IMPROVEMENT AND ASSESSMENT OF SPATIAL ABILITY IN ENGINEERING EDUCATION

G. Marunić[*] – V. Glažar

Department of Mechanical Engineering Design, University of Rijeka, Faculty of Engineering, Vukovarska 58, Rijeka, Croatia

ARTICLE INFO

***Article history*:**
Received: 21.3.2013.
Received in revised form: 17.9.2013.
Accepted: 11.10.2013.

Keywords:
Spatial ability
Engineering graphics
Test
Education
CAD
Assessment

Abstract:

The development of three-dimensional Computer Aided Design (3D CAD) technology has additionally spurred research into spatial ability to find the ways for its enhancement through teaching and instruction and to understand the mechanism of its assessment. The techniques involved in multimedia engineering environment of today as well as their inclusion into engineering curricula and courses have to be strongly supported by wider knowledge of spatial ability.

This paper is a review of research results applied to engineering graphics education by respecting spatial ability as a recognized predictor of success in engineering. The development of engineering graphics teaching based on research suggestions about spatial ability represents an increasingly complex approach that puts additional stress on engineering graphics educators. Thus classical tests for the assessment of spatial ability are described, the applied strategies for their solving are presented, the selected obtained results are compared, and a distinction is drawn between the strategies employed for more complex spatial tasks that engineering is dealing with.

1 Introduction

The ability to retain, retrieve and transform visual images is defined as spatial ability. Several components of spatial ability have been detected owing to different aspects of underlying processes. Five components were defined by Maier [1], but according to Barnea [2], three components resulting from some overlapping are usually cited.

Depending on the levels of difficulty, these components are: “spatial visualization” as the ability to understand accurately three-dimensional objects through their two-dimensional (2D) representation, “spatial orientation” as the ability to imagine what a representation will look like from a different perspective, and “spatial relations” as the ability to visualize the effects of operations (rotation, reflection, inversion), or to mentally manipulate objects.

Tartre [3] limited the components of spatial ability to 3D spatial visualization and spatial orientation. Spatial visualization involves /mental imagery of an object moving, while spatial orientation involves being able to move the viewpoint mentally while the object remains fixed in the space. Spatial visualization component is subdivided into mental

[*] Corresponding author. Tel.: +385 51 651 537; fax: +385 51 651 406
E-mail address: gmarunic@riteh.hr.

rotation and mental transformation. There is a distinctive difference between these two categories as mental rotation refers to the entire object which is transformed by being turned in the space whereas under mental transformation we mean when only a part of the object is transformed.

Educational psychology makes the distinction between spatial ability as an innate ability to visualize and spatial skills that are learned or are acquired through training. As it is difficult for engineering students to make a distinction between spatial ability and spatial skills, these terms are often used interchangeably [4]. Likewise, the term spatial visualization is often used interchangeably with the broader terms of visualization and spatial ability.

The widely declared roles of engineering graphics in the design process are visualization, communication and documentation [5] and [6] while some authors see the graphics as engineers´ tool for visualization, analysis, optimization and presentation [7]. Design problems in engineering education have been firstly solved with the method design-by-drawing. The carefully developed and precise drawing standards have been applied in conjunction with the acquired knowledge of shape description based upon Descriptive Geometry projection methods, regardless of the used tool, i.e., traditional drawing instruments or 2D CAD system. The development of computer hardware and software has initiated changes towards the method design-by-virtual models when 3D CAD model database represents the centre not only for all design activities but even wider [8].

The previous contents of engineering graphics courses have had to be carefully reconstructed to meet new demands, and at the same time to keep the effectiveness necessary for the still expanding role of engineering graphics.

With the need to meet new requirements, engineering students are expected to manipulate 2D images and additionally 3D geometry in order to effectively use 3D CAD system and its possibilities. The importance of spatial thinking and the improvement of visualization skills have become an important objective of an engineering graphics course.

Educational materials for engineering graphics have followed the described trends in engineering graphics curricula. The contents that support spatial reasoning through 3D geometrical modelling have been included along with the contents that are intended to give an insight into the importance of evolved engineering graphics and to give an overall picture of its recent role in the engineering environment [6], [7] and [9].

2 Improvement of spatial ability

Spatial ability (intelligence) is also defined as adoptive spatial thinking that is central to many scientific domains [10]. It involves "thinking about the shapes and arrangements of objects in space and about spatial processes, such as the deformation of objects, and the movement of objects and other entities through space". The concept of individual differences in spatial ability has represented important issue for the researches conducted through different domains and consequently 84 different careers have been suggested for which well-developed spatial skills are important. For engineering, i.e., technical domain, spatial ability/skills are of utmost importance [1].

Based on the results of psychological studies, several factors that influence spatial ability have been recognized and elaborated through numerous studies. In relation to the factor of experience, the activities like playing with construction toys in childhood, sketching, drawing in middle school, playing 3D computer games, the participation in some sport and well developed mathematical skills, have been indicated for the development of spatial skills [4]. On the other hand, Devon et al. [11] suggested that previous drafting or using CAD system has no impact on spatial visualization skills.

