Development of a Fast Remedial Course to Improve the Spatial Abilities of Engineering Students

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ABSTRACT

This paper presents the results of a pilot study designed to evaluate the feasibility of launching a fast remedial course based on 3D CAD modeling for improving spatial abilities of engineering students. The study was carried out with civil engineering students at the University of La Laguna (Spain) during the 2006–2007 academic year. The main requirements in the design of the course were: short and intensive (12 hours worth of work during 3 weeks), attractive for the students, and use of free 3D CAD modeling software. The chosen software was Google SketchUp. Exercises based on practice with this modeling tool had a measurable and positive impact on students' spatial ability, measured by both MRT and DAT:SR tests. The results are then compared to our previous studies at La Laguna University based on classic pencil and paper exercises, multimedia Web-based applications, and exercises using a sketch-based modeling application.

Keywords: 3D modeling, differential aptitude test, spatial visualization

I. INTRODUCTION

A recent survey performed by the Engineering Design Graphics Division of the American Society for Engineering Education concluded that the "ability to create 3-D solid computer models" and the "ability to sketch engineering objects in the freehand mode" were the two most important graphical communication outcomes for engineering students (Barr, 2004). Several authors have concluded that these skills also are related to spatial ones (Devon et al., 1994; Alias, Black, and Gray, 2002a; Company et al., 2004; Contero et al., 2005). Furthermore, it has also been verified by other authors that the development of spatial skills by engineering students is directly linked to future success in their professional work (McGee, 1979; Hsi, Linn, and Bell, 1997; Miller, 1996; Smith, 2002).

Traditionally, any engineering curriculum at European universities has included engineering design graphics subjects in which, during at least one academic year, students received basic training in systems of representation, sketching, technical drawing, and CAD. However, in this context, development of spatial abilities has not been an explicit learning objective, and the development of spatial abilities has been considered an indirect learning outcome.

Currently, at least in Spain, there is a tendency towards the progressive reduction of teaching hours dedicated to subjects related to engineering design graphics. This in turn is leading to a reduction in theoretical and practical contents, and the presentation of some topics in a very condensed form. This situation may generate problems in the process in which students develop their spatial skills. Moreover, the European Space for Higher Education (ESHE) (The Bologna Process, 1999) has recently established a new teaching framework which centers on learning, the active role of students, and the importance of acquiring skills which develop one's capacity for lifelong learning.

Teachers involved in pilot projects aimed at reformulating the new curriculum for engineering degrees have encountered a number of problems, which despite being found in Spain, may also perhaps be shared by other countries:

- A growing heterogeneity in students' backgrounds prior to attending university. There is a tendency towards enabling a greater degree of flexibility so as to permit students to configure their own curriculum at the high school level. This means that many students arrive at university without the required background in engineering graphics, thus making it difficult to establish an appropriate teaching strategy.
- Due to time constraints, there is enormous pressure regarding the selection of content that makes up the introductory engineering graphics subjects in undergraduate engineering programs. The use of CAD technologies in industry renders both some traditional contents related to Descriptive Geometry and the study of some classical geometric constructions obsolete, since computer applications now perform such tasks automatically. In many cases, however, content renewal is seen as a threat by certain sections of the academic community.
- Skills and attitudes become important learning outcomes in the ESHE context, but the traditional teaching approach is basically oriented towards knowledge transfer. Some authors agree (Jenison, 1997; Jerz, 2002) that engineering graphics

subjects should embrace topics such as standardized technical drawing, basic training in a 3D computer aided design tool, sketching, design principles, and spatial abilities.

In this context, one of the topics which we believe is of special importance and interest is the development of spatial abilities. A new formulation of the curriculum has made the development of these abilities an important learning outcome. However, many doubts have arisen in the academic community working in the field of engineering design graphics regarding its acquisition, its relationship with the classical contents of the discipline, and its measurability.

In the following sections, the structure of a fast remedial course for developing spatial abilities will be analyzed. First, a summary about the available strategies to improve these abilities and the related measuring tests is presented. Then the pilot study and the remedial course are described, and the results of a statistical analysis is presented. The final section presents the conclusions gained from this experience and proposing some future work.

