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Spatial ability through engineering graphics education

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Abstract Spatial ability has been confirmed to be of particular importance for successful engineering graphics education and to be a component of human intelligence that can be improved through instruction and training. Consequently, the creation and communication by means of graphics demand careful development of spatial skills provided by the balanced curricula based on the research results in multi disciplinary area. The approach to engineering graphics education had been transformed to meet spatial skills improvement even before significant and fast changes arose from the development of computer technology enabling the engineer powerful tools and techniques. The correlation and interference between new technologies widely introduced in engineering graphics education and spatial ability/skills, have initiated new studies to establish the basis of holistic engineering graphics education. This paper presents the overview of some efforts and possible answers resulting from intensive research into spatial ability and skills and their implementation in the conception of graphics education in engineering environment.

Keywords Spatial ability · Curriculum · Engineering graphics · Education

Introduction

Among eight parts that human intelligence consists of is spatial ability (Gardner 1983), as the ability to perceive visual spatial world accurately and to perform transformations on those perceptions. But this is only one definition of the term "spatial ability". Often the terms "spatial ability" and "spatial skills" are used interchangeably regardless of the distinction made between these terms in educational psychology (Sorby 1999). Spatial ability is defined as the innate ability to visualize, the ability of a person before any formal training has occurred, that is a person is born with this ability. Spatial skills are either learned or acquired through training. Spatial skills have taken an important role in

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educational psychology research since the 1920s or 30, and the attempts have been made to categorize them.

According to Mc Gee (1979) and Maier (1994) spatial skills (abilities) consist of five components: spatial perception, spatial visualization, mental rotations, spatial relations, and spatial orientation. As some overlapping occurs within these components, in the classification scheme based on the expected mental processes, two categories of 3D spatial skills have been proposed by Tartre (1990): spatial visualization and spatial orientation. Spatial visualization is defined as the ability to mentally manipulate, rotate, twist, or invert pictorially presented stimuli, whereas spatial orientation is the comprehension of the arrangement of elements within a visual stimulus pattern and the aptitude to remain unconfused by the changing orientation in which a spatial configuration may be presented (Mc Gee 1979).

Spatial visualization component involves moving an object with your mind while spatial orientation component involves being able to mentally move your viewpoint while the object remains fixed in space (Sorby 1999; Strong and Smith 2002), or unfolding flat patterns.

The classification scheme of spatial abilities (skills) is completed so that spatial visualization is additionally divided into mental rotation and mental transformation (Tartre 1990). Mental rotation involves transformation of the entire object by turning in the space, while with mental transformation only a part of the object is transformed. To measure spatial abilities, the researchers have added spatial relations (Contero et al. 2005), as was classified by Barnea (2000).

Often the term "spatial visualization" is used interchangeably or is combined with the broader terms of "visualization" or "spatial ability" (Braukmann 1991).

Spatial cognition and development of spatial skills

Spatial cognition is recognized as underlying mental process that allows an individual to develop spatial abilities (Miller 1996). Spatial cognition itself is defined (Olson and Bialystok 1983) as "inner space or spatial cognition, spatial features, properties, categories and relations in terms of which we perceive, store and remember objects, persons, events, and on the basis of which we construct explicit, lexical, geometric, cartographic, and artistic representations".

Four stages of spatial cognition have been identified based on age (Piaget and Inhelder 1967). The sensomotor stage, the first stage is from the birth to approximately 2 years. The intuitive or pre-operational stage is from the ages two to about seven. From seven through twelve follows the concrete operational stage. The last stage is formal operational stage from thirteen to adulthood.

The factors of influence regarding spatial cognition have been determined based upon numerous studies. Some of these factors are age, experience or individual differences and gender (Sorby 1999; Mc Gee 1979; Sorby 2007; Liben 1981). Unlike the age and experience that do not significantly affect spatial abilities (Sexton 1992a, b), the gender aspects are especially important for engineering education and have been continuously the subject of investigation.

The research indicated that spatial visualization could be correlated to the success in mathematics, whereas spatial orientation is more correlated to the sense of direction and field dependence—field independence (Mc Gee 1979).