The factors of age and experience indicated as significant in psychological domain have usually been neglected in engineering graphics domain. However, the factor of gender has been recognized as an important factor, leading to the differences in spatial ability between men and women. As far as engineering students are concerned, regardless of the obvious significant gain scores in post-testing for both men and women, the average post-test scores for women were found to be lower than the average pre-test scores for men. Testing was performed before and after an engineering or descriptive geometry course.

Contradictory results have been obtained from numerous researches that have tried to find the means for successful improvement of spatial ability/skills and undoubtedly a lot of work is still to be done in future. Some authors believe that spatial visualization skills are to be developed through our life experience [12], whereas others assume that they can be improved through adequate instruction. The second statement addresses in some degree more engineering graphics educators and therefore it is worth presenting the results of some researches.

Engineering graphics courses are usually carried out through the first year of study so that students with weaker spatial skills and lower spatial visualization ability might be discouraged at the very beginning. This has been recognized as an important reason for the development and implementation of introductory courses intended to improve spatial skills. An introductory course was established and students were supervised by a professor during six years [13] based on teaching how to use paper and pencil sketching techniques (isometric and orthographic sketching, pattern development, two and three - coordinate drawing, rotation of objects, cross sections of solids) and CAD (surfaces, solids of revolution, intersection of solids). First year engineering students who took this course to enhance 3D spatial visualization skills improved significantly their scores on measures of spatial visualization in comparison with the students who did not take it.

The sketching and drawing skills have been not only mostly proposed tool for the development of spatial skills and enrichment of spatial abilities but also recognized as a useful means for enhancement of capacity for visual imagery and creativity [14]. Sorby claims, "It seems that in order to develop 3D spatial skills, the answer is sketching, sketching, sketching!" [4]. The studies have found that in general, positive attitudes towards teaching activities enhance the successfulness of declared learning outcomes. Therefore, the insight into possible interaction between students´ attitudes considering the sketching, drawing and spatial visualization ability was investigated to support the teaching [15] and [16]. The model was proposed based on empirical evidence that illustrates the relationships between attitude, view and usage tendency in relation to sketching, drawing and spatial visualization ability [16]. Fig. 1 shows spatial visualization ability directly linked with the usage tendency of sketching and drawing, and indirectly linked with engineering students´ view of the professional role of sketching and drawing. Therefore, the adequate contents have to be added enabling the students more general insight into the role that engineering graphics has for the communication and analysis. This may exert an impact on the usage tendency of sketching and drawing and finally on the development of spatial visualization ability. These statements advocate a well established approach to engineering graphics literature that starts from the roles and importance of graphics for design process [5] and [6]. Considering the efficiency as one goal of teaching future engineers, the combination of three key elements, spatial visualization, freehand sketching and normalized view generation is recommended [17].

The development of new computer technologies such as simulation, animation, virtual reality and rapid prototyping has been seen and researched as a possible means for supporting spatial thinking and enhancing spatial ability/skills. The research into the benefits acquired by 3D solid modelling system and 3D wireframe system noticed that solid modelling enhances spatial visualization skills more than wireframe 3D CAD or traditional graphics [11]. The paper of Godfry [18] presents the comparison between 3D models and animated wireframes, and 2D models (orthogonal views, pictorial representations). The results did not indicate any predomination of 3D CAD models for the enhancement of spatial visualization. Moreover, it was shown that the mere application of 3D CAD solid modelling is less efficient for the development of spatial skills in comparison with traditional techniques, such as sketching [19]. The fact that students are accustomed to using different technological gadgets is considered and a traditional way of sketching and drawing for the enhancement of spatial ability is completed by applying the benefits offered by technology [17] and [20]. Starting with the combination of traditional/CAD teaching, a significant increase in number of drawings and learned concepts in comparison with teaching only traditional drafting methods can be noticed. The most positive feature of multimedia based instruction is the capability to capture and maintain students´ attention and to respect their specific learning abilities much more than by traditional teaching.

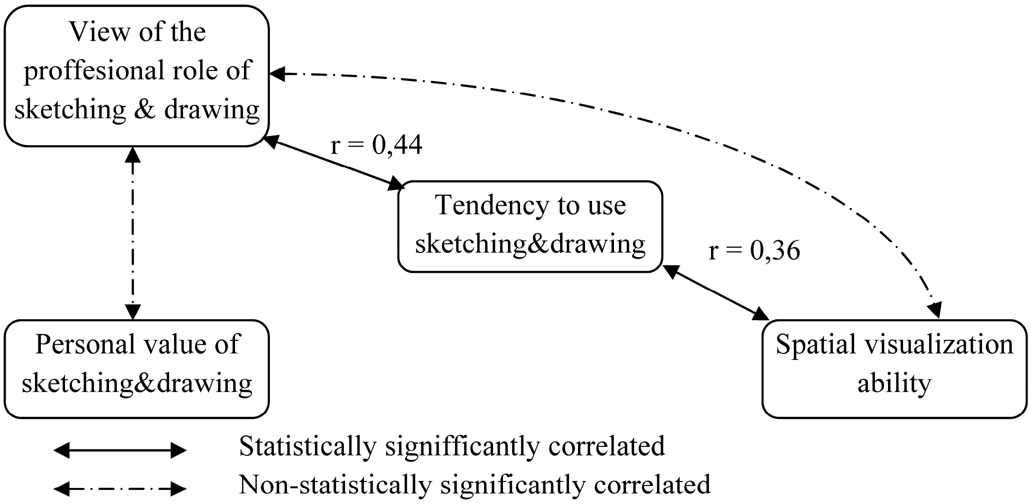

Figure 1. The model for the relationship between the attitude towards the sketching and drawing, and spatial visualization ability [16].

