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# Design and validation of an augmented book for spatial abilities development in engineering students

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## Abstract

This paper presents an application of Augmented Reality for improving spatial abilities of engineering students. An augmented book called AR-Dehaes has been designed to provide 3D virtual models that help students to perform visualization tasks to promote the development of their spatial ability during a short remedial course. A validation study with 24 Mechanical Engineering freshmen at La Laguna University (Spain) has concluded that the training had a measurable and positive impact on students' spatial ability. On the other hand, results obtained using a satisfaction questionnaire illustrate that AR-Dehaes is considered an easy to use, attractive and very useful technique for students. AR-Dehaes has proved to be a very cost effective tool insofar as it only required an ordinary PC with a webcam to be used.

## Keywords

*Augmented book, spatial ability, Augmented Reality*

# 1. Introduction

Development of spatial skills by engineering students is directly linked to future success in their professional work [1], [35], [47] and is critical to understand the contents of engineering graphics subjects [49][50]. This capability can be described as the ability to picture three-dimensional shapes in the mind's eye. Acquiring this skill can be done through an indirect process by means of Engineering Graphics subjects (this is a common approach in European universities) where students perform sketching tasks and, create and read orthographic and axonometric projections [3], [31]. However, there is another approach based on the development of specific training to develop spatial abilities. As Potter and Van der Merwe's [42] educational research over a 20-year period concluded; spatial ability influences academic performance in engineering, and can be increased through instruction focused on using perception and mental imagery in three-dimensional representation. Other training approaches have used multimedia technologies [36] computer-mediated engineering drawing instruction [45], web-based games [18] [44], Virtual and Augmented Reality [19], videogames [21][43] CAD applications [56] and, dynamic geometry software (DGS) [23][24].

Our research group [32] has reported that the spatial ability of freshmen engineering students can be improved through spatial activities consisting of physical object manipulations (polyhedral parts) and freehand sketching on paper. Other successful approaches tested by our group [15] are based on computer aided sketching applications and Web-based e-learning contents. In our previous works, it has been demonstrated that short remedial courses using some of the technologies previously described can be used to improve spatial abilities in freshman engineering students with underdeveloped spatial abilities. These remedial courses are offered as an elective course to these students at the beginning of their first semester at the university. The objective is that participant students could achieve a basic level in their spatial abilities at the end of this short remedial 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.

Our experience and other results from the scientific community [2] indicate that there are many valid approaches to stimulate the development of the spatial

ability, but there is an important factor that must not be overlooked: what technological profiles can we find in current freshmen engineering students? Nowadays, students are accustomed to managing technologies like Internet, 3D videogames, mobile phones, MP3 players and other technological gadgets. So asking them for classical paper and pencil exercises can be counterproductive, especially if we want to offer voluntary remedial courses to solve their deficiency in spatial ability. Our experience with these kind of short remedial courses is that it is very difficult to maintain the attention of first year students, and often they withdraw from the course before ending.

In this context, Augmented Reality (AR) appears as an attractive technology that promises to provide the needed tools to create compelling content for spatial ability training and development. The main objective of this work is to provide AR contents for a short remedial course, with the aim of improving freshman engineering students' spatial ability.

In the following section, we analyze previous experiences in the application of Augmented Reality in educational contexts. Then we describe the key technical elements of the augmented library design to support the augmented book implementation called AR-Dehaes that we have used in our research. After that, a short remedial course based on the didactic content of AR-Dehaes for developing spatial abilities will be analyzed, and the paper ends with the analysis of a validation study performed with 24 Mechanical Engineering freshmen to verify the effectiveness of the designed augmented book. Finally, conclusions and future work are presented.

## **2. Augmented Reality and education**

Augmented Reality (AR) is a recent technology that is similar to the Virtual Reality (VR) paradigm. As is the case for Virtual Reality, several formal definitions and classifications for Augmented Reality exist (e.g., [33], [34]). Some define AR as a special case of VR; others argue that AR is a more general concept and see VR as a special case of AR. AR combines 3-dimensional (3D) computer-generated objects and text superimposed onto real images and video, all in real time. An interesting definition of AR has been described by Azuma [6], as a variation of Virtual Reality. VR technology completely immerses a user inside a synthetic environment. While immersed, the user cannot see the surrounding real

world. In contrast, AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it. With AR applications it is possible to show the user a common space where virtual and real objects coexists in a seamless way. From a technological point of view AR applications must fulfill the following three requirements [6]: combination of real and virtual worlds, real time interaction and, accurate 3D registration of virtual and real objects.

Augmented Reality applications can be used under several setups including monitor based systems, see-through and video-see-through head mounted displays (HMD) and projection based spatial augmented reality.

As Billingham [11] states, although AR technology is not new, it's potential in education is just beginning to be explored. Several EU funded projects such as CONNECT [14], CREATE [17] and ARISE [4] are designing and developing AR applications in order to improve education techniques. They provide good examples of the capability of this technology to develop new tools, which based on 3D interactions with the user, will make certain concepts easy to learn for the students.

## **2.1 Augmented Reality and spatial ability**

Although spatial ability has been studied using Virtual Reality technology [20] there are a few studies [28] about the application of AR to train spatial ability. In 2006 Dünser et al.[19] presented the first large-scale study (215 students) that analyzed whether spatial ability can be trained using an AR application and which specific aspects of spatial ability can be improved. Construct3D was the application used to design and conduct the study [27]. Construct3D is a 3D geometric construction tool specifically designed for mathematics and geometry education. It is based on the mobile collaborative augmented reality system “Studierstube” [46]. Their work concluded that AR can be used to develop useful tools for spatial ability training. They also proposed that new tools are necessary to measure spatial ability directly in a 3-D environment. Table 1 makes a comparison between Construct3D and AR-Dehaes, the application presented in this paper.

*Table 1 goes near here*

Hartman et al. [25] in 2006 outlined the relationship to spatial abilities and computer graphics education and a methodology for pilot testing a working prototype of a virtual reality-based version of a spatial abilities assessment instrument.

## **2.2 Spatial ability and engineering education: the Spanish context**

University teaching in Europe is currently immersed in a major process of change arising from the creation of the European Higher Education Area [55]. This process is not designed to lead to a “standardisation” of higher education in Europe, but rather seeks to create a common and comparable system among all European countries [16]. The new teaching model entails a methodological change in education, shifting from a teacher-centred model to one that places greater importance on the work of the student.

In Spain, the Ministry of Education and the universities are working to adapt the current teaching system to the European model in the following terms:

- Review and introduce new qualifications based on contents and competences.
- The definition of contents and professional profile by areas of knowledge and the revaluation of levels of quality [12].

The Spanish Ministry of Education has drafted a base line document for each qualification [48], containing the guidelines for universities to design the syllabus for each qualification. According to these documents, engineering qualifications will have to provide students with “Spatial vision capacity and a command of the techniques of graphic representation, using both conventional methods of metric geometry and descriptive geometry on the one hand, and by applying computer aided design on the other”. This recognition of spatial ability as a basic capacity means that the development of specific training tools for its development is receiving a growing attention from the Spanish academic community.

## **2.3 The augmented book concept**

One of the most known AR educational applications is the “MagicBook” [10] [53] [26]. The “MagicBook” interface uses normal books with AR markers as the main interface objects. People can turn the pages of the book, look at the pictures, and read the text without any additional technology. However, if they look at the

pages through an AR display they see 3D virtual models appearing out of the pages, thus introducing an interesting way for smoothly transporting users between reality and virtuality using a physical object.

Tallyn et al. [51] make a comparative study of a paper book, a multimedia CDROM and an AR book, concluding that book's ergonomics provide a flexible and easily accessible interface which engenders fluid collaboration between pairs of children, and that these qualities are also observed when children work with the AR book.