II. Improving Spatial Abilities

Numerous studies have indicated that spatial abilities can be improved through training. Ben-Cham et al. (1988) and Alias, Black and Gray (2002b) found tactile manipulative tasks using cubes to construct buildings and other objects effective in this sense. Traditional graphics courses (sketching activities, orthographic projection, isometric drawing) were also found to validate the strategies of Dejong (1977), Lord (1985), Sorby (1999) and Alias, Gray and Black (2002b). Wiley (1990) concluded that 3D solid models and animation may help develop visual perception abilities. Leach (1992) contended that solid modeling brings a new capacity to engineering graphics education, which enhances the capability of spatial ability advancement. Miller (1990) concluded that instruction with real and computer models allowed students to further advance their spatial abilities as compared to traditional engineering graphics instruction. Devon et al. (1994) demonstrated that using solid modeling increased the students' visualization scores over using 2D CAD. Other researchers (Duesbury and O'Neil, 1996; Sorby, 1999) conclude that experiencing the opportunity to manipulate an object image actively on a computer screen is sufficient to improve spatial ability. Ault (2003) points out that it is "assumed by many that the use of solid modeling will enhance students' visualization skills" and other studies suggest that there could be a relationship between an individual's spatial ability and their ability to use solid modeling software (Yue and Chen, 2001; Alias, Black, and Gray, 2002b).

III. Measuring Spatial Abilities

The first problem that arises when measuring these abilities is the definition of "spatial ability" itself. Analyzing the literature, we see that a number of different approaches and definitions have been proposed. There are also different tests aimed at obtaining quantitative results in the measurement of these abilities. One of the most cited classification systems was designed by Linn and Petersen (1985), and proposes three categories:

- *Spatial Perception:* the ability to determine spatial relationships with respect to the orientation of one's own body, in spite of distracting information.

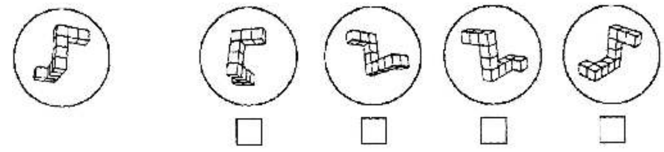

Figure 1. Example of MRT test question.

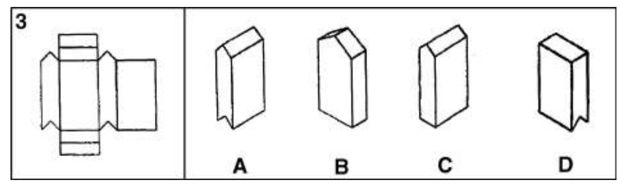

Figure 2. Example of DAT:SR test question.

- *Spatial Visualization:* the ability to manipulate complex spatial information when several stages are needed to produce the correct solution.
- *Mental Rotation:* the ability to rotate, in imagination, quickly and accurately two- or three-dimensional figures.

Other authors (McGee, 1979; Burnet and Lane, 1980; Pellegrino, Alderton, and Shute, 1984; Clements and Batista, 1992; Olkun, 2003) simplify this classification by limiting it to only two categories:

- *Spatial relations:* the ability to imagine rotations of 2D and 3D objects as a whole body (this includes mental rotation and spatial perception).
- *Spatial Visualization:* the ability to imagine rotations of objects or their parts in 3-D spatial by folding and unfolding.

Using this latter classification, we chose two tests, each corresponding to one of the main categories outlined above, to enable us to quantify the values of the spatial ability:

- Mental Rotation Test (MRT) (Albaret and Aubert, 1996) for spatial relations. A sample problem from the MRT is shown in Figure 1.
- Differential Aptitude Test—Spatial Relations Subset (DAT:SR) (Bennett, Seashore, and Wesman, 2002) for spatial visualization. A sample problem from the DAT:SR is shown in Figure 2.

This way, we will be able to compare our results with those of other experiences carried out within the context of engineering education (Devon et al., 1994; Sorby, 1999; Sorby and Baartmans, 2000; Gerson et al., 2001).

We should highlight some aspects of the strategies followed for developing spatial abilities.