Multimedia CD-ROM accompanied by the workbook is aimed at helping the development of skills in variety of technical careers including engineering [21].

Nine modules provide the experience in working with isometric drawings, orthographic projections reflections and symmetry, surfaces and solids of revolution, plus combining solids. Fig. 2 shows an example where the appropriate Boolean operation is to be indicated to obtain a shown object.

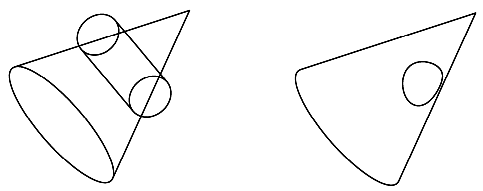

Figure 2. The combination of two objects by employing the Boolean operations [21].

The importance of spatial visualization ability/skills has increased as it is the most significant predictor for manipulation and utilization of numerous advantages offered by recent technologies [22-24]. On the other hand, the question related to spatial cognition defined by Miller [25] as “underlying mental process that allows an individual to develop spatial abilities”, has been widely researched considering the available computer based multimedia and its impact on cognitive load [26] and [27]. It was found that 3D models may lead to cognitive overload problems in hypermedia-learning environments. But the use of Internet has enabled the students to access the courses specially developed for the enhancement of spatial ability [28].

It is very often assumed that animations are really superior compared with static graphics, but some researchers found that effects of animations may not always be beneficial [29] and [30]. The comparisons across eight experiments showed no evidence that animations or static diagrams are more or less effective for the individuals with different abilities or knowledge, or that different types of animations are more or less effective for different individuals [30].

As rapid prototyping supplies the student with physical models in addition with 3D CAD virtual models, the justification of its introduction was investigated in relation to the improvement of visualization skills [31]. The visualization tests showed the greatest rise in scores for the level of board drafting instruction in comparison with 2D CAD and 3D CAD instruction, but there was no obvious rise for the use of rapid prototyping in comparison with 3D CAD instruction. In [32] a pilot study was performed to examine VR (Virtual Reality) technologies and their integration into design and engineering graphics courses. The results confirmed that VR models improved the ability of most students to visualize 3D objects more successfully, and thus pointed to VR as useful and promising tool for the improvement of students' learning and motivation. Furthermore, this research has actuated the questions about the relation between the used VR systems and the effectiveness of integrating VR models in the courses.

The research method of particular interest for exploring the ways for train spatial skills through the designed 3D immersive virtual environment is described by Imagery Lab. [33].

The conclusions have been that “the indicated results demonstrate that 3D immersive environment appears to be significantly more efficient for training imagery skills than 2D or 3D non–immersive environments.

3 Classical tests of spatial ability

A lot of tests for measuring and classifying spatial ability have been developed due to practical reasons such as predicting performance in various occupations, and engineering graphics educators have widely used these measures for educational research. Spatial visualization is the component of spatial ability that is predominantly measured by tests. Classical tests of significant interest for most engineering educators have been as follows.

Mental Cutting Test (MCT) [34] dating back to 1939 was first developed for the university entrance exam in the USA. It has 25 questions and each question consisted of a 3D object seen from one angle and cut by the plane. One of five options is to be selected that represents most accurately the section of the object (Fig. 3).

The Differential Aptitude Test: Space Relations (DAT: SR) [35] was found to be a predominant predictor of success in engineering graphics course in comparison with other spatial visualization tests. The test consisted of 50 items and the task is to choose an appropriate 3D object among four objects that would result from folding the given unfolded shape (Fig. 4).

Mental Rotations Tests (MRT) [36] are consisted of 20 questions. 2D representation of a 3D object composed of cubes is shown when seen from one angle. The participants have to identify two rotated versions of the object among four offered representations (Fig. 5).

The Purdue Spatial Visualization Tests: Rotations (PSVT: R) [37] were developed in 1977 and consisted of 30 items. The first given object is rotated in space. For the second given object, the choice among five objects is to be made when the second object would be rotated by the same amount in space as the first object was (Fig. 6).

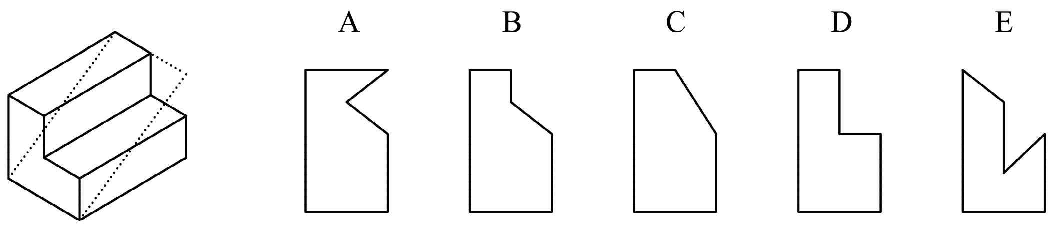

Figure 3. The example from Mental Cutting Test MCT [34].