The “basic” augmented book experience only requires adding a webcam to a typical PC configuration and the proper software. Using the computer screen to visualize the augmented scene is a cost-effective and eye-catching alternative in the educational context presented in this paper. It confirms previous works in the field of presence performed by our research institute [7] [8] , about the idea that if content is of high quality, then even simple technology will be effective.

### **3. Augmented book development**

In order to support the development of Augmented Reality applications our research group has developed a software library called HUMANAR. Although there are several public libraries with AR capabilities, we decided to develop HUMANAR in order to ensure the integration of AR into our applications and to overcome some drawbacks present in some public libraries. For example, the presented version of HUMANAR has been specially tuned to ensure a reliable implementation of the augment book described in this paper. This library uses computer vision techniques to calculate the real camera viewpoint relative to a real world marker. The key technical issues for the development of the AR book have been:

1. Camera calibration.
2. Marker detection.
3. Calculation of marker position and orientation (pose estimation).
4. Augmentation of virtual object.

HUMANAR library supports two different types of markers (Figure 1):

- Template-based markers.
- ID-based markers 4x4 code words.

For a brief description of different types of markers at the Augmented Reality environments, see [22].

*Figure 1 goes near here*

The figure 2 shows the block diagram of HUMANAR library. More details about this library are presented next.

*Figure 2 goes near here*

### 3.1 Camera calibration

First of all, to calculate the real camera viewpoint relative to a real world marker is determining the intrinsic camera matrix  $\mathbf{K}$  and a vector  $\boldsymbol{\gamma}$  with the distortion parameters.

$$\mathbf{K} = \begin{bmatrix} f_x & \sigma & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \quad \boldsymbol{\gamma} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \beta_1 \\ \beta_2 \end{bmatrix} \quad (\text{Eq. 1})$$

Where  $f_x, f_y$  are respective the focal length in the  $x$  and  $y$  direction,  $(c_x, c_y)$  is the camera's optical centre,  $\alpha_1, \alpha_2$  the radial distortion parameters,  $\beta_1, \beta_2$  the tangential distortion parameters and finally  $\sigma$  is the camera's skew between  $X$  and  $Y$  axes.

For this purpose it is only necessary to have different captures of planar checkerboard patterns. For the calibration step the Zhang's method is used [57]. The input of this algorithm is the correspondence between 2D image points and 3D scene points over a number of images. The output is the intrinsic camera matrix as well as the radial distortion coefficients. The scene points of the correspondence have to be in the same plane and to obtain a good result this plane should be different for every calibration image.

### 3.2 Marker detection

For marker detection it is necessary to binarize the grab camera frame. This can be made in different ways:

1. Using a fixed threshold.
2. Using an adaptive threshold.

Using a fixed threshold is recommended under ideal circumstances, where the lighting and camera parameters are constant. In this case this technique performs adequately. However, if the lighting conditions are different in each frame, using an adaptive threshold can be a better option. HUMANAR threshold determination



is based on Pintarić's technique [41]. Basically this algorithm operates on a per marker basis and evaluates the mean pixel luminance over a thresholding region of interest.

The next step is marker contour detection where the connected components must be extracted. Later the perimeter of each contiguous region of black pixels is traced to produce a chain representing an object border. A set of line segments are then fitted to these points, in such a way that all border pixels are within some minimum distance of a line segment. If the resulting polygon is sufficiently large and has exactly four sides, it is considered a candidate marker and passed on to the identification process. For stability reasons, it is necessary to refine the four landmarks localisations. This method iterates to find the sub-pixel accurate location of a corner, or "radial saddle point".

In the next step, the pattern is normalised by using a perspective transformation to square landmarks thus getting square landmarks. The transformation is applied to a square region of interest (see Fig. 3) and the interior part of the marker is extracted. At the next step it is necessary to identify the interior of the pattern. A different approach is used according to the marker type. For an ID-based marker, it must be designed in such a way that can be easily detected and be unique enough to be easily identified from others markers. Each marker must also provide some kind of hexadecimal code that fixes the marker orientation.

*Figure 3 goes near here*

For template-based markers, a candidate image is compared to the known images in each of the four possible orientations. A variety of methods are possible for comparing images. The mean squared error (MSE) is a common measure of image similarity, particularly when measuring image degradation [22]. For an MSE measure, small values indicate similarity. This approach is not luminance invariant, however. A better approach is the normalised correlation coefficient; at this approach the mean and standard deviations for the image and pattern are computed. If the coefficient for one image is maximal for the image set and exceeds a fixed threshold (0.5) the image is accepted. This approach has got several disadvantages over the ID-based markers, the main is inter-marker confusion (false-positives and positives-false).

### 3.3 Markers pose estimation

The camera pose can also be estimated from a planar structure when the internal parameters are known.

The relation between a 3D plane and its image projection can be represented by homogenous 3 x 3 matrix, called homography matrix. Let us consider  $Z = 0$  plane. The expression of the homography  $H$  that maps a point on to this plane and its corresponding 2D point  $m$  under the perspective  $P = K [R / t]$  can be recovered by writing:

$$m = PM = K(R^1 R^2 R^3 t) \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix} = K(R^1 R^2 t) \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = H \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \quad (\text{Eq. 2})$$

Where  $R^1$ ,  $R^2$  and  $R^3$  respectively are the first, second and third column of the rotation matrix  $R$ .

Conversely, once  $H$  and  $K$  are known, the camera pose can be recovered. The matrix  $H$  can be estimated from four correspondences  $M_i \leftrightarrow m_i$  using a Direct Linear Transformation (DLT) algorithm. Since  $H^t_w = K(R^1 R^2 t)$ , the translation vector  $t$  and the first two columns of the rotation matrix  $R$  of the camera pose can be retrieved from the product  $K^{-1}H^t_w$ . The last column  $R^3$  is given by the cross-product  $R^1 \times R^2$  since the columns of  $\mathbf{R}$  must be orthonormal. Generally the camera pose can be refined by non-linear minimization, since the anterior processes is sensitive to noise and, therefore, a lack of precision and the “jitter” phenomenon are produced. If the measurements are noisy, the camera pose should then be obtained by minimizing the sum of the reprojections errors, that is the squared distance between the projection of the 3D points and their measured 2D coordinates. We can therefore write:

$$[R / t] = \arg \min_{[R / t]} \sum_i \| PM_i - m_i \|^2 \quad (\text{Eq. 3})$$

The equation 3 will be solved using the Levenberg-Marquardt (LM) algorithm [37]. This method provides a numerical solution to the problem of minimizing a function, generally nonlinear, over a space of parameters of the function. These minimization problems arise especially in least squares curve fitting and nonlinear programming.

### 3.4 Augmentation of virtual objects

The graphical engine used for the augmentation of virtual object at the scene is Brainstorm eStudio [13]. This is an advanced, multiplatform, real time 3D graphics presentation tool. In order to include Augmented Reality functionality in Brainstorm eStudio, a plug-in has been developed in C++. This plug-in incorporates detection and tracking options from the HUMANAR library previously described.

Our library presents several advantages over other popular AR libraries like for example ARToolKit [5]. Among other it can be cited:

1. Support for different marker types (ARToolKit markers and ID-based markers).
2. Variable border width can be changed to use more area of the marker for pattern instead of the black border. This increases detection of very small markers. ID-based markers only.
3. Variable pattern size at the Template-based markers, (e.g: 16x16, 32x32, 64x64...)
4. Adaptive threshold for avoiding illumination variations at the scene.
5. Occlusion of black border at the Template-based markers.
6. Graphical interface for camera calibration and pattern creation.
7. Less jitter than ARToolKit.
8. Support for infrared marker detection.