- Based on the physical and physiological mechanisms for visual perception, "a person is able to represent the cutting projections of an object once they have integrated into their mental scheme of knowledge the representation of a three-dimensional object (perspective)" (Leopold, Gorska, and Sorby, 2001).
- The traditional approach of working with two dimensions first, (i.e., exercises of descriptive geometry), and then proceeding on to three dimensions, seems to not be a good strategy for improving spatial abilities in a short space of time (Pérez and Serrano, 1998).
- Working with physical objects provides students with better skills with regards to their interpretation and translation to orthographic projections. This means that when setting

sketching and orthographic view definition exercises, it is more productive to work with real objects than to use perspective drawings (Miller, 1990).

IV. Pilot Study

A. Justification

This pilot study has been designed to obtain experience so as to launch a remedial course to improve spatial abilities in freshman engineering students with underdeveloped abilities at the beginning of their first semester at the university. The objective is that participating students could achieve a minimum level in their spatial abilities at the end of this fast course, which should contribute to a successful participation in the regular engineering graphics course taught during the first semester in the majority of undergraduate engineering programs. In many Spanish universities it is a common practice to offer a series of remedial courses to freshman engineering students to improve their knowledge in basic subjects such as mathematics, physics, chemistry or engineering graphics. These courses usually are taught some weeks prior to the official beginning of the academic semester. In other cases, they are concentrated in the first weeks of the term. Participation is voluntary and these remedial courses are recognized as elective subjects in the student's curriculum.

B. Participants

Forty volunteer freshman students (twenty-five males and fifteen females) working on a civil engineering degree at the University of La Laguna in Spain participated in this pilot study. The majority of students were between 18 and 20 years old. Fifty percent had previously studied subjects related to engineering graphics at high school, and sixty-five percent were male. The majority were full-time students and considered themselves to have difficulties with spatial abilities.

C. Hardware and Software

Standard 2.80 GHz Pentium IV computers with 512 MB RAM and the Windows XP operating system were employed, running the free version of Google SketchUp 5 (Google SketchUp, 2006). This application is a 3D modeling program which can be freely downloaded from the Internet. Developed for the conceptual stages of design, it is a very easy-to-learn 3D software tool that combines a simple, yet robust tool-set, as shown in Figure 3, with an intelligent drawing system. It enables students to build and modify 3D models quickly and easily. These characteristics justify its selection as the modeling tool for the pilot study.

D. Didactic Material for Engineering Graphics

In this study we used the set of twenty-four physical parts presented in Figure 4 (Maditeg, 1997). These aluminum parts, painted in green, are extremely manageable and measure approximately 60 × 55 × 45 mm. Students have used these parts for orthographic view definition, and cuts and sections selection for complete geometric definition.

E. Instruction

The course was divided into three sessions: 8 classroom hours (ch) and approximately 4 homework hours (hwh). As noted previously, one of the objectives was to develop a fast course to be carried out at the beginning of the term. The pilot study involved a series of activities of increasing difficulty, detailed in Table 1.

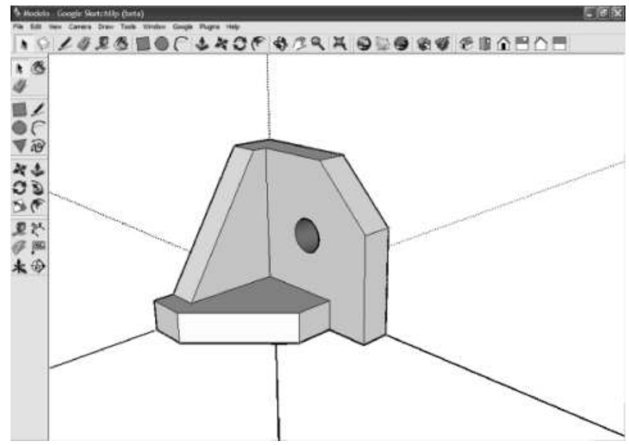

Figure 3. Google SketchUp screenshot.

Figure 4. Physical parts used for exercises.

1) Level 1—Initiation (3ch + 2 hwh): In this first stage, the objective was to provide basic training in the operation of Google SketchUp, version 5 (Google SketchUp, 2006). Students learned the most important functions of the program, such as drawing lines and polygons in a 3D space. They also learned how to make extrusions as a basic model operation. This is one of the differences with previous studies, where the teaching or use of CAD tools during the whole term is analyzed. In this case, learning the 3D modeling tool is part of the remedial course. This requires using software with a fast learning curve.

