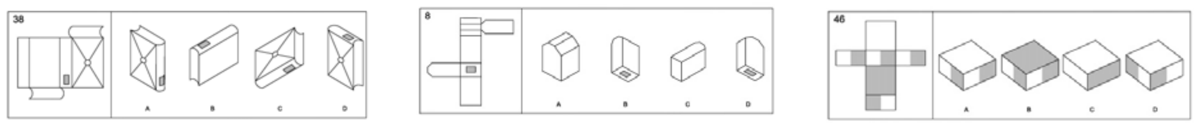
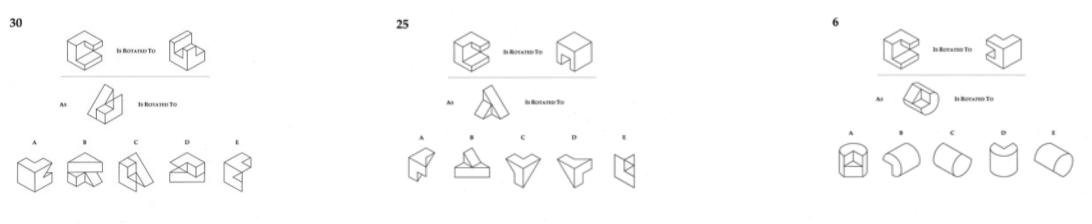
The concept of SA is split into multiple sub-factors and it is difficult to find a definition that may be unanimously accepted by the whole scientific community. However, we find two basic components of SA competence that are commonly accepted:

- *Spatial vision*: the ability to manipulate an object in an imaginary 3D space in order to create representations of the object from different points of view.
- *Spatial Orientation*: the ability to navigate through our surroundings and predict the movement and position of objects.

At present, various tests exist that enable us to focus on the different components of this skill [3]. The most commonly employed tests for measuring spatial vision are as follows:

- *DAT-SR, Differential Aptitude Test–Spatial Relations Subset* Mental folding. This consists in relating a three-dimensional shapes with the image of their development in 2D [14]..
- *MRT, Mental Rotation Test*. Mental rotation. Here it is necessary to identify 3D shapes as rotated representations of an object [15].
- *PSVT:R, Purdue Spatial Visualization Test*. Mental Rotation. Two images of the same solid are shown both before and after rotation. This consists in applying the same rotation to another given solid and selecting the resulting image [16-17].
- *MCT. Mental Cutting Test*. Given a figure intersected by a plane, it is necessary to determine the result of the section [18]. Table 1 shows test item examples.

Table 1: Test Item Examples

DAT-SR

PSVT:R

MCT


1.1 Virtual reality applied in spatial Ability

There are many precedents for the use of VR in learning and, in particular, in the improvement of spatial skills in engineering design [19],[20].

VR uses hardware and software to create a sensation of navigation, manipulation and immersion [21]. VR can be divided into three categories: text-based, desktop and immersive VR.

Text-based networked VR is based in text communication. This type of VR has commonly been used in education and training [22].

Desktop VR is an 3D images environment but without being considered immersive. [23]. The applications developed here are immersive VR. It consists of a combination of hardware, software and interaction that enable the user to be immersed in a computer-generated three-dimensional world [24].

VR can provide an effective resource to improve some skills. For instance, it is applied in simulators to train sensory motor skills [25]. VR is widely used in rehabilitation and surgical training [26].

Some interesting applications are those that enable students to visualize abstract concepts, such as chemical bonds and other chemistry-related contents [27],[28] or those that enable them to interact with objects that are otherwise unavailable due to distance, time or safety constraints [29],[30],[31],[32]. Other field of application is the training in maintenance and industrial manufacturing [33],[34],[35].

There are different ways in which VR technology can aid learning. W. Winn [36] and V.S. Pandelidis [37] identified the main contributions of VR as interaction or participation, immersion, and motivation.

Finally, some researchers are focused to improve spatial abilities in first engineering courses using virtual technologies: augmented reality and virtual reality. Many interesting VR contributions are related to computer graphics learning environments [38], immersive 3D VR HDM in spatial volumes [39], engineering graphics [40],[41] and virtual technologies to develop visual-spatial memory [42], [43], rotation capacity [44], orientation [45], open environments [46] ,virtual navigation [47], and visual-spatial ability by and large [48].
In summary, VR is used widely in learning processes. Moreover, VR boosted significant improvements in SA training.

1.2 Head-mounted display (HMD)

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.