## 4. Description of the didactic content

Using the AR library and graphical engine described in the previous point, a didactic toolkit, called AR-Dehaes, was developed. This toolkit provides the students a set of different kinds of exercises to train spatial abilities by means of an augmented book.

The AR-Dehaes toolkit is composed of these components (see Fig. 4):

- A software application that contains the three dimensional virtual models. These models will be visualized on the computer screen when fiducial markers are received by the webcam.
- A six minute explanatory video that introduces the theoretical contents of orthographic views and freehand sketching.

- A notebook with questions and exercises that have to be solved by the students.
- An augmented book that provides fiducial markers of virtual three dimensional objects. The students can turn, move or bring the notebook to the webcam. They will then be able to see different perspectives of the virtual model and complementary information for problem resolution.

The training is made up of five levels and each one has several types of exercises. The proposed content is an evolution of the Pérez-Carrión's work [40] where there are five exercise levels instead of the original six levels. The "Application level" [40] is not included because its exercises are too similar to those used in the MRT and DAT:SR tests.

*Level 1* is designed for a two hour session. As shown in Table 2, in this level, the students have to identify surfaces and vertexes on both orthographic and axonometric views of a three-dimensional virtual object, which is created on the augmented book.

*Table 2 goes near here*

*Level 2* (see Table 3 for details) is also expected to be completed in two hours. In this level, the students have to identify orthographic views of the virtual three dimensional models from the exercise book.

*Table 3 goes near here*

*Level 3* is devoted to the identification of the spatial relationship between objects. This is carried out by means of "recount" exercises, where students are asked to identify how many object are in touch with one selected. Also there are exercises about the selection of the minimum number of views to completely define an object. Some examples are provided in Table 4. This level is expected to be completed in two hours.

*Table 4 goes near here*

*Level 4* has a greater difficulty than the previous levels. It presents "synthesis" exercises to the students. There are exercises where the students have to sketch a missing orthographic view, knowing two orthographic views of a model, as seen in Table 5. In a second stage, using the virtual model as the only input, they have to sketch all the orthographic views. The duration of this fourth training session is also two hours.

*Table 5 goes near here*

The last session of the course is used for evaluating the advance of students. *Level 5* exercises are the most difficult ones for students, because they require a greater level of spatial ability. Students are provided with three orthographic views of each object, as seen in Table 6, and they have to build in their minds the corresponding three-dimensional model and then draw a freehand perspective of it. Students have one hour to complete six exercises, without any virtual model help.

*Table 6 goes near here*

When they have carried out the proposed isometric drawings, they can be verified. Students can visualize the three-dimensional model in augmented reality (augmented book) and they can check if 3D freehand sketches correspond to the three-dimensional virtual models which they are viewing.

It is advisable to carry out the training in five consecutive days and to complete a level every day.

## **5. Validation**

Spatial ability as one of the main components of human intelligence is a well studied topic in Psychology. This means that different approaches and classifications can be found in the literature to analyse it. Some authors [29], [30] classify the spatial ability in several sub abilities, each referring to different aspects: “*Spatial Relation*” refers to tasks that require the mental rotation of simple two-dimensional or three-dimensional objects [52]; “*Spatial Visualization*” as the ability to manipulate complex spatial information when several stages are needed to produce the correct solution; “*Spatial Orientation*” refers to tasks in which a given object or an array of objects has to be imagined from another perspective.

Other authors [38], [39] simplify this classification by limiting it to only two categories: “*Spatial Relations*” that includes spatial relation and spatial orientation previously described and “*Spatial Visualization*” as the mental manipulation and integration of stimuli consisting of more than one part or movable parts, where usually there is movement among the internal parts of a complex configuration and/or the folding and unfolding of flat patterns.

Using this latter classification, two tests have been chosen, each corresponding to one of the main categories outlined above, to quantify the values of the spatial ability of participants in the validation study:

- Mental Rotation Test (MRT): “Spatial Relation” [54] (20 items). Example in Fig. 5.
- Differential Aptitude Test (DAT-5:SR level 2): Spatial Visualization” [9] (50 items). An example question is presented in Fig. 6.

The purpose of this study is to evaluate the effectiveness of the instructional activities described previously.

### **5.1 Participants.**

The study has been conducted with first year architecture and engineering students in the University of La Laguna (Spain). The total population consisted of 445 first year Mechanical, Electronic, Civil, Agricultural, Chemical Engineering and Architecture students.

The mean age of the population is 19. We have collected data that plays an important part in the conclusions of this study: 75% of the students are extremely or very interested in information technology and new technologies, 52% regularly play video games for more than 3 hours a week and 29% play one or two hours a week. They use computers an average of 3 hours per day, for leisure and study purposes.

Twenty-four volunteer freshmen students of the Mechanical Engineering degree were called to take part in a short remedial course to improve spatial ability based on the AR-Dehaes toolkit described previously. The validation study was conducted during the first week of the academic year 2008/09 therefore, at the time of taking part in the experience, these students had not attended any Engineering Graphics subject in their degree course and were not repeating the academic year.

The control group is made up of 25 (1<sup>st</sup> year) agricultural engineering students that undergo no kind of spatial skills training. Table 7 shows the level of spatial skills of the population, experimental sample and the control group prior to undergoing the training course with AR.

*Table 7 goes near here*

Before launching the pilot study, the required sample size ( $n$ ) was determined considering the minimum gain to detect and the standard deviation of the population. The probabilities for Type I error ( $\alpha$  error) and type II error ( $\beta$  error) were fixed to 5% and 10%, respectively. To obtain the sample size ( $n$ ), it was used the expression  $[n=(Z_{\alpha} + Z_{\beta})^2 * SD^2 / d]$ , with the normal values for  $Z_{\alpha}=1.96$ ,  $Z_{\beta}= 1.28$ , where  $SD$  is the expected standard deviation and  $d$ , the expected precision. Using the previous expression, a sample of 24 students would be needed to detect a 3 point gain increase in the sample, with a standard deviation of 4.5 points. To detect greater gains, the size of the sample would be smaller. Our experience [15][16][32] with similar field studies says that usually the minimum gain is greater than 5 points. Hence it can be concluded that the chosen sample size is sufficient to conduct this study.

## 5.2 Materials and methods

The validation study was carried out in a computer lab equipped with standard PCs with a 2.80 GHz Pentium IV processor, 2 Gb of RAM and running the Windows XP operative system. Each PC had a Logitech Quick Cam Pro 9000 webcam configured at a 25fps frame rate.

The remedial course was conducted during five consecutive days with a total duration of nine hours (four sessions of two hours and a final session that lasted one hour).

The first day a faculty member introduced, in ten minutes, the course structure and objectives, using an explanatory video to give a basic background in Engineering Graphics, needed to understand and complete the training exercises. Then a ten minute demo of the AR book was performed, where the students could test the augmented book behaviour and usage. The training exercises are arranged in five difficulty levels as described in section 4. Each level is associated to a unique training session. Students during the training session have to work independently without any assistance from the teacher. Students were provided with a solution booklet to perform self correction and promote autonomous learning. For open ended questions, such as those in Level 5, where the students create perspective sketches from an orthographic view, the students could use the augmented book to verify their sketches against the virtual 3D models.

Before the first training session and after the final one, students performed an MRT and a DAT-5:SR test to measure their spatial abilities level.

During the last session, a satisfaction survey about AR-Dehaes was conducted. The participants had to answer the questions formulated in Annex 1. The questionnaire is formed by five blocks of questions. Blocks A and B contain questions on the materials and didactic contents from AR-Dehaes. In blocks C and D the participants expressed their opinion on the AR technology and about the training carried out with AR-Dehaes. The questions of block E, collect information and feedback to keep in mind in future projects and extensions of AR-Dehaes contents.