Once students had acquired basic modeling skills in Google SketchUp, they were asked to choose one physical part and generate its corresponding 3D model. They were recommended to make a pencil sketch of the part, with the dimensions labeled on it, before starting the modeling process. Figure 5 shows some CAD models with their corresponding physical parts.

As a complementary activity outside the classroom, students were told they could create a daily object, taking its measurements and then modeling it in three dimensions (Figure 6). The objective was to get students accustomed to the three dimensions of the objects using the proposed software. This approach required the use of the free CAD application.

This level of initiation lasted approximately five hours, divided into the following sections: half an hour for the operation of the

Level		Descrption	Time	Week
Level 1: Initiation	1.1	Build 3D models based on physical parts	3 ch	Week 1
	1.2	Create a daily object	2 hwh	
Level 2: Improvement		Generate the 3D models corresponding to parts given by their axonometric projection	3 ch	Week 2
Level 3: From Orthographic views to 3D models	3.1	Construct the 3D models of parts that are represented by their orthographic views.	2 ch	Week 3
	3.1	Group work	2 hwh	
		TOTAL	**8 ch + 4 hwh**	**3 Weeks**

Table 1. Summary of the activities.

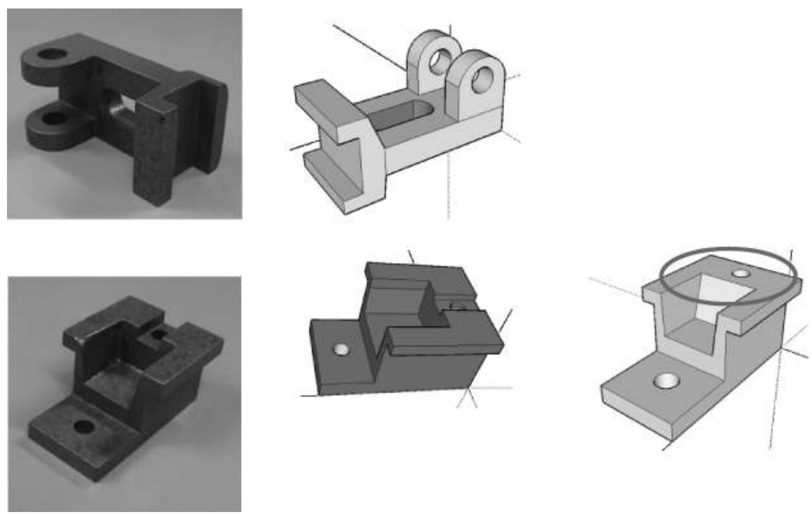

Figure 5. CAD models created by students.

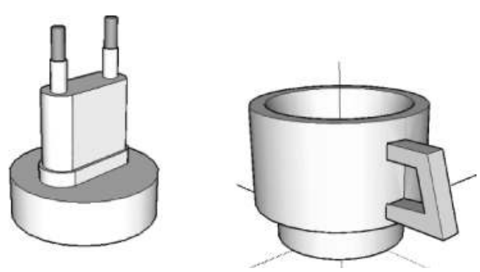

Figure 6. Examples of models generated during Level 1.

application, two and a half hours for the modeling of physical parts in class, and two hours for the daily modeling of objects outside the classroom.

As a summary of this introductory phase focusing on the methodology of active learning, we should stress that most students do not have any problems using the software (only those who have trouble with new technologies tend to encounter difficulties), and in many cases, this constitutes students' first experience of measuring real parts, and helps them understand the importance of sketching as a method of defining the geometry of the part in an informal way, while still including its dimensional characteristics.

2) Level 2—Improvement from 3D on paper to 3D in Google SketchUp (3 ch): At this stage, students were asked to generate the 3D models corresponding to the parts given by their axonometric projection (Pérez and Serrano, 1998), as presented in Figure 7 (left). During the first hour-long session, we tried to detect whether or not they were able to interpret the three-dimensional volume from a two-dimensional perspective. It is important to clarify that this stage did not include any specific teaching on orthographic views or perspective. Students found themselves in different situations depending on the knowledge they had acquired at previous education levels.

The parts selected for axonometric projection had a similar geometric complexity to the physical parts in Figure 4, in order to ensure exercises of equivalent difficulty. This level lasted three hours.