History of spatial ability research and impact on engineering graphics

The citation from Grinter Report (Grinter et al. 1955) stated as actual in 1999 (Sorby 1999), characterizes engineering graphics education as: “Graphical expression is both a form of communication and means for analysis and synthesis. The extent to which it is successful for these purposes is a measure of its professional usefulness. Its value as a skill alone does not justify its inclusion in a curriculum. The emphasis should be on spatial to convey ideas, especially by free-hand sketching, which is the normal mode of expression in the initial stages of creative work”.

These statements have been extent for 60 years and historical overview of spatial ability, spatial visualization research and the corresponding development of engineering graphics curriculum have shown and proved their validity even more when computer technology and its unavoidably impact have been considered.

Three distinct phases of the history on spatial visualization research were established by Eliot and Smith (1983), and additional fourth phase was proposed by Strong and Smith (2002).

Phase one was situated from 1901 to 1938 and characterized by an attempt of psychologists to identify a single spatial factor. The studies to establish visualization as an important aspect of intelligence were made, because verbal tasks were viewed at that time as a major indicator of intelligence. It is worth mentioning, that there is a continuous interest of the study and development by the Engineering Design Graphics Division of the American Society of Engineering Education (EDGD). A historical review of early research in spatial development of a predecessor organization to the EDGD from the 1920s through 1940 was presented by Miller (1996). In this early period, spatial ability testing was developed and introduced in curricula. The enhance of visual ability was achieved indirectly and engineering graphics curricula were focused on understanding and solving descriptive geometry problems, sketching and reading technical drawings.

Phase two from 1938 to 1961, was searching for several spatial factors and two major categories of them were identified. The first category is related to the ability of spatial configuration recognition and the second one considers the ability of mental manipulation with these configurations. Numerous pencil and paper tests were developed for spatial ability assessment. The descriptive geometry and orthographic drawing were important, and special emphasis was put on the free hand sketching.

During the phase three from 1961 to 1982, further separation of various spatial factors was performed. The effects of age, sex, and experience on individual spatial ability were studied and reported. The engineering curricula were supplemented by 2D–3D transformations, pictorial representations and 2D CAD models. Since 1970s and beyond, CAD systems have been established as efficient and unavoidable tool.

Traditionally, spatial skills have been acquired implicitly supported by the contents that enable understanding and solving Descriptive Geometry problems and successful manipulation with technical drawings. At the beginning, 2D CAD software package just replaced traditional tool for the development of 2D CAD models—engineering drawings, saved in CAD model data base or printed.

Phase four (Strong and Smith 2002) have arisen out of engineering graphics and have included the process of establishing computer technology effects on spatial skills and measurement of these skills. The 2D and 3D CAD systems were introduced in engineering graphics education and have been utilized until today.

The graphics educational materials mainly dedicated to the engineering students have reflected these changes through different approaches and stresses.

Giesecke et al. (1998) elaborated traditional engineering graphics contents and design process by employing the use of the CAD system, and later the same authors included 3D CAD modelling and parametric modelling (Giesecke et al. 2002).

The importance of connection among spatial ability research, development theory and engineering graphics curriculum was investigated (Miller and Bertoline 1991) and the need of research results and curriculum alignment was underlined.

About the 2000s much effort was done to redesign engineering graphics curricula for undergraduate students (university and professional) and to include contents addressing visualization skills.

Based on an introductory course intended to enhance 3D spatial visualization skills of first year engineering students (Sorby and Bartmans 2000), it was concluded that year after year the students showed statistically significant gains in scores and maintained higher retention rates for the material in comparison with the students that did not have this course. A hybrid model was applied where isometric and orthographic sketching, pattern development, rotation of objects and cross sections of solids were involved by using free hand sketching. The contents comprising surfaces, solids of revolution and the intersection of solids were accomplished by introducing the 3D CAD system.