In blocks A, B and C, the participants used a five level Likert scale to provide their opinion. The scale was formulated as: strongly disagree, disagree, neither agree nor disagree, agree, strongly agree.

The questions from blocks D and E were formulated by using different kinds of questioning (dichotomy, multiple choice and semantic differential).

### **5.3 Data analysis and results.**

The mean values of the MRT and DAT-5:SR tests of the experimental group and control group, prior to undergoing the training, are very similar to those of the total population (table 7).

Table 8, summarises the result of the analysis of variance (ANOVA) for MRT and DAT-5:SR measure in the three groups (total population, AR group and control group). There were no significant differences between groups prior to spatial training ( $F_{2,442}=0.439$ ,  $p=0.64$  on MRT and  $F_{2,442}=0.173$ ,  $p=0.84$  on DAT-5:SR). In other words, all the groups were statistically equivalent in spatial visualisation and spatial relation at the outset of this study.

*Table 8 goes near here*

After attending the training course with AR-Dehaes, spatial skills were measured again. Table 9 shows the results of the pre and post-tests.

*Table 9 goes near here*

For the statistical analysis, the Student's  $t$ -test was used, taking as the null hypothesis ( $H_0$ ), the fact that the mean values for spatial abilities did not vary at the end of the training sessions, in other words, "AR-Dehaes training group and control group do not improve their spatial skills". The result of the comparison of mean pre and post-tests with the Student's  $t$ -test is shown in table 10. The



obtained values indicate a statistically significant difference between the before and after values of the group that carried out the AR course, therefore the null hypothesis is rejected. This means that there is an improvement of spatial ability after the training with AR-Dehaes. On the other hand there isn't a statistically significant difference among the control group's mean values, therefore there isn't an improvement significant in the spatial abilities of this group, and the null hypothesis is accepted for it.

*Table 10 goes near here*

*Figure 7 goes near here*

The control group, as seen in table 9 and figure 7, presents a gain value that although is not statistically significant, could be attributed to the existence of a memory effect of the test. An analysis of covariance (ANCOVA) was used to study it. The ANCOVA method allows eliminating the difference of pre test scores between groups, and then the adjusted post test scores, revealing the real effects of the experimental treatment. Hence, it eliminates the possible memory effect. This statistical procedure also tested the interaction between groups (Training AR and control). The dependent variables, co-variants and independent variables were post-test measurements, pre-test measurements and type of group respectively. The suitability of using this analysis was tested by first conducting the analysis using a statistical model containing interaction terms between the co-variants (pre-test mean scores of MRT and DAT-5:SR) and the independent variables to assess the assumption of homogeneity of the gradients. The analysis of the ANCOVA to test this assumption is summarised in table 11 and table 12.

*Table 11 goes near here*

*Table 12 goes near here*

After adjusting for covariates (pre-test scores), it is checked again that there was a significant difference between control group and training AR group on the gain scores,  $F_{1,46}=7.47$ ,  $p=0.009$  (MRT) and  $F_{1,46}=6.55$ ,  $p=0.014$  (DAT-5:SR).

The results of tables 13 and 14 show the correction of the mean post-test value for each kind of course. The comparison of the AR training group with the control group revealed a mean difference of 3.721 on MRT and 4.259 on DAT-5:SR .

*Table 13 goes near here*

*Table 14 goes near here*

With respect to the satisfaction survey, the results are summarized in Figures 8, 9 and 10. In general, all students expressed a highly positive attitude to the material

and contents. They considered the material well presented and well structured. Students admitted that they were able to resolve the exercises in the stipulated time. Easiness and intuitiveness (question C4), learnability (question C1) and controllability (question C3) receive more than 4 points

*Figures 8, 9 and 10 go near here*

The learning measurement in this course was taken with an exam where the maximum possible score was 6 points. Participants obtained a mean score of 5.71 points. Regarding the location where the training takes place, the majority of students considered that it was best to carry it out in the computer lab although they have the possibility to do it at home.

The overall appreciation of the course was excellent-good (question D12) and most students considered it very useful (67%), very interesting (79%) and they were satisfied with the technology and methodology (83%).

All participants (100%) considered that AR-Dehaes system was pleasant to use (question D1) and useful for improving spatial skills (question D2). However they wouldn't have preferred this course to be carried out only with paper and pencil (question E3).

## **6. Conclusions and future works.**

Augmented books are a promising technology to provide students with added value contents with respect to traditional books, giving new life to traditional paper and pencil exercises. In this work, we have concluded that a simple and cheap hardware setup that only requires a PC equipped with a webcam is an effective tool to promote spatial abilities development, as the validation study shows. The remedial course carried out in the validation study had a positive impact on students' spatial ability. The experimental group (AR-Dehaes) showed a gain in scores of 8.04 in MRT and 9.29 in DAT, which is statistically significant. This is not the case of the control group whose gain is not statistically significant. Besides, it is important to note that AR-Dehaes magicbook achieved its main objective: participant students reached a basic level in their spatial abilities when they finished this short remedial course. They obtained a mean value (std. dev. between parenthesis) of 38.46 (7.05) points in DAT-5, and 27.71 (7.83) points in MRT, that compared positively with other reference values for freshmen engineering students:

- DAT-5 reference value for the Spanish population is 34.57 (8.56) [9].
- MRT example values in two published studies are: 24.39 (3.01) points [45] and 24.50 (8.50) [32].

In addition to the results provided by the satisfaction questionnaire, faculty members that participated in the validation study perceived a very positive and receptive attitude by students. This is very important because it is difficult to avoid a high withdrawal rate in remedial courses when the tools or procedures are not enough attractive to capture students' interest. Nowadays freshmen students have a very high technological profile in relation to a huge set of technological gadgets they are accustomed to use. In many cases, this represents a serious handicap to engage them in activities based on classic pen and pencil exercises. The AR-Dehaes toolkit has proved to be a low cost solution to create a compelling environment for the development of spatial abilities. Taking into account the good results obtained in the satisfaction questionnaire, this opens the opportunity to explore more complex interactions such as dynamic cutting sections and dynamic projection tools to enrich the feature set implemented in the current version of the augmented book.

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ANNEX - QUESTIONNAIRE **USERS SATISFACTION**

Assess your agreement in the following questions

		1	2	3	4	5	6
		Totally Disagree	Disagree	Neither Agree nor disagree	Agree	Totally Agree	Do not know
<b>QUESTIONS</b>		<b>DEGREE OF AGREEMENT</b>					
<b><u>AR MATERIAL.</u></b>		<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
A1	The course material is well and carefully presented (design notebook, Augmented book, Software, WebCam)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A2	The structure of the course has been comfortable, working in two separate notebooks, one for the exercises and the other for the marks.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A3	The structure of the course regarding levels and typology of exercises is adequate.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A4	It is easy to locate the exercises from the Design notebook in the fiducially marks book.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A5	The size of the notebooks (A5) is adequate to carry out the exercises and manipulate the virtual elements.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A6	The formative short videos are clear, with a language and graphics easy to understand.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A7	The Augmented Reality application has been stable (doesn't block).	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<b><u>AR COURSE CONTENTS</u></b>		<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
B1	The numbers of exercises proposed are sufficient for the intended working hours.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
B2	I felt myself capable to resolve the exercises presented.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
B3	I have had enough time in each session to complete the exercises marked by the teacher.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
B4	The formative videos are sufficient to know the theoretical contents. It isn't necessary any other type of explanation to complete the exercises.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
B5	In the evaluation level there are 6 exercises. How many correct answers did you obtain?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<b><u>"AR" TECHNOLOGY IN THIS COURSE</u></b>		<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
C1	The familiarisation with gestures and manipulating virtual objects has been easy.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
C2	Upon manipulating the virtual figures there is no delay in the screen, the virtual image does not produce "image leaps".	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
C3	The three-dimensional virtual figures are clear and do not present definition difficulties.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
C4	Utilising materials (design notebook) and Augmented Reality technology has been easy and intuitive.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<b><u>COURSE OPINION.</u></b>							
D1	Augmented Reality technology has been interesting to use in this training. <input type="checkbox"/> Yes <input type="checkbox"/> No						
D2	Do you think the training you have completed, provided by Augmented Reality, is useful to improve spatial skills? <input type="checkbox"/> Yes <input type="checkbox"/> No						
D3	Could you have done this course on your own?, i.e., without the need for the teacher to be there. <input type="checkbox"/> Yes <input type="checkbox"/> No						
D4	Do you think that additional theoretical material in this course is necessary? <input type="checkbox"/> Yes <input type="checkbox"/> No						
D5	¿Dónde preferirías realizar este entrenamiento con RA? Where would you rather do this AR training? <input type="checkbox"/> In graphic engineering laboratory(1) <input type="checkbox"/> In computer classes at the university (2) <input type="checkbox"/> On a computer at home (3)						



