Developing visuospatial ability by creating the virtual models of cubic solids for 3D printing

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Spatial ability is an integral part of everyone's life which is why its practice and deepening are very important. In this article, we reflect on one aspect of 3D printing that contributes to and helps just developing spatial ability. This aspect is the creation of a virtual 3D model of a 3D object in the Rhinoceros software. In this virtual 3D model creation, different visuospatial abilities are involved in other parts of the structure. Our goals are to assign the appropriate visuospatial abilities and categories of identified actions to individual construction steps in the Rhinoceros and PrusaSlicer software for the successful completion of the 3D printing process.

Keywords: Spatial ability, visuospatial abilities, spatial orientation, mental rotation, 3D printing.

Introduction

Visuospatial abilities are one of the crucial abilities of every human being. Without people realizing it, they use visuospatial abilities in their everyday life, e.g. when they need to find their way in the city, in nature, when reading and orienting on maps, parking cars, arranging decorations in rooms, etc. Of course, professionals such as architects, builders, astronomers, doctors, mechanical engineers, and others cannot do their jobs without visuospatial abilities. Samsudin, et al. (2011) mentioned that these abilities were previously regarded as innate, but evidence from experimental studies suggests that significant improvement is possible through proper and specific training. Wang, et al. (2021) stated that in recent years, with the rapid development of 3D printing technology and the popularization of its educational application, researchers began to pay attention to how to use 3D printing technology to improve students' spatial ability. This paper describes the preparatory work for the planned actual case study that will be done by the team members of the project iTEM (project of the EHP Funds between TUL and NORD University with the following main goals: researching spatial ability, Mathematikus, 3D printing, and micro:bits) at chosen schools in the Czech Republic, Norway, and Germany. It is planned to find out if at all and in which way the usage of the spatial ability in modelling virtual 3D models as a basis for 3D printing differs with the age of students, next, which aspects of visuospatial activities students use while creating virtual 3D models, and if students are able to construct 3D virtual models according to 2D drawings of the models (Olkun, 2003). The creation of virtual 3D models of 3D objects is an aspect that leads to the creation of physical educational aids that can help weaker students in their learning process and encourage possibilities of using pupils' manipulative activities.

Spatial abilities

Many works deal with spatial ability, and its essential components are also mentioned in them. For example, Braukmann & Pedras (1993), Gardner (2011), and McGee (1985) point out that the visuoabilities to mentally manipulate, rotate, bend or flip the depicted object are some of the critical aspects of intelligence. Linn & Petersen (1985) define spatial ability as an ability used for representation, generation, transformation, and evocation of symbolic and pictorial facts. They categorized visuospatial ability using three modules: mental rotation (the ability to quickly and precisely turn 2D or 3D objects, to imagine properties of a rotated object afterward it was revolved around an axis by a specific number of angular degrees), spatial perception (the ability to identify the spatial relationships of an object with regard to the orientation of one's own body), and spatial visualization (the ability manipulate in one's brain with complex spatial data about the object, including the configuration of its individual components). While Maier (1994) uses the division of spatial ability into five components, see Table 1.

Aspects of spatial ability		**Description**
A1	*spatial perception*	solvers are demanded to designate spatial relations with regard to the orientation of their own bodies, in spite of distracting information
A2	*spatial visualization*	the ability to visualize the object and its parts in the space
A3	*mental rotation*	the ability to rotate the object in the mind
A4	*spatial relation*	the ability to imagine spatial objects, their parts and their relationships
A5	*spatial orientation*	the ability to orient oneself in space

Table 1: Aspects of spatial ability according to Maier (1994)

As can be seen from the above, spatial ability is able to be used as a trigger tool in learning and teaching actions in mathematics and geometry, as described by Cruz, et al. (2000). The usage of visual-spatial representations in solving geometric problems conclusively correlates with problem-solving exercise in general, as described by Battista, et al. (1982), van Garderen & Montague (2011), McGee (1985).