The role of 3D CAD modelling and the developed CAD database represented as graphics has been early recognized in some textbooks and introduced in engineering curricula. The importance of graphics referring to traditional and concurrent engineering design process was noted. Unlike traditional engineering design process, concurrent engineering is a non-linear approach which encompasses the input, processes and considered output owing to the common 3D model data base shared by various experts from the very beginning. As shown in Fig. 1 (Bertoline 1999), three intersecting circles represent three major parts of concurrent engineering design process that are subdivided into

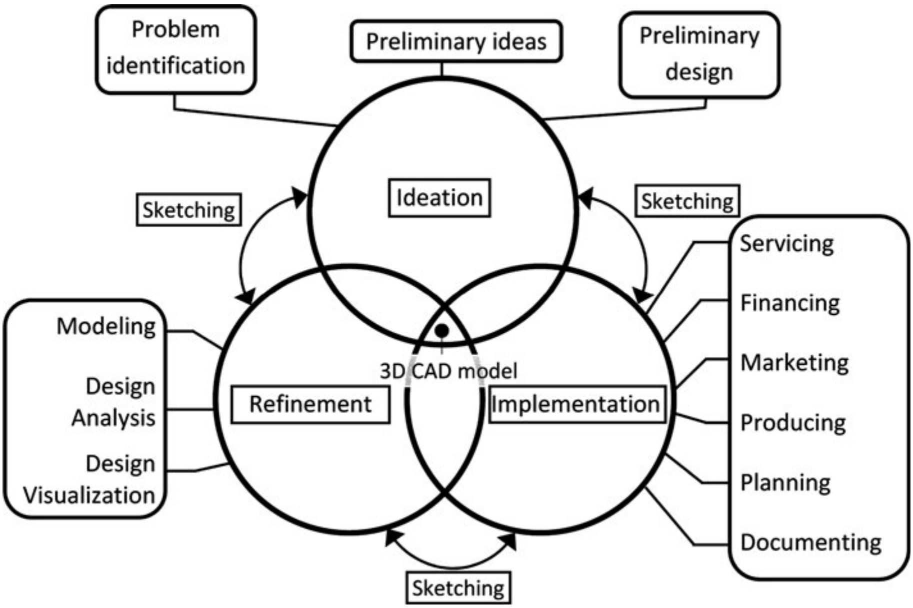

Fig. 1 Concurrent engineering design: three overlapping areas of the process have the same 3D CAD database and sketching is used for the communication (Bertoline 1999)

smaller segments, while the sketching is used for the communication. Additionally, the importance of good visualization ability was underlined not only to picture things in engineer's mind but also to control this mental image (Bertoline 2005).

The summarized form of the importance of visualization for the design process (Ferguson 1992) was also cited, (Bertoline 2005): "It has been non verbal thinking, by and large, that has fixed the outlines and filled in the details of our material surroundings for, in their innumerable choices and decisions, technologists have determined the kind of world we live in, in a physical sense. Pyramids, cathedrals, and rockets exist not because of geometry, theory of structures, or thermodynamics, but because they were first a picture literally a vision-in the minds of those who built them".

The textbooks and curricula have become based on the combination of traditional and CAD contents till nowadays. Madsen et al. (2007) introduced traditional contents and covered even Descriptive Geometry, CAD (Computer Aided Drafting) but also basic design theory, 3D CAD modelling, and the contents related to the possibility of 3D CAD geometrical model data base utilization for other applications. Graphic representation of 3D CAD database provides information for different expert groups (Bertoline 2005), technical and non-technical, and the engineers using the CAD must additionally know how to manage the graphics display of marketing, sales etc. (Fig. 2).

Similar hybrid contents can be mostly found in engineering graphics literature varying only in particular content extent (Chevalier 2003; Opalic and Kljajin 2010). In the preface of book, the authors Lieu and Sorby (2009) stated: "Visualization, Modelling and Graphics for Engineering Design (the name of book) was written from the ground up to take a brand-new approach to graphic communication within the context of engineering design and creativity". The structure of this book put the emphasis on the background, development, types and assessing of visualization skills at the very beginning, before the setting up of an engineering drawing is introduced. Figures 3 and 4 show the exercises proposed for the development of 3D visualization skills.

The materials by Sorby and Wysocki (2003) have been intended to assist in the developing 3D spatial visualization skills and contain nine separate modules with software as well as with workbook. The need for this kind of materials has arisen from the facts that well developed spatial skills have been shown to be critical to a person's ability to develop creative design solutions linked to person's ability to interact with a computer, and that most people can eventually acquire the skills through the patience and practice. Figure 5 is an example for the exercise and it illustrates the combination of two overlapping objects through the Boolean operations to make a new object by joining, cutting or intersecting.