- D6 How do you value the Augmented Reality technology working with three-dimensional models?  
Which three-dimensional models?  
 Excellent  Good  O.K.  Bad  Very bad
- D7 Augmented Reality technology seems...  
 Very Interesting  Interesting  Not very interesting
- D8 Augmented Reality technology seems...  
 Very original  Original  Not very original
- D9 Augmented Reality technology seems...  
 Very useful  Useful  Not very useful
- D10 Augmented Reality technology seems...  
 Satisfying  Average  Frustrating
- D11 Augmented Reality technology seems...  
 Flexible  Average  Rigid
- D12 **Overall opinion of the course**  
 Excellent  Good  O.K.  Bad  Very bad
- 
- 

**YOUR OPINION WILL HELP US IN THE FUTURE**

- E1 Do you believe that the use of three dimensional tools can improve attention and motivate you to study the contents of Graphics Engineering subjects?  
 Yes  No
- E2 Do you believe a fast remedial course is suitable to improve engineering student's graphic engineering knowledge?  
 Yes  No  I do not know
- E3 Would you have preferred this course to have been based on pen a paper sketches?  
 Yes  No
- E4 If not on Augmented Reality, on what other support would you have liked to do this course?  
 Draw freehand (1)  Computer programme (2)  Mobile telephone (3)  Over the Internet at home (4)  
 Any support based on information or entertainment technologies (5)  No other. I liked doing it on Augmented Reality (6)
- 
-

## **FIGURE CAPTIONS**

**Fig. 1.** Example of different types of markers supported by HUMANAR library. Left: Template-based markers. Right: ID-based markers

**Fig. 2.** HUMANAR block diagram.

**Fig. 3.** Example of pattern normalization.

**Fig. 4.** AR-Dehaes toolkit

**Fig. 5.** Example of MRT test question

**Fig. 6.** Example of DAT-5:SR test question

**Fig 7.** MRT and DAT gain scores and standard error

**Fig. 8.** User satisfaction questionnaire: results of A, B and C blocks (mean value and std. error)

**Fig. 9.** User satisfaction questionnaire: results of D block

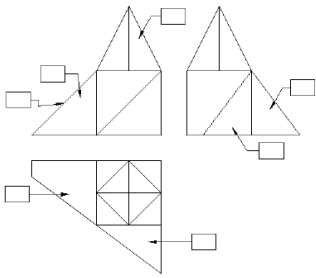
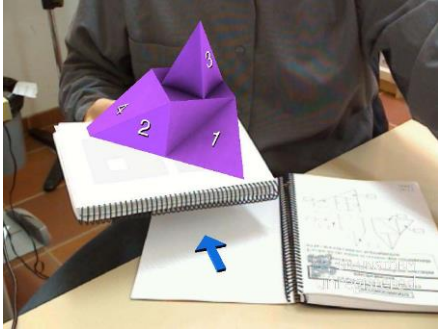
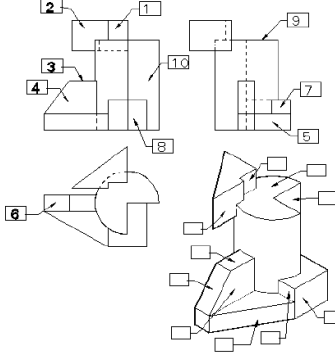
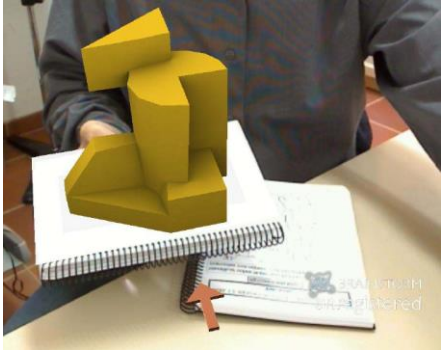
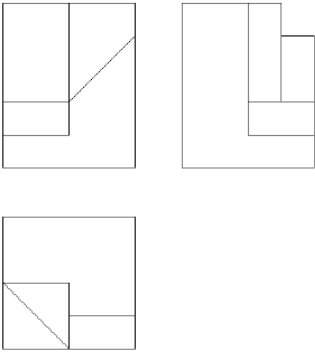
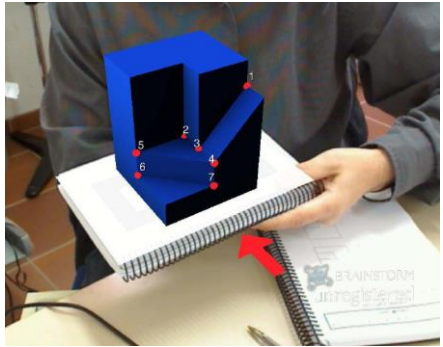
**Fig. 10.** User satisfaction questionnaire: results of E block

## TABLES

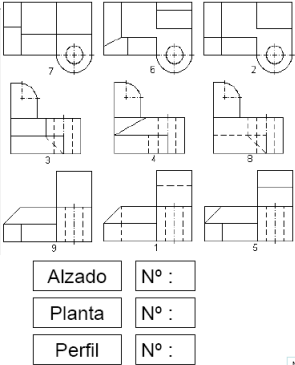
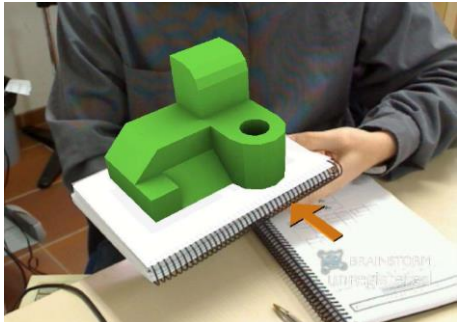
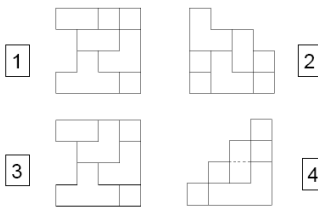
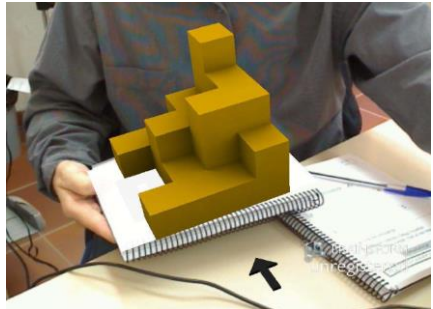
**Table 1.** Construct3D and AR-Dehaes comparison.