3) Level 3—From orthographic views to 3D models (2 ch + 2 hwh): During this stage, as shown in Figure 8, students were asked to construct the 3D model of parts represented by their orthographic

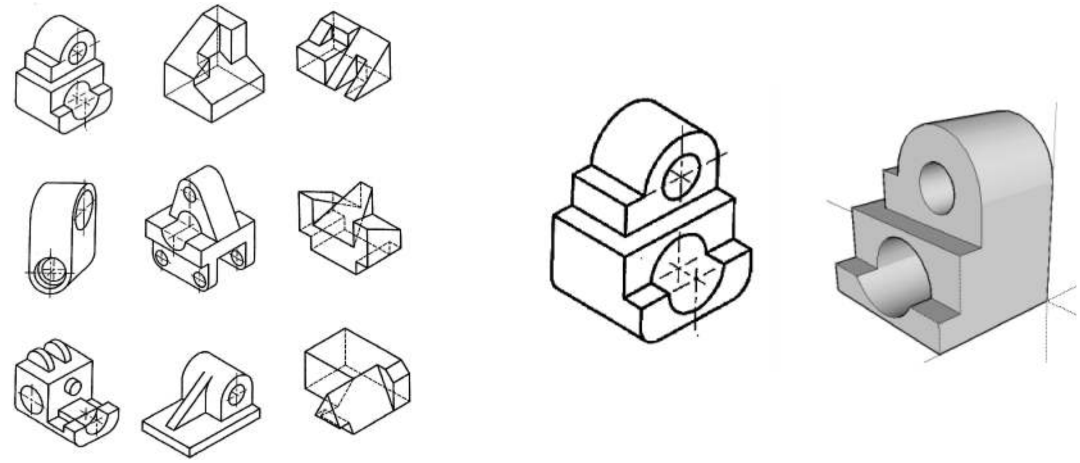

Figure 7. Parts used for exercises presented as axonometric projections (left) and an example of the exercise for Level 2 (right).

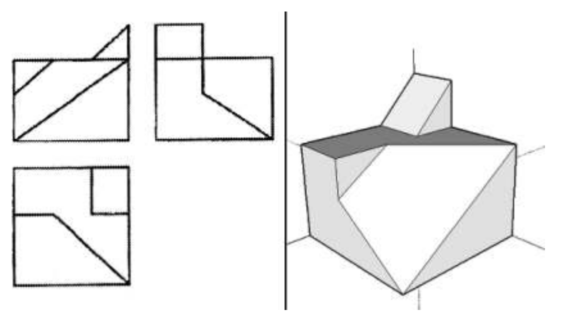

Figure 8. Example of the exercise for level 3.

views. Students received a one hour class on the basics of orthographic views (European system) and later discussed the proposed exercises in groups for approximately two hours. The aim of this class was to provide students with the background knowledge they required to solve the exercises presented at this level.

This level is usually the most difficult for students, because it requires a greater level of spatial abilities. Students have to imagine and construct a mental image of the part using only the information provided by its orthographic projections. Because of this, we approached it in two different phases: the first one based on group work and the second one based on individual reflection.

We proposed the creation of working groups (three to five components), not only to solve the exercises in this level, but also to develop social abilities related to group work and negotiation, invite students to share, discuss and defend their position with their classmates, involve those students that normally do not collaborate or participate in group activities, and establish a climate of cooperation.

The students assessed this stage very positively. We transferred the responsibility for the learning process to them: one group proposed a solution and the others participated by discussing and improving it, or by proposing alternative solutions with the teacher's help. The presentation of results in class to one's classmates proved very rewarding and enabled us to analyze many different exercises and their difficulties in a short period of time (one hour).

At the end of this learning stage, we published the parts generated by the students (both the individual and the group ones). These were then used for the second phase, in which students used the exercises and the published solutions for individual reflection and analysis.

V. Data Analysis

As stated previously, the pilot study was carried out with 40 volunteer civil engineering students at the beginning of the first semester of the 2006–2007 academic year. By doing it this way, we tried to avoid other subjects in the course from influencing the results of the spatial abilities test measures. Table 2 shows the scores obtained by students in the MRT and DAT:SR tests. As a reference, in a similar study performed in the University of La Laguna during the academic year 2004–05, the mean score for the MRT test was 16.51 (standard deviation 7.76) and for DAT:SR was 43.07 (standard deviation 9.78). These scores were obtained considering all the students enrolled in engineering graphics courses at the beginning of that academic year. At the end of the semester the students were tested again to analyze the effects of attending an engineering graphics subject. Mean gain was 9.18 in MRT and 8.83 in DAT:SR (Contero et al., 2005, 2006).