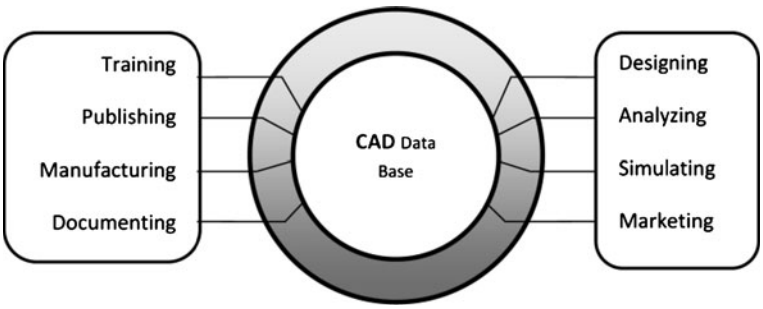

Fig. 2 The 3D CAD database represented as graphics—a supplier of technical information (Bertoline 2005)

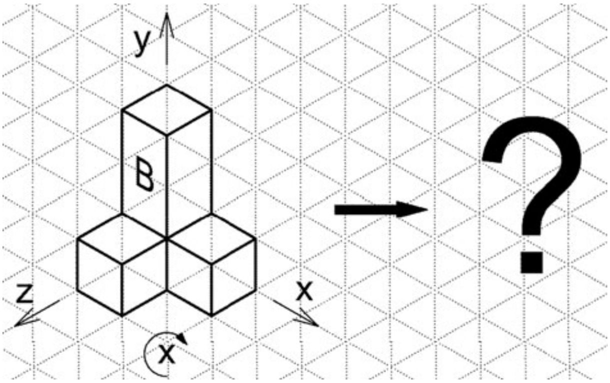

Fig. 3 Sketching the image that results from the rotation of an object (Lieu and Sorby 2009)

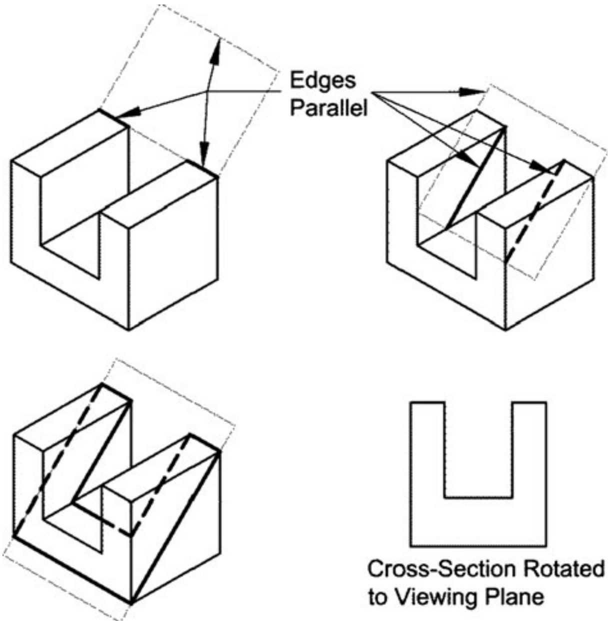

Fig. 4 Sketching the cross section of an object (Sorby and Wysocki 2003)

The engineering graphics curricula have changed when reflecting the changes of graphics role in design, and through the introduction of new tools, technologies, and the research outcomes of spatial ability.

Based on spatial ability research and development theory, it was pointed to the need of connecting research and curricular direction (Miller and Bertoline 1991). At the end of 20th century, the opinion was that the most important rated topic for the inclusion in engineering graphics curricula is the development of visualization skills (Barr 1999). The curricula of introductory course of engineering graphics have followed that trend and along with the idea of 3D model as a centre of design process, the visualization was involved (Jenison 1997; Branoff et al. 2002; Barr et al. 2002).