Construct3D	AR-Dehaes
<b>Domain</b>	
<ul style="list-style-type: none"> <li>• Construct3D is a three dimensional geometric construction tool specifically designed for mathematics and geometry education.</li> </ul>	<ul style="list-style-type: none"> <li>• AR-Dehaes is a three dimensional visualization tool designed for spatial abilities development based on simple technical drawing concepts.</li> </ul>
<b>Previous knowledge</b>	
<ul style="list-style-type: none"> <li>• Prior knowledge of geometry and mathematics are necessary to carry out the operations in Construct3D.</li> </ul>	<ul style="list-style-type: none"> <li>• Prior knowledge in technical drawing is not necessary.</li> </ul>
<b>Equipment cost and availability</b>	
<ul style="list-style-type: none"> <li>• Sophisticated and expensive equipment.</li> <li>• Only can be used at a computer lab with special equipment</li> </ul>	<ul style="list-style-type: none"> <li>• Simple and low cost equipment (a computer and Web camera).</li> <li>• Can be used at home. A regular computer lab can be used adding webcams to the typical PC configuration</li> </ul>
<b>Content and learning mode</b>	
<ul style="list-style-type: none"> <li>• Open content: the teacher can propose new exercises to be solved with the system.</li> <li>• The teacher is the guide in the learning process. Face-to-face interaction between teacher and student.</li> </ul>	<ul style="list-style-type: none"> <li>• Closed content: magicbook approach, exercises are hard-coded.</li> <li>• Autonomous learning approach after initial presentation of the magic book operation. The teacher assistance is only required for the initial presentation.</li> </ul>
<b>Learning outcome</b>	
<ul style="list-style-type: none"> <li>• Primary outcome: learning of mathematics and geometry</li> <li>• Secondary outcome: development of spatial abilities</li> </ul>	<ul style="list-style-type: none"> <li>• Primary outcome: development of spatial abilities</li> <li>• Secondary outcome: learning of some basic concepts of technical drawing</li> </ul>

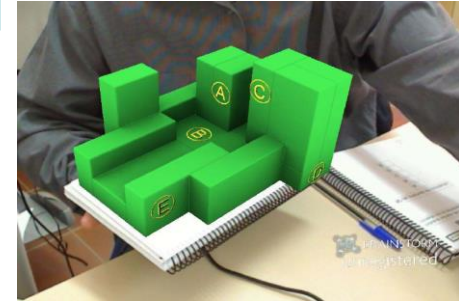
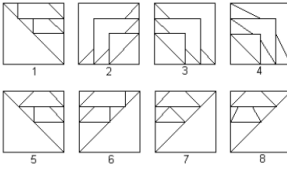
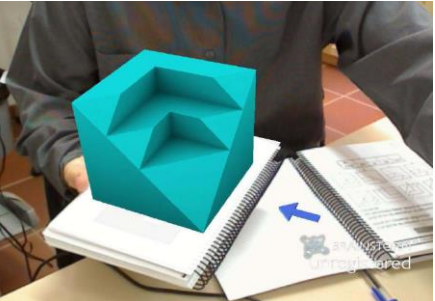
**Table 2.** Description of “level 1” exercises.

<p>Task 1.1.</p> <p>Identification of surfaces.</p> <p>Orthographic views.</p> <p>(10 exercises)</p>		
<p>Task 1.2.</p> <p>Identification of surfaces.</p> <p>Axonometric projection.</p> <p>(10 exercises)</p>		
<p>Task 1.3.</p> <p>Identification of vertexes.</p> <p>(6 exercises)</p>		

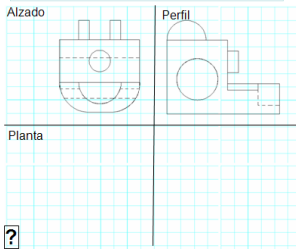
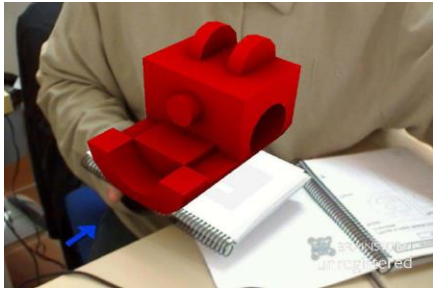
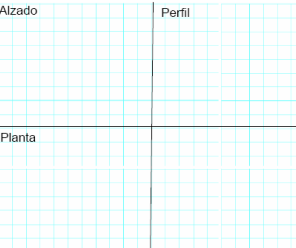

**Table 3.** Description of “level 2” exercises.

<p>Task 2.1.</p> <p>Identification of orthographic views.</p> <p>(12 exercises)</p>	 <p>Alzado N° : <input type="text"/></p> <p>Planta N° : <input type="text"/></p> <p>Perfil N° : <input type="text"/></p>	
<p>Task 2.2.</p> <p>Identification of wrong orthographic views.</p> <p>(15 exercises)</p>	 <p>Vista incorrecta N° : <input type="text"/></p>	

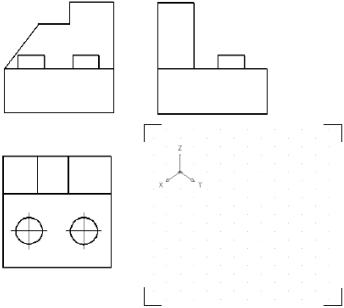
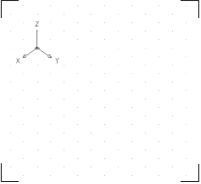
**Table 4.** Description of “level 3” exercises.

<p>Task 3.1.</p> <p>Recount</p> <p>(9 exercises)</p>	<p>NIVEL 3.1. RECUENTOS</p> <p>ANÁLISIS</p> <p>Indica el número de prismas que están en contacto con el señalado por la letra.</p> <p>N° de prismas en contacto:</p> <p>A: <input type="text"/></p> <p>B: <input type="text"/></p> <p>C: <input type="text"/></p> <p>D: <input type="text"/></p> <p>E: <input type="text"/></p>											
<p>Task 3.2.</p> <p>Selection of the minimum number of orthographic views to define an object.</p> <p>(10 exercises)</p>	<p>NIVEL 3.2. VISTAS MÍNIMAS</p> <p>ANÁLISIS</p> <p>Localizar el número mínimo de vistas necesarias para su correcta definición.</p> <p>Indica en el recuadro el número de las vistas que se necesitan para definir la pieza de forma correcta.</p>  <table border="1" data-bbox="710 1870 917 1915"> <tr> <td>Vista</td> <td>Alz</td> <td>Pl</td> <td>Pf</td> <td>Otra</td> </tr> <tr> <td>N°</td> <td><input type="text"/></td> <td><input type="text"/></td> <td><input type="text"/></td> <td><input type="text"/></td> </tr> </table>	Vista	Alz	Pl	Pf	Otra	N°	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Vista	Alz	Pl	Pf	Otra								
N°	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>								

**Table 5.** Description of “level 4” exercises.

<p>Task 4.1.</p> <p>“Missing view” exercises.</p> <p>(12 exercises)</p>	<p>NIVEL 4.1. OBTENCION DE VISTAS</p> <p>SINTESIS</p> <p>Dibujar a mano alzada (croquis) la vista propuesta.</p> <p>Alzado Perfil</p> <p>Planta</p>  
<p>Task 4.2</p> <p>Orthographic views sketching.</p> <p>(10 exercises)</p>	<p>NIVEL 4.2. OBTENCION DE VISTAS</p> <p>SINTESIS</p> <p>Dibujar a mano alzada (croquis) las vistas del modelo tridimensional propuesto.</p> <p>Alzado Perfil</p> <p>Planta</p>  