Technical characteristics of Oculus Rift:

Display	
Resolution	960 x 1080 per eye
Refresh Rate	75 Hz, 72 Hz, 60 Hz
Persistence	2 ms, 3 ms, full
Viewing Optics	100° Field of View (nominal)
Internal Tracking	
Sensors	Gyroscope, Accelerometer, Magnetometer
Update Rate	1000 Hz
Positional Tracking	
Sensors	Near Infrared CMOS Sensor
Update Rate	60 Hz

1.3 Development software for Oculus Rift

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 animation was created using Unity's Legacy tool.

2 METHODOLOGY

In a previous study [1], participating 812 freshman students of Industrial Engineering at the Universitat Politècnica de Catalunya, Barcelona TECH, we obtained the correlation between the SA values and the academic results from the thematic blocks (3D modeling with 2D drawings (20h) and solid geometry (15h).

There was a clear relationship between the initial DAT-PRE and the test that assesses students' knowledge of solid geometry. Therefore, we propose to harness the potential of these activities with solid geometry in order to maximize the development of SA. It is for this reason that VR exercises in spatial geometry were proposed.

The VR scenarios are built step by step and the students can regulate the progress between stages while observing the geometric components at the scale and in the point of view they wish. The activities consisted of creating applications to model three-dimensional geometric shapes, introducing the concepts of geometry progressively. 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 animations that progressively build the elements by following the instructions for the exercise.

The notation and iconography used in the reference software (Solid Works) has been included to aid comprehension (Figure 1).

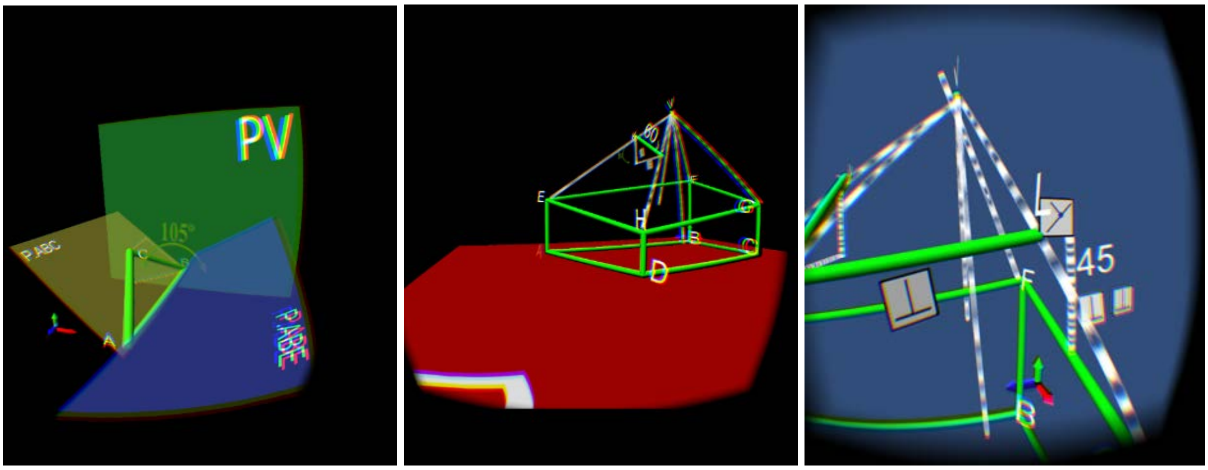


Figure 1. Screenshot from exercises. Annotations and symbols

The methodology can be summarized in the following steps:

1. Students take the DAT:SR, PSVT:R and MCT prior to the activities (pre). They also take the survey on controlled variables that can affect SA (1.15 h).
2. The students individually complete the exercises with the 3D modeling software Solid Works (10 h).
3. The IVLE 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 3.
4. Students take the (DAT:SR, PSVT:R and MCT after the IVLE activities (pos). At the end, the groups that have worked in the IVLE also take the satisfaction survey (1.15 h).
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 and those described in the IVRL.
6. Finally, the analysis of the spatial abilities test data, controlled variable surveys, 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 IVLE activities to improve the levels of spatial ability obtained on the tests.

Figure 3. IVLE sessions. HMD

3 RESULTS

3.1 Improvement of spatial skills

Table 2 shows the means and standard deviations of the tests performed. The course start (pre), the course end (pos) and the improvements obtained (post-pre). The pre- and post-tests are useful for demonstrating progress in learning and for perfecting teaching approaches, thereby addressing the identified erroneous concepts and applying new and/or different didactic strategies [10],[49],[50].