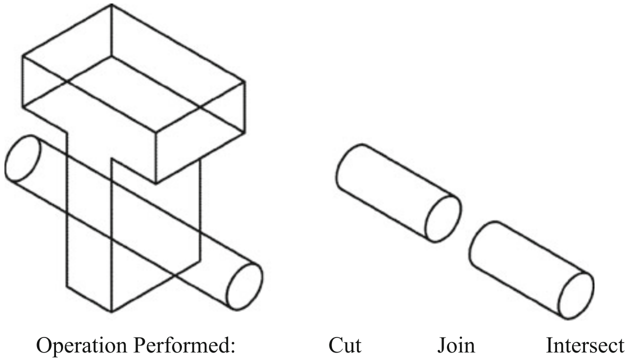

Fig. 5 The combination of two objects by employing the Boolean operations (Sorby and Wysocki 2003). The appropriate word (cut, join or intersect) has to be *circled* indicating the performed operation

The changes that have occurred subsequent to the development of a European Higher Education and Research Area were well elaborated in the work of Contero et al. (2006). The statements of the CRE Bologna Declaration (1999) and the shift in the education paradigm from a teacher—centred model to a student—centred model, have initiated careful reassessment of many engineering courses among them those consisting of engineering graphics contents.

Some objectives of a programme, specified through the learning outcomes and competences, have been previously acquired indirectly, but now in an explicit form. Therefore, visual reasoning is to be considered, in the terms of learning outcomes and competences, as a critical aspect of future engineers' education (Contero et al. 2006). These statements are obviously in accordance with the previously mentioned older ones (Bertoline and Wiebe 2005). Since the skills are needed in concurrent engineering design where 3D CAD model takes a central place, the question of curricula efficiency becomes very important.

Nevertheless, some author's opinion (Contero et al. 2005) was that in spite of changes in various textbooks and curricula, spatial abilities are still considered as a secondary goal during engineering graphics education.

It has become a generally adopted opinion that along with the mentioned new contents in engineering graphics, the sketching and sketches as through the design process (Fig. 1) are crucial. Therefore, they have been widely recommended for the enhancement of spatial skills (Sorby 1999; Bertoline and Wiebe 2005). The sketching (or drawing) seems to be especially effective for the development of spatial skills (Sorby 1999), but it was also recognised as the mean for the capacity development of visual imaginary and creativity (Ferguson 1992).

When spatial visualization skills are a course objective, the sketching has to be underlined regardless of the introduction of 3D CAD systems and its additional importance arises from the modus of 3D model development through CAD system in the engineering design process.

Applied computer technology and development of spatial skills

The instruction of engineering graphics has involved new technologies that have enabled simulation, animation, virtual reality and rapid prototyping. These new possibilities have

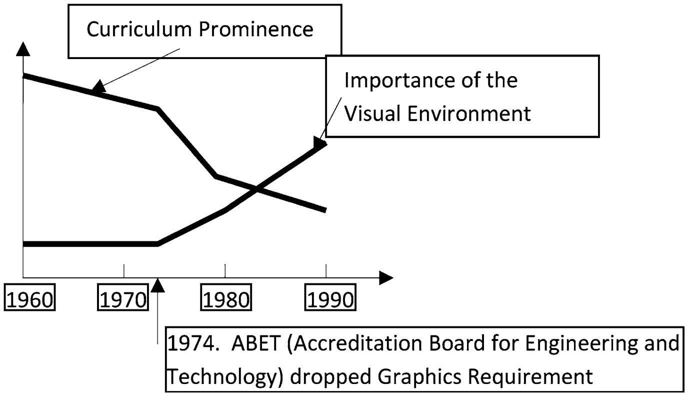

Fig. 6 The illustration of graphics curriculum prominence versus the importance of visual environment (Pleck 1990)

arisen from the advent of CAD systems and web-based resources so additional issues considering the interactions between spatial ability research and new approach to the means of engineering graphics education have appeared.

Pleck (1990) noted that the advances in computer technologies increased the importance of visualization skills as the graphics was deemphasized in the engineering graphics curricula. The decreasing of graphics curriculum prominence in relation to the increasing importance of visual environment is illustrated in Fig. 6. Apart from the visualization improvement based upon 3D CAD model (texture, colour, rendering), the possibility to develop some additional skills (e.g. simulation, analysis, rendering) has been also offered.

