INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
9-10 SEPTEMBER 2021, VIA DESIGN, VIA UNIVERSITY COLLEGE, HERNING, DENMARK

ADAPTING COURSE DESIGN TO FOSTER THE DEVELOPMENT OF SPATIAL ABILITIES IN ENGINEERING EDUCATION – A CASE STUDY

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ABSTRACT
Spatial skills are crucial for engineering designers, particularly when interpreting views of an object represented by drawings, visualising parts, or manipulating geometry in CAD. Spatial skills can be improved through instruction, teaching, and training. Several interventions are described in the literature. Established approaches in engineering education are, for example, sketching exercises and technical drawing tasks. Emerging visualisation possibilities such as Virtual Reality, Augmented Reality or Mixed Reality is the subject of current studies in the field. However, their effect on the development of spatial skills needs further studies.
In a previous study, the authors have investigated which visualisation techniques can positively influence the development of student's spatial skills. Here we want to take a more detailed look at the following question: How can we adapt an introductory engineering design course to match these findings?
In this paper, we report on our experiences from using various training to develop spatial skills. First, we will show the interventions that have already been considered in the teaching concept. The use of technical sketching and CAD will be explained in detail. The findings of our previous study, which informed the modification of the course, will be summarised. This includes specific interventions and training, covering machine elements and sketching exercises and interactive e-learning content.

Keywords: Spatial ability, engineering education, spatial training, engineering graphics

1 INTRODUCTION

The role of spatial abilities, especially in engineering and engineering education, has been investigated over the last decades. In general, spatial ability is understood to be the ability of the human brain to produce, retain, retrieve, and transform 3D models as well as virtual images and objects [1]. Typically, "spatial ability" denotes the innate ability a person has, and "spatial skill" is learned or acquired through training. In this paper, the term mental skill is used because of the lack of knowledge regarding prior cognitive skill training.
Spatial skills are fundamental for novice engineers and often needed in engineering design where interpreting views of an object represented by drawings, visualising parts, or manipulating geometry in CAD are important activities. So, a lack of spatial abilities is not only resulting in particular problems during the introductory engineering design course, but it may also affect the professional career of students.
As a central component of multi-factorial spatial concepts, the capability to imagine and transform spatial information (mental rotation) is mostly used as a marker for spatial abilities. Mental rotation performance, in general, can be improved due to a variety of measures [2] which are described in the literature. The measures range from special spatial materials and tests to playing video action games [3], use of Augmented or Virtual Reality [4], interactive animation, and virtual objects [5] and also the use of rapid prototyping [6], [7]. An interesting finding of a meta-analysis regarding the development of spatial skills [2] is that basic engineering tasks such as sketching 3-dimensional objects [8] and technical drawing [9]–[11] can greatly improve mental rotation skills and also had a positive effect on students learning [12]. Furthermore, studies revealed that interacting with three-dimensional displays [5], [6] and actively manipulating these displays is more beneficial for the development of spatial skills [13].