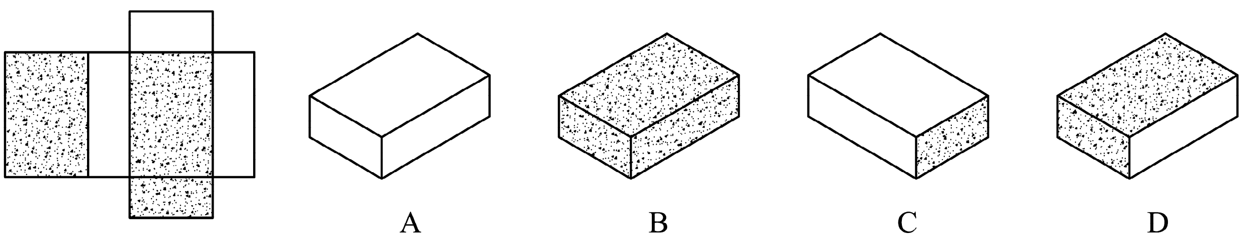

Figure 4. The example from the Differential Aptitude Test: Space Relations DAT:SR [35].

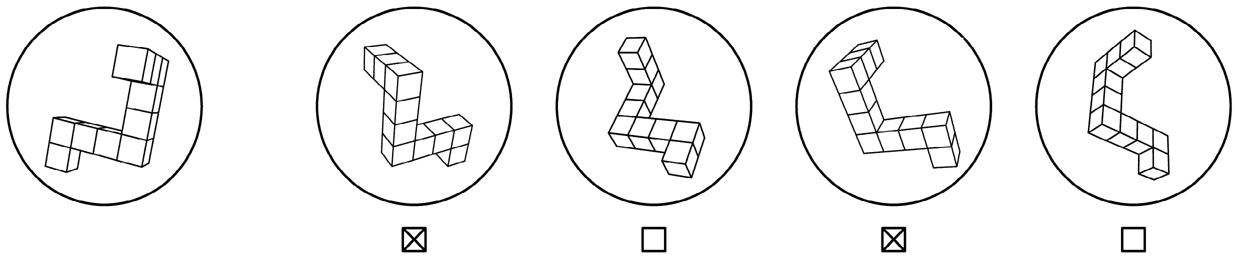

Figure 5. The example from Mental Rotations Tests MRT [36].

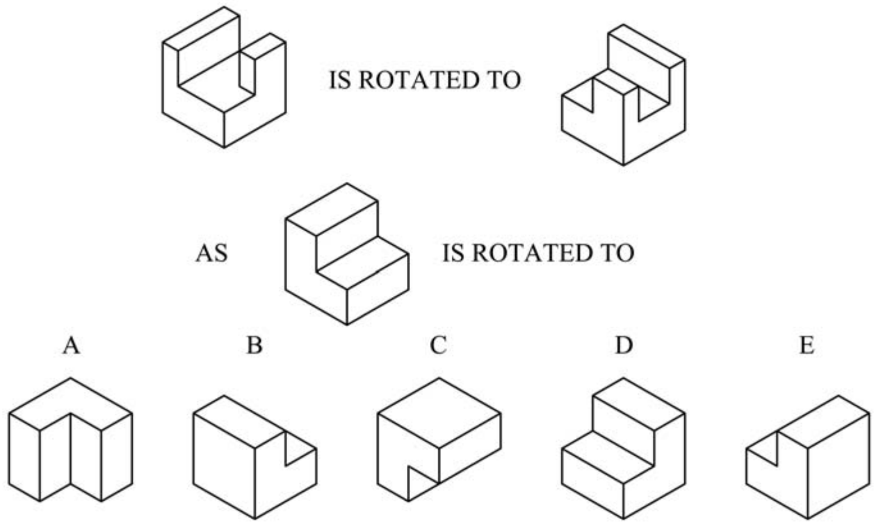

Figure 6. The example from The Purdue Spatial Visualization Test: Rotations [37].

The research results indicated as before for DAT: SR this test as the most significant predictor of success in engineering graphics course [38].

PSVT:R was modified in [39] by means of AutoCAD, and 3D solid models were developed as a realistic pictorial view characterized by features as 3D volume and dimensions, colours, lighting and shades, surface textures, material, perspective view, etc. Based on the fact that isometric drawing original PSVT:R is simplified and partly distorted view of a 3D object, the testing results by applied original and modified tests were compared and the obtained test scores for a realistic 3D test were found higher with the enhanced performance on spatial visualization.

In 1998, a 3-Dimensional Cube (3DC) was designed [40], the test for the assessment of ability to visualize rotated solids. It consisted of 17 items that are scored.

The criterion cube with different patterns on each of six sides is shown. The student must choose one of six given positions of the cube that corresponds to the rotated given cube. Two additional choices are available, as shown in Fig. 7.