**Table 6.** Description of “level 5” exercises.

<p>Task 5.1. Perspective sketching from orthographic views.</p> <p>(6 exercises)</p>	<p>NIVEL 5. OBTENCION DE PERSPECTIVAS.</p> <p>EVALUACIÓN</p> <p>Dibujar a mano alzada (croquis) la perspectiva de las vistas propuestas.</p>  
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**Table 7.** Pre-tests results: mean scores, standard deviation (SD), and sample size (n)

	Total Population N=445 Mean (SD)	AR Group n=24 Mean (SD)	Control Group n=25 Mean (SD)
Pre-MRT	18.65 (8.35)	19.67 (7.91)	17.44 ( 9.82)
Pre-DAT-5:SR	29.41 (9.18)	29.17 (7.29)	28.40 (10.17)

**Table 8.** Analysis of variance for MRT and DAT-5:SR between groups.

Summary of ANOVA for Pre-MRT					
	Sum of Squares	GL	Mean Square	F	Sig.
Between Groups	61.459	2	30.730	0.439	0.645
Within Groups	30 912.150	442	69.937		
Total (Corr.)	30 973.609	444			
Total		445			
Summary of ANOVA for Pre DAT-5:SR					
	Sum of Squares	GL	Mean Square	F	Sig.
Between Groups	29.294	2	14.647	0.173	0.841
Within Groups	37 424.270	442	84.670		
Total (Corr.)	37 453.564	444			
Total		445			

**Table 9.** Pre and post-test results: mean and standard deviation

	Pre-test		Post-test		Gain	Gain
	MRT	DAT-5:SR	MRT	DAT-5:SR	MRT	DAT-5:SR
AR Group n = 24	19.67 (7.91)	29.17 (7.29)	27.71 (7.83)	38.46 (7.05)	8.04 (5.31)	9.29 (4.08)
Control group n=25	17.44 (9.82)	28.40 (10.17)	22.08 (9.94)	33.52 (11.77)	4.64 (4.36)	5.12 (7.13)

**Table 10.** Level of significance comparing pre vs. post-test scores (MRT and DAT-5:SR) within each group.

	(Pre/Post-MRT) p-value	( Pre/Post-DAT-5:SR) p-value
AR Group n=24	p= 0.0009< 0.01 t=3.541	p= 0.00004< 0.01 t=4.49
Control Group n=25	p=0.066> 0.05 t=1.88	p=0.092> 0.05 t=1.718

**Table 11.** ANCOVA. Analysis of Covariance for Post-MRT

Source	Sum of Squares Type III	Df	Mean Square	F-Ratio	P-Value
Corrected Model	(a) 3 139.087	2	1 569.543	70.259	0.000
Intercept	722.024	1	722.024	32.321	0.000
CO-VARIANTS					
Pre-MRT	2 751.191	1	2 751.191	123.155	0.000
EFFECTS					
Training Condition (AR vs Control)	166.838	1	166.838	7.468	0.009
Error	1 027.607	46	22.339		
Total	34 393.000	49			
TOTAL (CORRECTED)	4 166.694	48			

(a) R squared = 0.753 (R squared corrected = 0.743)

**Table 12.** ANCOVA. Analysis of Covariance for Post-DAT-5:SR

Source	Sum of Squares Type III	Df	Mean Square	F-Ratio	P-Value
Corrected Model	(a) 3 208.934	2	1 604.467	47.436	0.000
Intercept	449.290	1	449.290	13.283	0.001
CO-VARIANTS					
Pre-DAT-5:SR	2 910.316	1	2 910.316	86.044	0.000
EFFECTS					
Training Condition (AR vs Control)	221.648	1	221.648	6.553	0.014
Error	1 555.882	46	33.824		
Total	68 053.000	49			
TOTAL (CORRECTED)	4 764.816	48			

(a) R squared = 0.673 (R squared corrected = 0.659)

**Table 13.** Multiple Range Tests for MRT Gain by Group

Level	Count	Mean Adjust	Std. Error	95% Confidence Interval		
AR	24	26.735(a)	0.969			
CONTROL	25	23.014(a)	0.949			
Parameter	B	Std. Error	t	Sig	Lower Bound	Upper Bound
Intersection	7.141	1.645	4.341	0.000	3.830	10.452
Pre-MRT	0.857	0.077	11.098	0.000	0.701	1.012
TRAINING_AR	3.721	1.362	2.733	0.009	0.980	6.462
CONTROL_GR	0(a)					

(a). Covariance evaluated Pre-MRT: 18.53

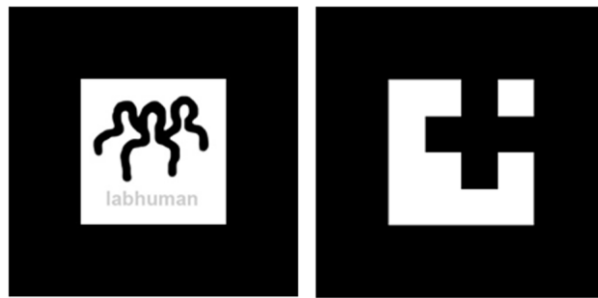


**Table 14.** Multiple Range Tests for DAT-5:SR Gain by Group

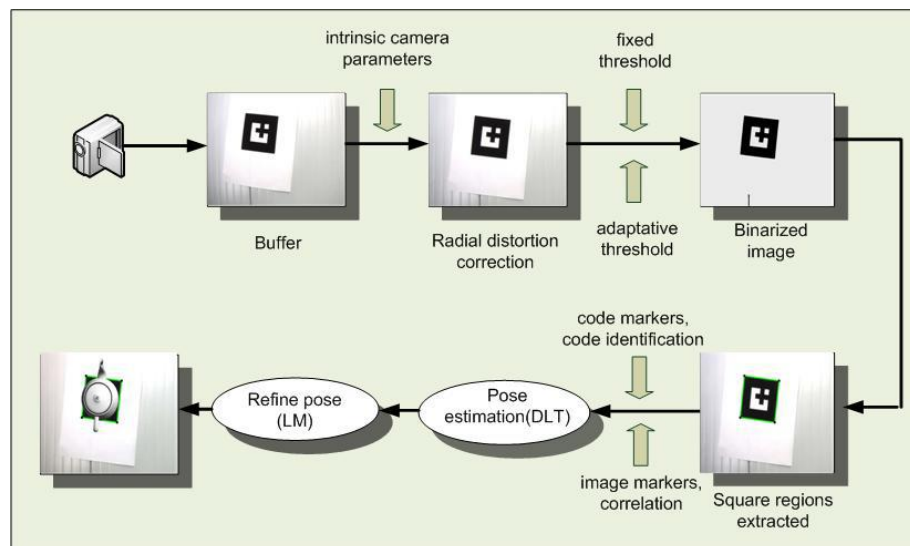
Level	Count	Mean Adjust	Std. error			
AR	24	38.112(a)	1.188			
CONTROL	25	33.853(a)	1.164	95% Confidence Interval		
Parameter	B	Std. Error	t	Sig	Lower Bound	Upper Bound
Intersection	8.344	2.953	2.826	0.007	2.400	14.288
Pre-DAT-5:SR	0.886	0.096	9.276	0.000	0.694	1.079
TRAINING_AR	4.259	1.664	2.560	0.014	0.910	7.607
CONTROL_GR	0(a)					