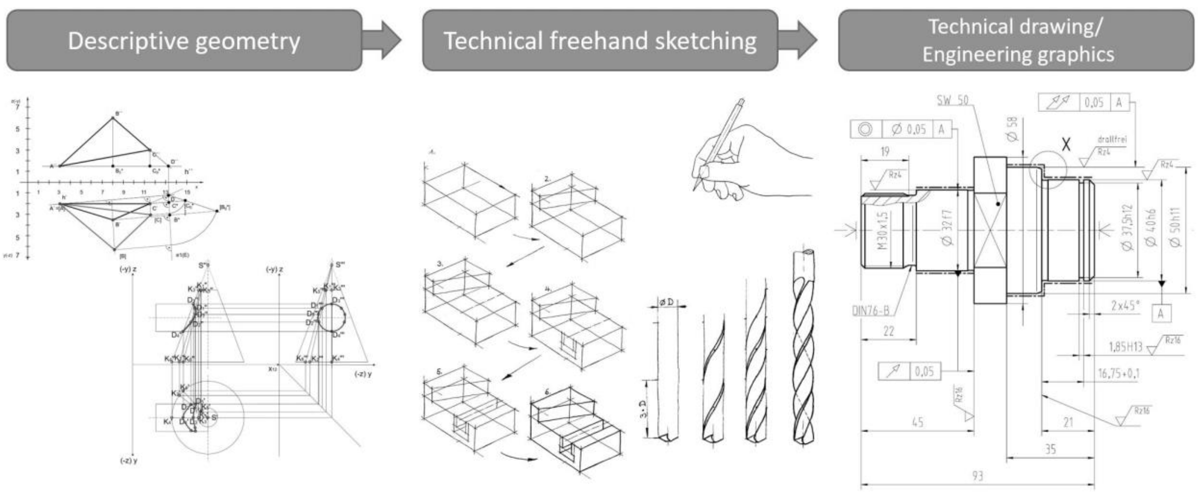
The studies examined in the meta-analysis indicate various training options, which are, however, for the most part, considered and examined in isolation.
This led to the following questions for the design of the engineering design course:

- Which measures described in the literature are most appropriate for the engineering design course?
- How can the effectiveness of the implemented measures be assessed?
- How do the studies, in turn, inform the design of the course?

The paper is structured as follows. First, we shortly describe the original course design and addressing research question 1. Afterwards, the paper addresses the second research question by reporting an empirical study conducted previously by the authors [14]. The paper concludes by explaining the adaptation of the course.

2 ORIGINAL COURSE DESIGN

The introductory engineering design course which lasts 14 weeks is offered during the student's first semester. The total number of course participants averages around 200 students enrolled in different study programmes including mechanical engineering, biomedical engineering, industrial engineering but also mechatronics and prospective teachers.
This course is focused on teaching theoretical content regarding construction theory and technical representation and also developing individual skills. During the course, the students learn the basics of descriptive geometry, technical freehand-sketching, engineering graphics, and technical drawings' conventions (Figure 1). Of the measures to foster spatial imagination mentioned in the introduction, technical sketching was thus already implemented in the course design.



- Fundamentals of projections
- Orthogonal Multiview projection
- Geometrical construction of cuttings and intersection between multiple bodies (2D in orthogonal projection)

- sketching techniques
- Sketching elementary elements and objects
- Procedures for sketching more complex structures

- Conventions of technical drawing including line types, representation of technical objects, entry of dimensions, sectional views
- CAD Training (Constructing the parts and deriving technical drawings)

Figure 1. Main topics of the course

In addition to the lectures and exercises in the individual subject areas, the acquired knowledge is tested with the help of test exercises. These tests also serve as a prerequisite for the examination and have to be completed by all course participants. The tests covered basic elements in orthogonal projection (digital multiple-choice test) and the geometric construction of three-dimensional intersection between two bodies (manually on paper). Furthermore, there was a three-staged task covering all topics. The first part was the making of a scale freehand sketch of a previously unknown technical object. This sketch should contain an isometric view in addition to the three main views. Subsequently, in section two, the sketch was to be converted into a 3D component using a CAD tool and afterwards into a two-dimensional technical CAD drawing in the third section.

3 A STUDY OF VISUALIZATION MEDIA AND ITS INFLUENCE ON THE DEVELOPMENT OF SPATIAL ABILITIES IN ENGINEERING EDUCATION

The second research question has been addressed in the study, previously conducted by the authors that aimed to evaluate the effectiveness of the effect of the different visualisation media in developing students' cognitive skills. To assess the students' spatial abilities, imagined spatial transformations of objects, so-called mental rotation, were studied. Simultaneously, it was investigated which visualisation tools can positively influence students' spatial skills development. The study design and two of the main findings are briefly described below. A detailed description of the study and complete results can be found in [14].

3.1 Study design and test procedure

In order to measure the degree of improvement, a mixed study design approach was used, with a pre- and post-test for the control- and the treatment groups. The pre-test took place at the start of the semester. The second (identical) post-test was performed at the end of the semester after everyone finished the three-staged task.