For the statistical analysis we used a Student's *t*-test, taking as the null hypothesis (H_0) the fact that mean values for spatial visualization abilities did not vary after the end of the course. The *t*-test for paired series was applied and the p values are shown in Table 3. The level of significance is always less than.

Hence the null hypothesis is rejected and we can conclude, with a significance level of higher than 99.9 percent, that the mean scores for the experimental group underwent a positive variation. In other words, the course using Google SketchUp had a measurable and positive impact on the spatial ability of students, measured by both MRT and DAT:SR tests. The average increase of values is 5 points in MRT and 8 points in DAT:SR, regardless of sex (applying *t*-test for independent series $p = 0.552$ and $p = 0.868$, respectively). We should highlight the fact that the pre-MRT scores obtained by women were significantly lower than those obtained by men ($p = 0.013$), although this difference was not significant in relation to pre-DAT scores ($p = 0.542$).

Figure 9 shows the obtained scores in the MRT and DAT:SR tests. The results are shown separately for males (M) and females (F). The right-hand part of the graph shows the results of the DAT test and the left-hand side shows the scores for the MRT test.

		MRT			DAT:SR		
		Pre MRT (std. dev)	Post MRT (std. dev)	Gain MRT (std. dev)	Pre DAT (std. dev)	Post DAT (std. dev)	Gain DAT (std. dev)
SketchUp	Total	19.03	24.50	5.48	41.58	49.88	8.30
2006-07	$N = 40$	(7.60)	(8.50)	(5.66)	(10.34)	(7.47)	(6.73)
$N = 40$	Men	21.28	27.24	5.96	42.36	50.52	8.16
	$N = 25$	(7.25)	(7.72)	(4.20)	(11.05)	(7.22)	(7.77)
	Women	15.27	19.93	4.67	40.27	48.80	8.53
	$N = 15$	(6.83)	(7.95)	(7.60)	(9.25)	(8.00)	(4.76)

Table 2. Mean pre- and post-test scores and score gains.

	MRT	DAT:SR
Google SketchUp based course	$p = 0.00000035 < 0.001$	$p = 0.0000000018 < 0.001$

Table 3. Level of significance for Google SketchUp course.

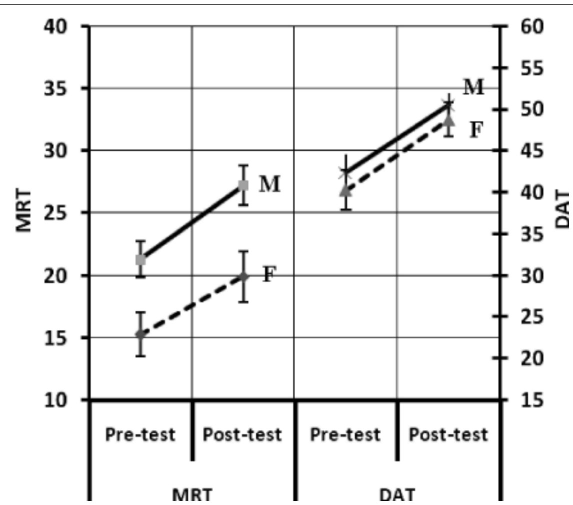

Figure 9. MRT and DAT:SR scores (N = 40).

A. Comparison with the Results Obtained in Previous Remedial Courses in 2004–2005

During the 2004–05 academic year, three remedial courses (Contero et al., 2005, 2006) were held for students with problems related to spatial abilities. The first course was based on "classic" paper and pencil exercises. The second one used a Web-based application with exercises for developing spatial abilities and the last one used a sketch-based modeling application called e-CIGRO, developed by the REGEO Research Group (Regeo Research Group, 2008).

Participating students were selected from among the 20 percent with the lowest pre-test scores (Contero et al., 2005, 2006). Thus, in order to make a correct comparison with the SketchUp-based course, we have selected a subgroup of students with similar scores to those participating in the previous experience. Table 4 shows a summary of the results.