(a). Covariance evaluated Pre-DAT-5:SR: 28.77

**FIGURES**



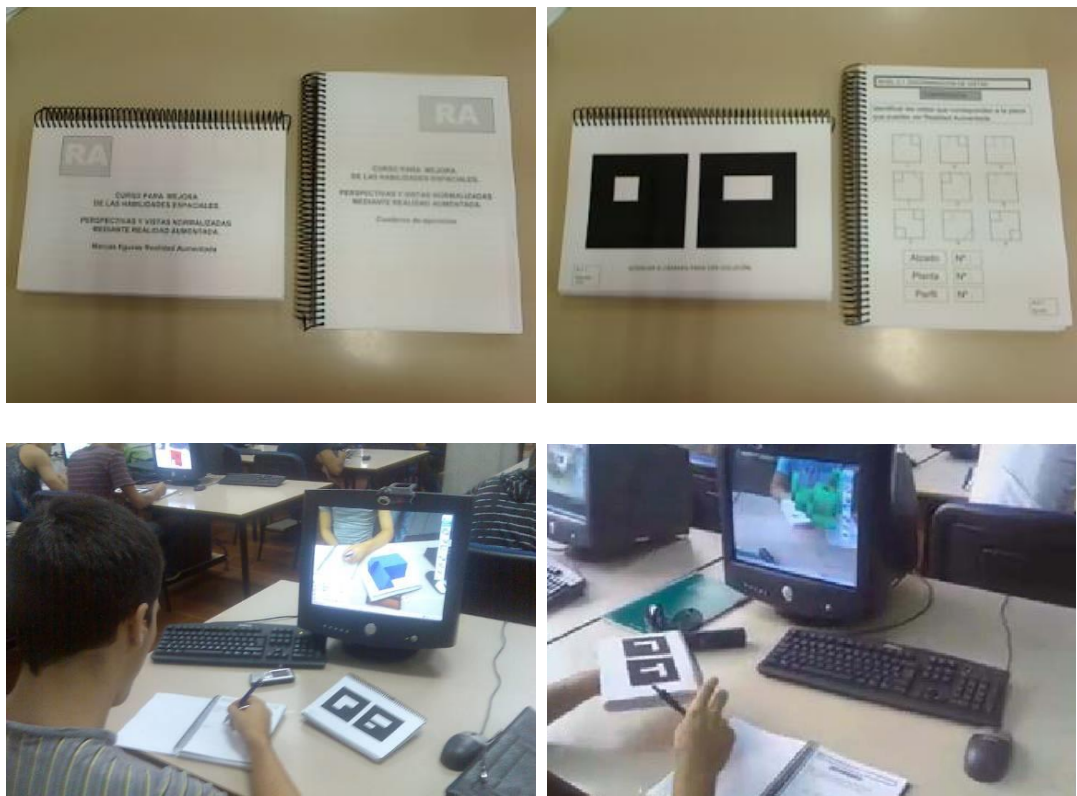
**Fig. 1.** Example of different types of markers supported by our library. Left: Template-based markers. Right: ID-based markers .



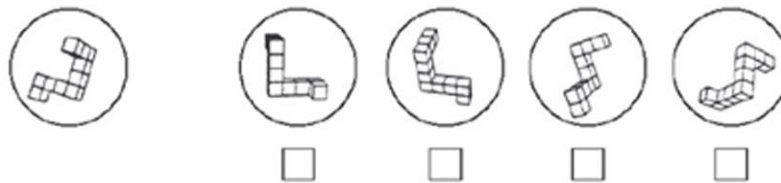
**Fig. 2.** HUMANAR block diagram.



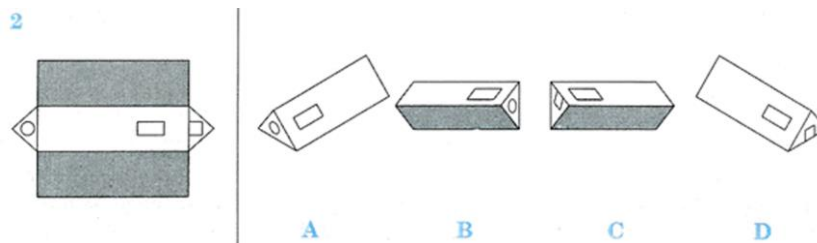
**Fig. 3.** Example of pattern normalization.



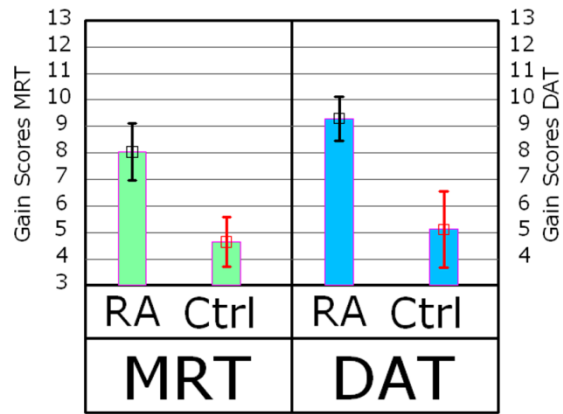
**Fig. 4.** AR-Dehaes toolkit



**Fig. 5.** Example of MRT test question



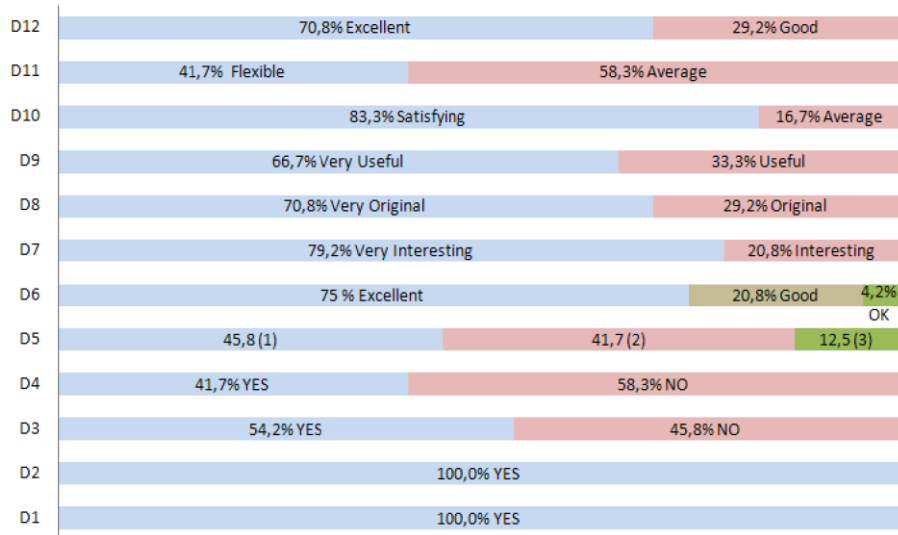
**Fig. 6.** Example of DAT-5:SR test question



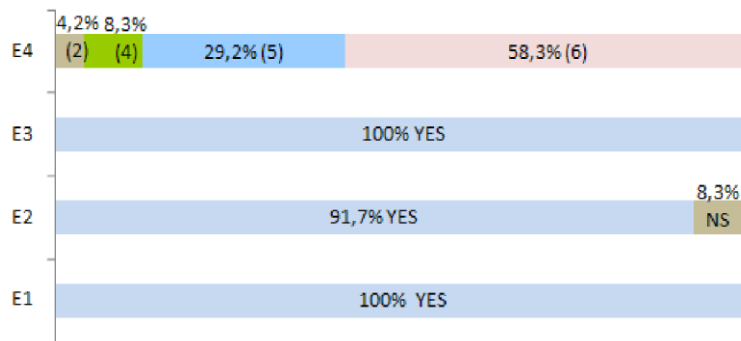
**Fig 7.** Main gain scores and standard error for MRT and DAT-5:SR tests



**Fig 8.** User satisfaction questionnaire: results of A, B and C blocks (mean value and std. error)



**Fig. 9.** User satisfaction questionnaire: results of D block



**Fig. 10.** User satisfaction questionnaire: results of E block