A redrawn version [15] of the paper-pencil Mental Rotation Test (henceforth referred to as "MRT") developed by Vandenberg and Kuse [16] was used to evaluate the mental rotation performance. The test is composed of various stimuli that are consistent with the cube figures created by Shepard and Metzler [17]. Peters and Battista [18] provide different redrawn versions of these 3D cube figures. Stimuli with alternating black and white cubes against a white background were chosen from their library, for better distinction.

The MRT is composed of two sets of twelve items each. As shown in the figure below (see Figure 2), each item consists of five stimuli with the target stimulus on the left side and four sample stimuli on the right side. The participants have to determine which two stimuli on the right side are rotated versions of the target stimulus. Incorrect choices are either mirror reflections of the target or structurally different.

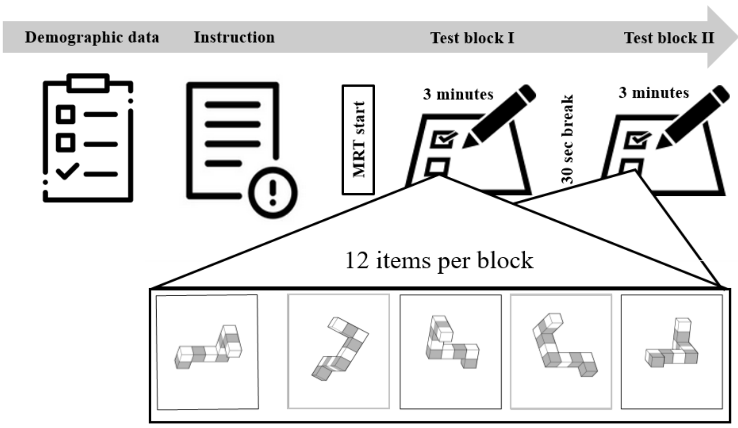


Figure 2. Schematic representation of the Mental Rotation Test setup and procedure

Following the standard scoring developed by Peters [15], one point was given if both items were identified and marked correctly. A maximum number of 24 points were achievable.

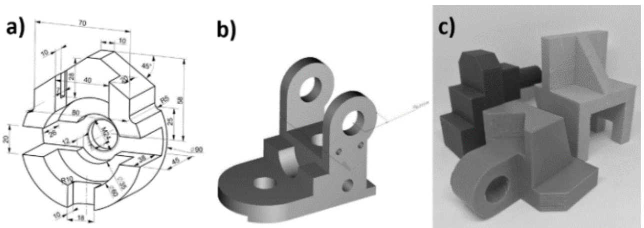


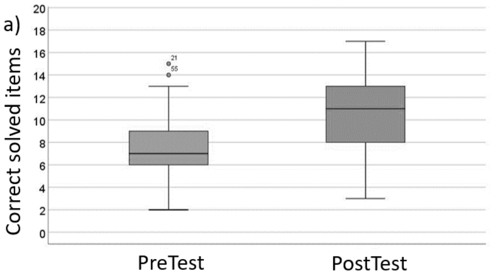
Figure 3. Intervention in the tree-staged task: a) 2D dimetric drawing, b) digital measurement in a 3D-Pdf c) 3D-printed model

For the intervention, the participants were randomly assigned to three groups. These groups differed with regard to the media used to visualise the technical objects (start point of the three-staged task) and the interaction possibilities provided by the media (Figure 3). The first group (Group1) served as a reference-group and started with a two-dimensional representation of a dimensioned dimetric component view. This is the usual way of displaying components and machine elements in engineering design. The first treatment group (Group 2) received a virtual object in the form of a 3D-pdf file in which they had to measure the dimensions digitally. The second treatment group (Group 3) received objects physically in the form of 3D-printed components, which they had to measure independently on a specific date.