The maximum scores are different in each test: DAT-SR = 60, PSVT: R = 30 and MCT = 25. To be able to compare the results, in this case scores are shown in percentages of hits over 100. The scores improved an average of 10.9% on the total score in DAT-SR, 8.8% in PSVT: R, and 9.5% in MCT. The significance of the gains was checked with the T test for related samples and Wilcoxon ($p < 0.01$).

Table 2. Average scores (%) Pre, Pos, Gain and Standard deviation (SD) in DAT-SR, PSVT-R and MCT.

Average scores (%) (SD)								
DAT-SR			PSVT-R			MCT		
Pre	Pos	Gain	Pre	Pos	Gain	Pre	Pos	Gain
73,1 (15,9)	83,0 (13,6)	10,9 (10,0)	75,1 (16,0)	84,8 (11,1)	8,8 (11,1)	61,0 (17,8)	67,6 (19,4)	9,5 (11,6)

67% of students improved in MCT. In the DAT test, the percentage was higher (87%). However, if the number of students who improved more than a 10% score is considered,

the percentage is very similar in DAT and MCT (44.9 and 43.9% respectively) and is reduced in PSVT: R at 29.6%.

The improvements after studying Graphic Expression are very similar to those described by Torner (2009) [1] and Contero *et al.* (2006) [51] in the DAT-SR test; similar to those of Mataix (2014) [52], superior to Connolly (2009) [53] in PSVT: R and similar to Leopold *et al.* (2001) [2] in MCT.

3.2 Correlations between marks and SA tests

One of the objectives of this work is to determine if the spatial skills tests, DAT-SR, PSVT: R and MCT can predict the academic result in the different thematic blocks of the Graphic Expression subject. The results allow detecting students with poor spatial skills and allow proposing didactic activities to improve them.

Students with DAT-SR pre-test scores fewer than 40, PSVT-Pre under 20 or MCT-Pre under 16 were provided with complementary leveling activities.

The subject Graphic Expression is imparted with the 3D modeling software "Solid Works" and includes the following thematic blocks: 3D modeling with 2D drawings (20h) and Solid Geometry (15h). The two modules are evaluated with the DAO 1 and DAO 2 tests.

The DAT-SR pre-test is the best one correlated (Pearson) to the DAO 1 and 3D modeling with 2D drawings ($r = 0.36$, $p < 0.001$). If only 3D modeling is evaluated (without 2D drawings), DAT-SR and MCT have very similar correlations: DAT-SR-Pre ($r = 0.43$, $p < 0.001$) and MCT-Pre ($r = 0.41$, $p < 0.001$). In Solid Geometry (DAO 2, test), the highest correlation is obtained with MCT-Pre ($r = 0.36$, $p < 0.001$).

The SA test best related to the final grade of the subject is MCT-Pos ($r = 0.46$, $p < 0.001$). It suggests that skills required in Graphic Expression are more related to the ability to mentally cut a solid by a plane than with mental folding or mental rotation.

Positive correlations of the academic results with MCT have also been observed in other studies [50],[2],[54].

3.3 Satisfaction survey results

The students' opinion with regard to the proposed activities are positive. They have the perception that the system is easy to use, enable them to better understand the contents presented and they consider it to be useful. Therefore, in agreement with the findings of Lau, K. *et al.* [55], the use of VR motivates students during their learning process.

Table.3. Satisfaction survey results

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%

4 CONCLUSIONS

After including VR, Interesting results were obtained: substantial increases of 10,9% in DAT, 8,8 % in PSVT:R and 9,5% in MCT pre and post-tests . We obtained the correlation between the SA values and the academic results from the thematic blocks (3D modeling with 2D drawings (20h) and Solid Geometry (15h). The greatest correlation occurred between the DAT pre-test and the MCT pre-test and the assessment of solid geometry. MCT seems to be a good indicator of success in the module since it shows the highest amount of correlations.

The students' opinion of IVLE/HMD activities is positive and its use motivates students during their learning process.

Future works could introduce: 3D tests, Geometric immersive 3D graphic design software and Augmented Reality (AR).

3D tests could be used. Currently the tests are presented in forms (Google Drive template) incorporating 2D images, taken from the test paper [56]. Some cases already exist in which immersive 3D tests have been applied, such as the Virtual Reality Spatial Rotation (VRSR) system (Rizzo, A. A. *et al.*, 1998) [57], which make it possible to administer the Mental Rotation Test (MRT) directly in 3D, providing improvements over the administration of the paper-and-pencil MRT.

Geometric immersive 3D graphic design software could also be added. Dünser, A. *et al.* (2006) [58] 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.

Augmented reality (AR) uses a combination of the user's physical environment and real-time interactive computer representations. 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 [59-63].

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

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