The previously mentioned multimedia CD-ROM and its accompanying workbook [21] embrace the variations of items that exist in the above mentioned tests but also offer some additional possibilities.

Hegarty [10] alerted that the development of spatial ability measures had not been systematic and theoretically motivated and there had been no systematic attempts to establish tests that could measure firstly identified basic components of spatial intelligence.

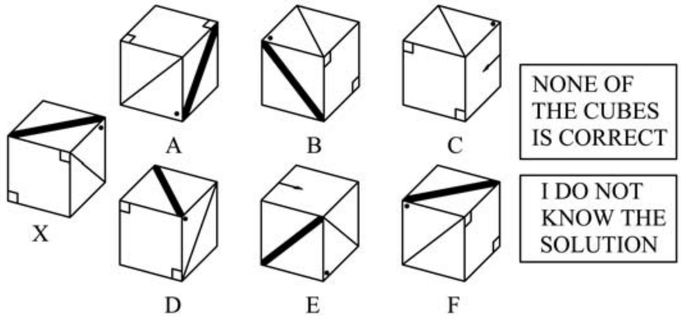

Figure 7. The example from 3 - Dimensional Cube 3DC [40].

The research results indicated that tests of spatial visualization were not only the tests of ability to form a mental images of objects, but they also comprised the variety of strategies including more analytical ones [41] and [42]. According to Hegarty, it was confirmed that "spatial intelligence involves not just visualization ability, but flexible strategy choice between visualization (mental imagery) and more analytic thinking processes as well" [10]. The interplay between these types of thinking for solving tests of spatial ability is shown in Table 1 for the strategy use in Mental Rotation Test.

4 Complex spatial tasks

Spatial thinking in the domains such as mechanics, medicine and chemistry, seems to be considerably more complex than those included in psychometric tests of spatial ability. The visualization is augmented in complex spatial thinking by two types of analytical thinking: task decomposition and rule-based reasoning.

The pattern of results [10] indicated that the behavior of a complex system is accomplished by decomposing the task into a sequence of simple interactions when less information is visualized at a time. The rule-based reasoning includes the observation of regularities when more analytical thinking is employed. The example for a rule-based reasoning is shown in Fig. 8.

For the solution, the motion of individual gears was firstly mentally simulated, acquiring the simple rule of gear movement direction. A rule-based strategy was then used, but for every new gears arrangement, a new mental simulation strategy was used.

Table 1. Strategy use in the Vandenberg and Kuse Mental Rotation Test [10]

	Number of participants who reported the strategy
Mental imagery strategies	
I imagined one or more of the objects turning in my mind	34 (92%)
I imagined the objects being stationary as I moved around them to view them from different perspectives	13 (35%)
Spatial analytic strategies	
I noted the directions of the different sections of the target with respect to each other and checked whether these directions matched the answer choices	30 (81%)
I figured out whether the two end arms of the target were parallel or perpendicular to each other and eliminated answer choices in which they were not parallel	23 (62%)
Pure analytical strategy	
I counted the number of cubes in different arms of the target and checked whether this matched in the different answer choices	20 (54%)
Test taking strategy	
If an answer choice was hard to see, I skipped over it and tried to respond without considering that choice in detail	8 (22%)

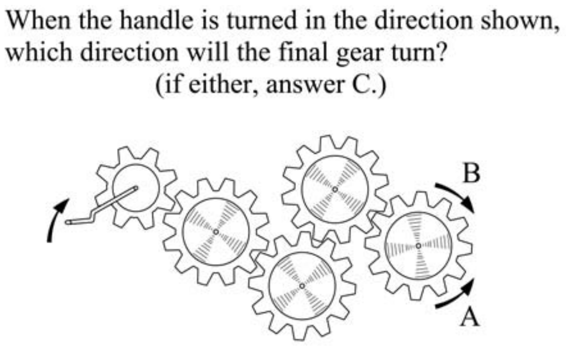

Figure 8. The gear problem where rule-based reasoning takes over [10].

5 Results of studies concerned with spatial ability assessment

At the University of Rijeka Faculty of Engineering, Croatia, the assessment of spatial ability was performed in acad. years 2012 and 2013. The students of university undergraduate studies of mechanical engineering and naval architecture, and the students of electrical engineering study were tested by means of two classical tests: Mental Rotation Test (MRT) [36] and Guay – Lippa Test (VVT) [43]. For VVT, a 3D object is given in isometric view positioned in the middle of the glass-box, and below it the same object is represented from a new viewing position. The corner of the glass-box from which the object is viewed has to be identified. By the chosen tests, the measures for student`s spatial visualization and spatial orientation are included.

The first testing was accomplished before and after introductory engineering graphics course during the first semester. For both studies under consideration, the course represents the combination of traditional contents and tools, and 2D CAD tools running through multimedia environment. As the curriculum of university undergraduate electrical study contains only this course of engineering graphics, it diverges from the course of undergraduate mechanical engineering&naval architecture study in the additional contents dealing with the basics of 3D CAD modelling. The intention was to examine the connection between students` spatial ability and decision to approach certain study, the possible correlation between initial spatial ability and final course achievement and the difference among the obtained gain in scores for post-tests in relation to pre-tests.