3.2 Main Findings

Out of 135 students (112 males, 23 females), 79 students participated in the second test. Nine participants did not follow the test procedure correctly and were excluded from the test analysis. The final group of participants consisted of 59 males and 11 females.

The first main findings were that the training during the fundamental design engineering course resulted in a significant improvement of mental rotation performance with a large effect size (Figure 4). The mean performance of the participants improved substantially during the semester, regardless of the respective treatment (see Figure 4). The overall mean value (M) increased during this period from $M_{PreTest}$=7.37, with a standard deviation of SD=2.89, to $M_{PostTest}$=10.83, SD=3.58 correct solved items.



b)

		N	Min	Max	Mean	SD	95% Confidence Interval for Mean: Lower Bound	95% Confidence Interval for Mean: Upper Bound	Variance
PreTest	All	70	2	15	7.37	2.89	6.68	8.06	8.32
	male	59	2	15	7.61	2.91	6.85	8.37	8.48
	female	11	3	10	6.09	2.47	4.43	7.75	6.09
PostTest	All	70	3	17	10.83	3.58	9.98	11.68	12.81
	male	59	3	17	11.00	3.61	10.06	11.95	13.03
	female	11	4	16	9.91	3.42	7.61	12.21	11.69

Figure 4. a) Point distribution and b) descriptive statistics for Pre-and Post-Test

Furthermore, the impact of the media used for the task definition was investigated. Therefore, the improvement (I) in mental rotation performance, as the difference between the initial mean score and the Post-Test score, was determined for each participant. Figure 5 shows the mental rotation performance of every group (M = mean number of points, SD =standard deviation). The secondary axis indicates the mean improvement in relation to the initial performance (relative mean improvement MI_r).

	M	SD	MI_r [%]
PreTest	7,61	3,16	38
PostTest	10,52	3,22	
PreTest	7,43	2,96	45
PostTest	10,76	3,45	
PreTest	7,5	2,96	36
PostTest	10,2	4,33	
	M	SD	MI_r [%]

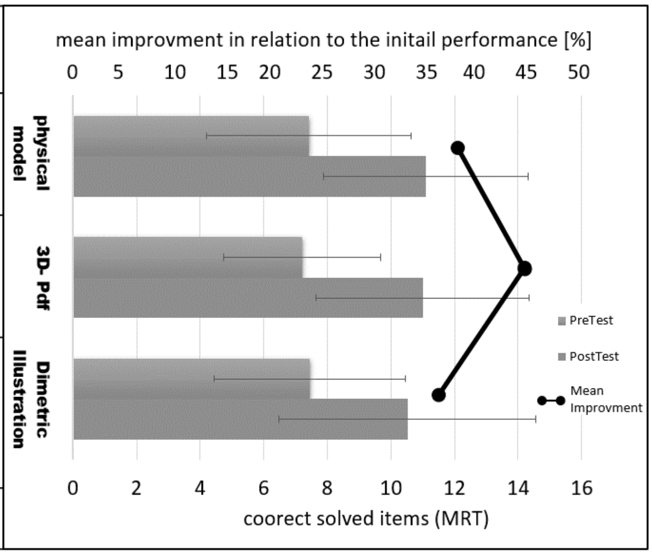


Figure 5. Development of the average score depending on the group

The second main finding was that, although an independent samples t-test did not reveal significant differences in the improvement of mental rotation performance, a trend was observed (Figure 5).

Visualisation media which offer some interaction with an object help students to capture the object's spatial reality, thus lead to a considerable improvement of mental rotation performance. The most considerable improvement with a value of MI_r=45% (MIt1=3.33) was observed in the group with the target object presented as 3D-pdf. This media allowed the user direct manipulations of the object so that the student can see the intermediate steps. For example, to complete the given task, the students had to rotate the object into the respective view to take the measurements. The live feedback about the direction of rotation and the resulting views is exactly what is examined in the MRT. Furthermore, 3D-pdf offers the opportunity to show arbitrary sections. The second-highest performance increase at a value of MI_r= 38% (MIt2=2.91) was in the group with the hand-held physical model of the target object. Although rotation was equally possible with this model, it is assumed that it is carried out unconsciously. On top of that, no section can be illustrated with this media. In the reference group with the dimetric illustration, the lowest mental rotation performance increase at a value of MIr= 36% (MIC=2.7) was detected. The two-dimensional representation does not offer any kind of interaction to support the participants' understanding of the object's spatial reality.