Spatial skills have been recognized as main engineering skills when geometrical design is leading through engineering graphics according to the so-called "design-by-drawing" method. The importance of these skills has grown severely as a new method "design-by-virtual models" has taken place reflecting the power of the applied 3D CAD systems (Contero et al. 2005).

To teach technical drawing using advanced information and communication technology tools, Kabouridis elaborated (2010) that "the main task is adequate preparation of the content. The other prerequisite is the selection and preparation of learning contentm.

The importance of appropriate content and method, along with the duration of curricula, were also investigated (Sexton 1992a, b). The research recommendations have led to the previously mentioned combination of traditional engineering curriculum with 3D CAD contents, such as e.g. modelling theory.

In order to better develop spatial skills, valuable opinion was elaborated (Sorby1999) in relation to the sequence of topics in engineering graphics curriculum and educational textbooks. Very often a multi-view sketching/drawing is placed at the beginning and then follows the pictorial sketching, which is not in accordance with natural progression of learning as the movement is from abstract to concrete. The proposal was to work first with the models when constructing pictorials and to make multi-view sketches/drawings afterwards.

The relation between spatial skills level and successful usage and manipulation of computer database was found, with the conclusion that a person's spatial skill level is the most significant predictor of success when interacting with and taking the advantage of computer interface (Norman 1994). Sorby (1999) found the relation between spatial skills and effective CAD software learning.

A widely accepted opinion is that visualization skills can be improved through working with 3D CAD solid models. The results of many researches that compared 3D CAD solid models with traditional 2D models (orthographic projections and pictorial representations) did not reveal that these models are predominant for the enhancement of spatial ability (Sexton 1991; Godfrey 1999). In comparison with 3D CAD solid models, traditional visualization skills improvement by sketching have proved to be more effective (Sorby and Gorska 1998). The investigation of 3D CAD instruction benefits over 2D CAD ones, was on the side of 3D method (Thomas 1996), while the comparison of the effectiveness of teaching by use of modular drafting methods and traditional instructor led methods showed no significant difference (Rogers 2004).

Also, the impact of spatial ability on the comprehension of 3D computer visualizations was noted (Keehner et al. 2004). The presence of 3D models reflects differently and leads to a cognitive overload for persons with low spatial ability, while the persons with high spatial ability take advantage from these models (Huk 2006). Furthermore, it was underlined that the presence or absence of 3D effects in monocular static display makes no difference to the effectiveness of spatial memory (Tavanti and Lind 2001).

Various means of 3D representation that have become available (dynamic viewing, 3D animations) were noted to be a possible way for changing and improving person's incomplete mental models (Wu and Shah 2004).

The effects of spatial ability on learning from the animations can be framed in the terms of interplay between the perception of external visualizations (animations and static diagrams) and internal visualization processes (spatial ability) (Hegarty 2004). Additionally, the effects of knowledge and spatial ability on learning from the animation were summarised (Hegarty 2007). When comparing several experiments, there was no evidence of any interactions between the ability or knowledge and any type of instructions that the persons received. Furthermore, no evidence was found confirming that the animations or static diagrams are more or less effective in relation to different abilities or knowledge, or that different types of animations are more or less effective for different individuals. Moreover, some research results indicated that instructional effects of animations might not be always advantageous due to oversized demands on the learners for the information processing and decreasing of important processing activities extent of learners (Lowe 2002).

Lewalter (2003) found that dynamic visuals are not generally superior to static ones as the scores for the persons.

with animations are not better in comparison with the persons with static visuals in relation to the recall, but the comprehension is slightly better.

Computer technology and the accompanying development of 3D CAD systems have offered a new dimension to the engineering graphics and design curricula. The curricula, even in a first year of engineering graphics course, have been extended by inclusion of 3D CAD model data base possible applications to create virtual prototype and to employ rapid prototyping (Barr et al. 2002; Leon and Winek 2000).