The second testing was performed for the students of undergraduate mechanical engineering & naval architecture study before and after the course dealing with 3D CAD modelling running through the second semester. The research results were aimed to answer whether CAD instruction affects student`s spatial ability or not as different results have been reported until now, which makes the issue actual. The results of testing are analyzed in detail and are to be published.

In Table 2, the results obtained at the University of Rijeka Faculty of Engineering are presented along with the selected research results accomplished by the mostly utilised classical spatial ability tests that cover the measurement of different spatial ability components. The table contains the information about mean scores, mean percent correct and also standard deviation where available. The included data regards to introductory courses aimed to enhance spatial ability/skills as well as to the courses that belong to the curriculum of certain engineering studies, the, are considered.

It is evident from the presented results that the achieved test scores differ from measure to measure, regardless of pre-test or post-test.

The test gain scores when the students were tested before and after certain form of engineering graphics course are always considerable ones whether traditional engineering graphics course is running or not through multimedia environment. The same trend can be noticed for the students at the University of Rijeka, Faculty of Engineering, but the test gain scores for pre-test and post-test pointed to the 3D CAD modelling course as an effective means for fostering spatial ability unlike some reported research results. The scores achieved for the pre-tests can represent both the indicator in the student performance of various spatial tasks and a possible predictor of the course final exam scores.

The obvious gain of scores for post-tests related to pre-tests that generally occur regardless of wide variations, can supply with important information about the validity of course content and tuition modus for the improvement of spatial ability/skills.

Table 2. The selected research results of students` spatial ability assessment obtained by the mostly used classical tests

Author/s	Number of students	Pre-test mean/% correct (SD)	Post-test mean/% correct (SD)	Eng. graphics/spatial ability tuition between pre and post-test
	MRT			
Marunić&Glažar, 2012	86 (Mech. Eng.&Nav. Arch.)	9.8/49.1 (19.7)	13.5/67.3 (18.7)	Traditional eng. graphics topics (2D CAD modelling, multimedia environment), 45 h
	56 (Elect. Eng.)	9.7/48.5 (19.8)	13.1/65.3 (17.0)	
Marunić&Glažar, 2013	104 (Mech. Eng.&Nav. Arch.)	11.1/55.3 (4.0)	13.8/68.9 (3.9)	3D CAD modelling, 45 h
Sorby, 2007 [44]	186	/61.9	/71.9	Traditional spatial skills course, 2h /week for a semester
	61	/53.0	/72.8	Multimedia spatial skills course, 2h /week for a semester
Leopold et al., 2001 [45]	220	12.7/63.3 (21.8)		Traditional eng. graphics course (descriptive geometry), up to 60 h
	196	12.3/61.4 (22.17)		Traditional eng. graphics course, up to 45 h
	55	12.3/61.3 (19.4)		Traditional eng. graphics course, up to 40 h
	VVT			
Marunić&Glažar, 2012	86 (Mech. Eng.&Nav. Arch.)	12.1/60.7 (31.4)	14.6/73.0 (23.2)	Traditional eng. graphics topics (2D CAD modelling, multimedia environment), 45 h
	56 (Elect. Eng.)	11.3/56.5 (29.3)	13.3/66.6 (25.1)	
Marunić&Glažar, 2013	104 (Mech. Eng.&Nav. Arch.)	12.4/51.5 (6.5)	14.8/61.6 (6.7)	3D CAD modelling, 45 h
	PSVT:R			
Connolly, 2009 [46]	54	/79.4	/84.3	Introductory eng. Graphics cours (Geometric Modelling for Visualization and Communication), 16 week semester
Ferguson, 2008 [47]	31	22.0/73.3 (5.6)	23.6/78.6 (4.6)	Two instructional methods to influence spatial ability (traditional eng. graphics + hand-held mechanical dissection manipulatives), 15 h
Sorby, 2007 [44]	186	/50.9	/77.0	Traditional spatial skills course, 2h /week for a semester
	61	/49.0	/73.3	Multimedia spatial skills course, 2h /week for a semester
Yue, 2001 [48]	18	22.7/75.6	22.9/76.5	Applied CAD, 45 h
	24	25.0/83.2	24.5/81.5	Computer Aided Design, 60 h

6 Conclusions

Based on the research results, numerous recommendations have been offered for the improvement and enhancement of spatial ability confirmed to be a crucial intelligence component and a predictor of success in engineering. The development of visualization skills is a particular goal of modern engineering graphics courses [7] and spatial reasoning as a core competence for future engineers' gains relevance in current and future engineers´ curricula [17].

For the purpose of improving spatial skills, the today´s approach adopted through engineering graphics courses and the accompanying material, is a hybrid model that consists of traditional contents (sketching, orthographic projection-views, pictorial views, sectioning, auxiliary views) and the contents that embrace modelling, visualization and sketching by exploiting the results of multidisciplinary research and recent technologies. The instrument drawing has been mainly replaced by CAD system tool and descriptive geometry contents have been reduced. As free hand sketching has been highly recommended by the researchers for the improvement of spatial ability/skills, a great emphasis has been placed on its inclusion. The preceded contents to the free hand sketching that highlight the role of engineering graphics in engineering design process and engineering generally and therefore foster students´ motivation, have been also taken into consideration.

