

# 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<sup>+</sup>13].

Evidence exists [Bor16], [AAH<sup>+</sup>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 or 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).

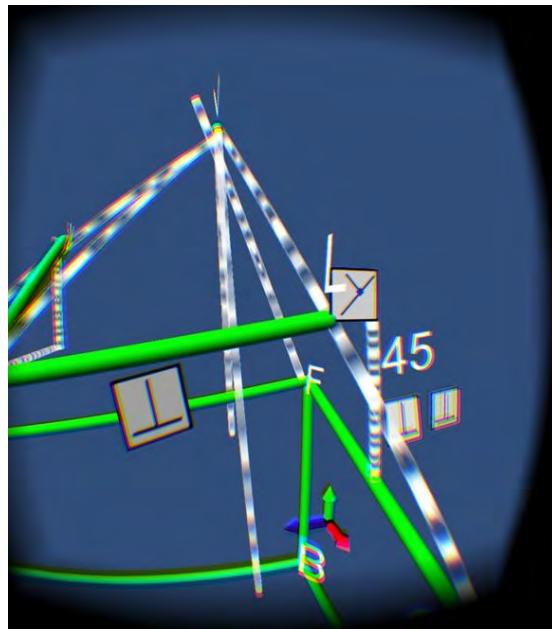


Figure 1. Screenshots from VR exercises.

#### 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  $\theta$ , the angle between this straight line and the line perpendicular to the plane is complementary to  $\theta$ :  $(90-\theta)$ .
- If a straight line has a slope of  $X\%$ , this means that it has an angle with the horizontal plane of  $\theta = \text{arctg}(X/100)$ .