As rapid prototyping provides the students with valuable physical model, the benefits of spatial visualisation have been proved by the results of investigation about the improvement of spatial skills based on the application of rapid prototyping technology (Czapka et al. 2002). Based upon the improvement in rotation tests (pre to post) and on the scores from the part sketching (auxiliary, missing and section views) of an engineering graphics exam, it was concluded that the use of physical models helps to improve visualization skills to a greater extent than with traditional teaching methods alone. The students were tested for visualization skills at different instructional levels: without drafting instruction, drafting instruction, CAD instruction in 2 and 3D models, and rapid prototyping of 3D part (Frey and Baird 2000). The visualization tests showed a sharp distinction between the level two (drafting) and three (2 and 3D CAD) that accomplished higher scores, while for the use of rapid prototyping technology of level four, substantial increment in visualization scores did not occur. It was concluded that the use of costly rapid prototyping machines would be justified by some additional considerations.

In spite of the previous findings, practical integration of rapid prototyping technology into many general courses in the engineering curricula was described (Maletsky and Hale 2003). The proposals were not only given for introductory courses dealing with topics such as drafting or CAD, but for design methodology courses and advanced design courses as well. With regard to engineering graphics courses, it was suggested that the models could be helpful when a part is constructed from orthogonal views and then checked and compared with a physical model. The rapid prototyped parts/components of an assembly offer the student valuable hands-on experience.

Among several key objectives of engineering graphics course, the first declared was the visualization of objects and ideas (Johnson et al. 2009). To achieve the objectives, four course/lab modules were developed: development of 3D solid models using rapid prototyped models, class lecture on rapid prototyping, generation of multi view drawings assisted with rapid prototyped models and FAB@AASU—Desktop rapid prototyping based on the desktop rapid prototyping Fab@Home kit (Malone 2008). In spite of the fact that only qualitative results of this project were reported in the form of students' comments, the students' feedback was found to be very positive.

The engineers' education has responded to the demands and needs arising from recent industrial practice and the topics considering rapid prototyping have been included in engineering graphics textbooks (Bertoline and Wiebe 2005; Madsen et al. 2007; Lieu and Sorby 2009; Lockhart and Johnson 2012).

The Internet has been used to provide useful educational tools attractive to the learners and intended to enhance spatial abilities (Gaughran et al. 2012). Based on realistic representation of 3D objects and interactive animated effects, various forms of improvement and testing of spatial ability (rotating, paper folding), along with the possibility to enrich their visualization skills using drawn orthographic and isometric views, are offered to the learners.

VRML technology integrates 3D graphics and multimedia, provides a virtual world simulation and offers numerous capabilities for the creation of animated and interactive content that can facilitate and enhance spatial experience of the user. This technology has been spread over different domains such as medicine, chemistry, earth science as well as engineering (Crown 2003; Angelov et al. 2007; Hijazi et al. 2008).

The access to the environment under study that is necessary throughout the design process was enabled by the application of virtual reality VRML (Virtual Reality Modelling Language) world in an engineering graphics course (Crown 2003). It was noted that rich interactive design environment provides for the presentation and display of ideas and helps to develop necessary design skills, being at the same time great motivator to the students.

The experience with 3D immersive virtual environment has suggested that this environment is considerably more efficient for training spatial ability skills than 2D or 3D non-immersive ones (Imagery Lab/Mental Imagery and Human–Computer Interaction Lab).

Multiple opportunities offered permanently by new technologies as well as their impact on spatial skills and vice versa have been under investigation. Additionally, the questions relating to the development of an effective and up to date holistic engineering graphics education are still actual.

Conclusions

The results of research into spatial ability have actuated the process of content adjustment and approach to engineering graphics education, and have moved the accent in engineering textbooks and curricula. Being the component of CAD system, the user manipulates geometry so that the presence of spatial reasoning has become conditio sine qua non in efficient 3D modelling.

Leading textbooks contents have shown similar trends like the reorganised curricula: traditional engineering graphics contents are still going together with 3D CAD ones. Considerable differences can be noted in relation to the adopted approach that is more or less successful when trying to apply new cognition of spatial ability/skills and giving an overall picture of the role and importance of engineering graphics and its teaching in an engineering environment.

A well balanced engineering graphics curricula focused on the development of spatial skills and aligned with results of multi disciplinary research and impact of recently emerging technologies are the basis for engineering education and appear to be the necessity for future engineers.

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