The proved means for the enhancement of spatial ability/skills are also the adequate preparation and selection of learning content, additional courses for the students with poor spatial abilities, and the use of hand-held models.

The research into classical tests of spatial visualization ability shows that when solving these tests the use of visualization is an important process that is to be accompanied by a number of more analytical strategies. In the case of complex spatial tasks in engineering that are more complex in comparison with tasks in psychometric tests, the visualization is augmented by more analytical thinking such as task decomposition and rule-based reasoning.

The concrete research results considering spatial ability that are important for and applicable to engineering education area have been always followed by the questions that are to be answered in some further studies.

Engineering graphics educators have got the responsibility to take these studies into account when developing and adjusting the courses and accompanying materials to the environment determined by modern technologies.

References

[1] Maier, P.H.: *Raeumlishes Vorstellungsvermoegen*, Frankfurt: Lang, Frankfurt am Main, 1994.

[2] Barnea, N.: Teaching and Learning About Chemistry and Modelling With a Computer Managed Modelling System. In: *Developing Models in Science Education*, Kluwer Academic, Dordrecht, 2000, 307–324.

[3] Tartre, L.A.: Spatial Skills, Gender and Mathematics. In: *Mathematics and Gender*, Teachers College Press, New York, N.Y., 1990, 27-59.

[4] Sorby, S.A.: *Developing 3D Spatial Visualization Skills,* Engineering Design Graphics Journal, 63 (1999), 2, 21-32.

[5] Bertoline, G.R., Wiebe, E.N.: *Fundamentals of Graphics Communication*, McGraw Hill Higher Education, Boston, 2005.

[6] Lockhart, S.D., Johnson, C.M.: *Engineering Design Communication: Conveying Design Through Graphics*, Prentice Hall, Boston, 2012.

[7] Lieu, D.K., Sorby, S.A.: *Visualisation, Modelling and Graphics for Engineering Design*, Delmar Cengage Learning, 2009.

[8] Contero, M., Naya, F., Company, P., Saorin, J.L., Conesa, J.: *Improving Visualization Skills in Engineering Education*, IEEE Computer Graphics and Applications, 2005, 24-31.

[9] Madsen, D.A., Madsen, D.P., Turpin, J.L.: *Engineering Drawing and Design,* Thomson Delmar Learning, Clifton Park, NY, 2007.

[10] Hegarty, M.: *Components of Spatial Intelligence*, Psychology of Learning and Motivation, 52 (2010), 265-297.

[11] Devon, R., Engel, R.S., Foster, R.J.: *The Effect of Solid Modelling on 3D Visualization Skills*, The Engineering Design Graphics Journal, 58 (1994), 2, 4-11.

[12] Bertoline, G.R.: *The Implications of Cognitive Neuroscience Research in Spatial Abilities and Graphics Instruction*, The

International Conference on Engineering Design Graphics, Austria, 1988.

[13] Sorby, S.A., Baartmans, B.J.: *The Development and Assessment of a Course for Enhancing the 3-D Spatial Visualization Skills of First Year Engineering Students,* Journal of Engineering Education, 89 (2000), 3, 301-307.

[14] Ferguson, E.S.: *Engineering and the Mind´S Eye*. MA: The MIT Press, Cambridge, 1992.

[15] Yokomoto, C.F., Buchanan, W.W., Ware, R.: *Problem Solving: An Assessment of Students Attitudes, Expectations and Beliefs*, The 1995 Frontiers in Education Conference, Atlanta, 1995.

[16] Alias, M., Gray, D.E., Black, T.R.: *Attitudes Towards Sketching and Drawing and the Relationship with Spatial Visualization Ability in Engineering Students,* International Education Journal, 3 (2002), 3, 165-175.

[17] Contero, M., Company, P., Saorin, J.L., Naya, F.: *Learning Support Tools for Developing Spatial Ability in Engineering Design*, International Journal of Engineering Education, 22 (2006), 3, 470-477.

[18] Godfry, G.S.: *Three-Dimensional Visualization Using Solid-Model Methods: A Comparative Study of Engineering and Technology Students*, Unpublished PhD diss., Northern Illinois University, 1999.

[19] Sorby, S.A., Gorska, R.A.: *The Effect of Various Courses and Teaching Methods on the Improvement of Spatial Ability*, The 8th International Conference on Engineering Design Graphics and Descriptive Geometry, Austin, 1998.

[20] Strong, S., Smith, R.: *Spatial Visualization: Fundamentals and Trends in Engineering Graphics*, Journal of Industrial Technology, 18 (2002), 1, 1-6.

[21] Sorby, S.A., Wysocki, A.F.: *Introduction to Spatial Visualization: An Active Approach.* Thomson Delmar Learning, Clifton Park, NY, 2003.

[22] Norman, K.L.: *Spatial Visualization – A Gateway to Computer – Based Technology,* Journal of Special Educational Technology. 12 (1994), 3, 195-206.