4 ADAPTED COURSE DESIGN

Based on these findings, the course design was adapted. First of all, sketching technical objects (the literature is unanimous on this) promotes the development of spatial skills. A new finding of the study was that media that offer interaction possibilities are conducive to the development of spatial perception. Based on these findings, various interventions were implemented. The distribution of the media used and the proportions in the individual subject areas are shown in Figure 6.

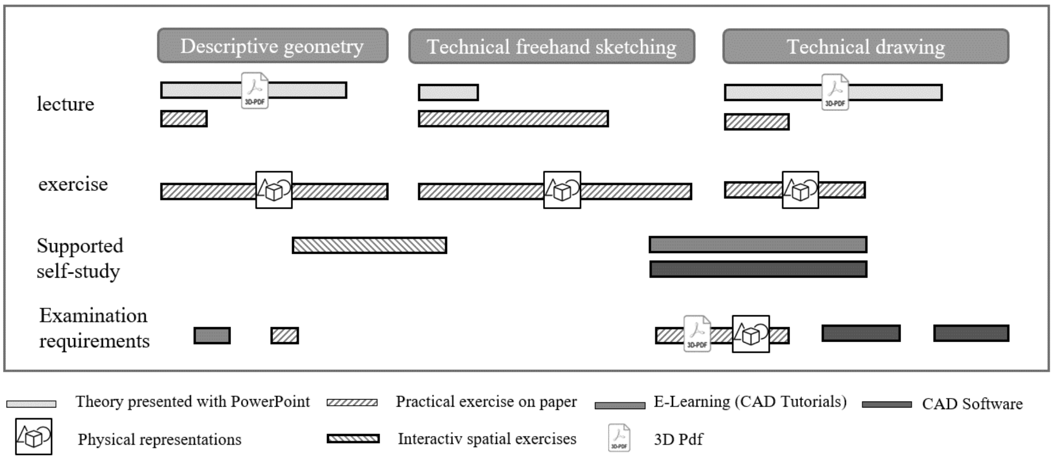


Figure 6. Overview of the use of media in the subject areas of the design course

On the one hand, 3D-Pdf is now used as a basic visualization tool to accompany the presentation of tasks in exercises. On the other hand, it is used as an additional visualisation in teaching theoretical lecture content (Figure 6). Furthermore, physical models are now increasingly used in the exercises of all subject areas. Mainly we use 3D printed objects.

Regardless of the new media available, two-dimensional representations of technical objects are still widely used in engineering. For this reason, we have created an interactive e-learning module that aims to train the recognition and mapping of figures and their projections.

Another modification is the support of teaching by a team of tutors. Implementing all measures is very time-consuming and cannot be completed only during the regular course hours. Therefore, an additional exercise is offered via tutored hours. The tutors are MSc students that have successfully completed the supported courses. However, at the time of the study, these were not yet included in the learning concept and therefore not shown in the figure. The content of the tutored courses is working with physical objects. Here, for example, gears are assembled, and dissembled, and various objects are measured and sketched. Furthermore, tutors support the handling of the CAD system.

5 CONCLUSION AND OUTLOOK

The study has shown that the course design created, in the sum of all the measures taken, promotes the development of spatial imagination. Proven influencing factors are sketching and also the creation of technical drawings. Furthermore, the presented study revealed a trend that modern visualization media, which offer the possibility to interact with the object, can foster the development of spatial skills. Based on these findings, it is concluded to that a combination of proven classical forms of representation and modern visualisation media is beneficial for the development of spatial skills of engineering design students. The influence of these and other media will be investigated in future studies.

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