An analysis of variance (ANOVA) was performed to determine the effect of the course type (see Table 5) on MRT and DAT:SR tests. With respect to the MRT test, the effect of the course type was not significant ($F_{3,60} = 0.83$ and p-value = 0.483). However, for the DAT:SR test, the course type was significant ($F_{3,60} = 4.35$ and p-value = 0.008) and the Tukey test indicated that the mean gain in group 2 (Web-based) was significantly lower than in groups 1 (Paper and pencil) and 4 (Google SketchUp). Method 3 (Sketch-based modeling) showed no differences with respect to the two previous homogeneous groups.

VI. Conclusions and Future Work

From our experience with the pilot test, as well as with previous remedial courses, we can conclude, in relation to the use of instruction methods for improving spatial abilities, that:

- The development of spatial abilities can be achieved effectively through specific training. A remedial course approach based on Google SketchUp has proven to be a good option.
- Fast remedial courses (6–12 hours) can provide a significant gain in spatial abilities scores. The average gain is around 5 points in MRT and 8 points in DAT:SR, compared with 8 points in MRT and 9 points in DAT:SR, obtained in a "regular" engineering graphics course.
- With training, both male and female students on average gain equally as demonstrated by MRT and DAT:SR tests.
- The pilot test proved that a Google SketchUp-based course is a good option to implement a remedial course for improving spatial abilities. At this point we must emphasize that the results obtained both in this experience and in previous ones in the three remedial courses launched in 2004–2005 offer a similar range of spatial ability improvements. Remedial courses based on paper and pencil exercises and the new one based on Google SketchUp appear to reveal significant differences

Nº	Course Type	Pretest MRT	Postest MRT	Gain MRT	Pretest DAT:SR	Postest DAT:SR	Gain DAT:SR
1	Paper and pencil	8.18	13.53	5.35	28.47	39.35	10.88
	N = 17 6 hours	(4.60)	(6.12)	(4.35)	(8.57)	(10.09)	(5.48)
2	Web-based	9.60	13.27	3.36	30.53	35.67	5.13
	N =15 6 hours	(4.46)	(4.80)	(5.85)	(5.40)	(5.60)	(5.25)
3	Sketch-based	7.85	12.05	4.20	33.00	40.40	7.40
	Modeling *N* =20 6 hours	(3.56)	(5.33)	(4.49)	(6.26)	(8.92)	(5.92)
4	Google SketchUp	10,58	16.83	6.25	31.00	43.42	12.42
	N =12 12 hours	(4.32)	(7.77)	(6.55)	(7.41)	(6.24)	(7.59)

Table 4. Mean pre- and post-test and gain test scores (std. dev.) for previous remedial courses and Google SketchUp.

Nº	Course Type	MRT	DAT:SR
1	Paper and pencil	$p = 0.000115 < 0.01$	$p = 0.0000004 < 0.01$
2	Web-based	$p = 0.0430 < 0.05$	$p = 0.002 < 0.01$
3	Sketch-based modeling	$p = 0.000505 < 0.01$	$p = 0.0000218 < 0.01$
4	Google SketchUp	$p = 0.007 < 0.01$	$p = 0.00015 < 0.01$

Table 5. Level of significance comparing pre- vs. post-test scores (MRT and DAT:SR) within each courses types.

regarding gain scores in the DAT test. Future research should be aimed at identifying what kind of exercises and training has a better effect on each of the spatial ability factors.

Further research in the future may focus on developing educational strategies based on short duration remedial courses that try to integrate computer applications running on mobile devices such as personal digital assistant (PDA) devices, mobile phones, portable computers and/or handheld video game consoles.

During the first semester of the current academic year (2007–08), a condensed version of the remedial course described in this paper has been adapted to the regular engineering graphics course in civil engineering and electronic engineering. Students were surveyed at the end of the semester. There was a specific question on the survey about motivation. It received a mean score of 4.1 points, using a five-point Likert scale, where the maximum score corresponded to strongly agree that the SketchUp-based practices promoted their positive attitude towards the engineering graphics course. This confirms the instructors' perception about a positive change in the motivation of the students using similar exercises to the ones described in this paper. Our intention is to progressively incorporate this experience in the regular engineering graphics course and analyze its impact on the transcripts of participating students.

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