[23] Pleck, M.H.: *Factors Affecting the Engineering Design Graphics Curriculum: Past, Present, Future*, The NSF Symposium on Modernization of the Engineering Design Graphics Curriculum, Austin, 1990.

[24] Stanney, K.: *After Effects and Sense of Presence in Virtual Environments: Formulation of a Research and Development Agenda*, International Journal of Human Computer Interaction, 10 (1998), 2, 135-187.

[25] Miller, C.L.: *A Historical Review of Applied and Theoretical Spatial Visualization Publications in Engineering Graphics*, The Engineering Design Graphics Journal, 60 (1996), 3, 12-33.

[26] Huk, T.: *Who Benefits from Learning with 3D Models? The Case of Spatial Ability,* Journal of Computer Assisted Learning, 22 (2006), 392-404.

[27] Keehner, M.: *Effects of Interactivity and Spatial Ability on the Comprehension of Spatial Relations in a 3D Computer Visualization*, The 26th Annual Conference of the Cognitive Science Society, Mahwah, 2004.

[28] Gaughran, B.: *To Investigate the Effectiveness of 3D Computer Modelling in the Development of Visualisation Skills*, from http://www3.ul.ie/tilde_accs/mearsa/www/9519211/genises.htm, accessed on 2013-03-07.

[29] Narayanan, H.N., Hegarty, M.: *Communicating Dynamic Behaviours: Are Interactive Multimedia Presentations Better Than Static Mixed Mode Presentations? In: Diagrams 2000*, Springer-Verlag, Berlin Heidelberg, 2000, 178-193.

[30] Hegarty, M.: *Effects of Knowledge and Spatial Ability on Learning from Animation. In: Learning from Animation*, Cambridge University Press, New York, 2007, 3-29.

[31] Frey, G., Baird, D.: *Does Rapid Prototyping Improve Student Visualization Skills*, Journal of Industrial Technology, 16 (2000), 4, 2-6.

[32] Smith, S.S-F. & Lee, S - L.: *A Pilot Study for Integrating Virtual Reality into an Introductory Design and Graphics Course*, Journal of Industrial Design, Vol. 20 (2004),4, 1-7.

[33] Imagery Lab.: *Mental Imagery and Human-Computer Interaction Lab*, from http://www.nmr.mgh.harvard.edu/mkozhevnlab/, accessed on 2013-03-07.

[34] CEEB.: *Special Aptitude Test in Spatial Relations (MCT),* College Entrance Examination Board, USA, 1939.

[35] Bennet, G.K., Seashore, H.G., Wesman, A.G.: *Differential Aptitude Tests, Forms S and T*, the Psychological Corporation, New York, 1973.

[36] Vandenberg, S.G., Kuse, A.R.: *Mental Rotations: A Group Test of Three Dimensional Spatial Visualization*, Perceptual and Motor Skills, 47 (1978), 599-604.

[37] Guay, R.B.: *Purdue Spatial Visualization Test: Rotations*, Purdue Research Foundation, West Lafayette, 1977.

[38] Bertoline, G.R., Miller, D.C.: *A Visualization and Orthographic Drawing Test Using the Macintosh Computer*, Engineering Design and Graphics Journal, 54 (1990), 1, 1-7.

[39] Yue, J.: *Spatial Visualization by Realistic 3D Views,* Engineering Design and Graphics Journal, Vol. 72 (2008), 1, 28-38.

[40] Gittler, G., Glueck, J.: *Differential Transfer of Learning: Effects of Instruction in Descriptive Geometry on Spatial Test of Performance,* Journal for Geometry and Graphics, 2 (1998), 1, 71-84.

[41] Hegarty, M., Waller, D.: Individual Differences in Spatial Abilities. In: *Handbook of Visuospatial Thinking*, Cambridge University Press, New York, 2006, 121-169.

[42] Lohman, D.F.: *Spatial Abilities as Traits, Processes, and Knowledge*, Advances in the Psychology of Human Intelligence, 4 (1988), 181-248.

[43] Guay, R., Mc Daniels, E.: *The visualization of viewpoints*, The Purdue Research Foundation, West Lafayette, 1976 (as Modified by Lippa, Hegarty and Montello, 2002).

[44] Sorby, S.A.: *Developing 3D spatial skills for engineering students*, Australasian Journal of Eng. Education, 13 (2007), 1, 1-11.

[45] Leopold, R. Gorska, S. Sorby, S.A.: *Experiences in Developing the Spatial Visualization Abilities*, Journal for Geometry and Graphics, 5 (2001), 1, 81-91.

[46] Connolly, P. E.: *Spatial Ability Improvement and Curriculum Content*, Engineering Design Graphics Journal, 73 (2009), 1, 1-5.

[47] Ferguson, C., Ball, A., McDaniel, W., Anderson, R.: *A Comparison of Instructional Methods for Improving the Spatial – Visualization Ability of Freshman Technology Seminar Students*, Proceedings of the 2008 IAJC-IJME Int. Conference on Engineering & Technology: Globalization of Technology-Imagine the Possibilities!, Nashville, 2008.

[48] Yue, J. 2001: *Does CAD Improve Spatial Visualization Ability?,* Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition, Albuquerque, 2001.