With respect to all these given and many other studies, spatial ability can be interpreted as an ability to perform mental transformations of objects in space, imagine how an object looks like when viewed from different points of view, and understand relations among objects and their components to each other.

Many studies show spatial ability is able to be made better and expanded (e.g. Baenninger & Newcombe, 1989, 1995). Practicing spatial ability is a big topic in the current teaching of geometry. It turns out that in recent years, only a few pupils or students are able to create the correct and corresponding visualization of a 3D object according to a planar drawing in their minds. The development of spatial ability seems to be problematic, especially when using online teaching. In this form of teaching, without the possibility of working with real 3D objects, it is necessary to look for other ways to enable students to imagine 3D objects. Given the importance of visuospatial abilities, it is certainly essential to use all available methods to develop these abilities. Today, we are surrounded by modern technologies more than ever before, and therefore it is certainly desirable to use them properly and meaningfully. For example, 3D printing is becoming increasingly popular and promoted today. In this article, we discuss possibilities to develop spatial ability by creating printable files.

Creating a visual model of a cubic solid in Rhinoceros

Spatial models, created specifically either for some topics of mathematics or geometry, or for some specific groups of students, can be created by teachers themselves and, of course, also by the students in various geometric software mentioned above (GeoGebra, Rhinoceros, Thinkercad,...) and then printed on a 3D printer, which is increasingly available today, as well as some of the mentioned software. In addition to modelling virtual 3D objects in suitable software and the subsequent 3D printing of the created virtual model on a 3D printer, students' spatial ability can be practiced and developed through manipulative activities.

When designing a virtual model of a 3D object in geometric software, various components of the spatial ability are always involved to construct the required virtual model of a 3D object correctly. To characterize more comprehensively the creation of a virtual model of a 3D object, we supplement the above-mentioned Maier's (1994) categorization of spatial ability into five components with the results of the case study of Dilling & Vogler (2021). We chose both studies because they fit very well for the purposes of our planned case study in comparison with the other studies concerning the same topic. They describe eight identified categories of actions **C1** to **C8** of students (Table 2) when working with CAD software. These are related to aspects of visuospatial ability. It describes the processes that are directly related to the development of various aspects of visuospatial ability:

C1	*selecting basic solids*	Choosing the right basic solid from a number of predefined solids. To select it, a user has to have a good idea of the composition of the resulting object.
C2	*changing parameters of solids*	Basic parameters (e.g. length, width, height, etc.) of solids can be changed.
C3	*changing position of solids*	Repositioning solids. A solid changes its position relative to others, which is related to aspects of spatial perception and spatial visualization.
C4	*rotating solids*	Rotation of solids around either points or axes into asked positions. Good user's spatial perception and mental rotation are necessary for the correct space rotation of a solid.
C5	*duplicating solids*	This action is related to an aspect of spatial relations, more exactly of copying solids. A user must imagine he needs some solid more than once to create the correct virtual model of a 3D object.
C6	*connecting solids*	Joining solids using Boolean operators. It is needed especially when modelling objects for 3D printing.
C7	*zooming in and out*	It is related to the necessity to shrink or enlarge the resulting solid for a better overview of the spatial situation, and the spatial relations by zooming out and zooming in a whole scene. This is directly related to the spatial orientation aspect. This category is needed when modelling objects for 3D printing.
C8	*rotating the total view*	This action is related to the ability to rotate either the whole scene or the whole object so that the user more easily creates or verifies his solution. Overall object rotation can also help in solving a given task. It relates to the aspects of spatial orientation and mental rotation.

Table 2: Categories of the identified actions according to Dilling & Vogler (2021)

Further, we use Dilling & Vogler's (2021) categorization mentioned in Table 2 and the aspects of spatial ability according to Maier (1994) (see Table 1) for their assignation to the particular steps of creating virtual models of 3D objects, more precisely of cubic solids. Modelling the particular virtual models of cubic solids, a user had to choose a basic solid for their creation (usage of **C1**). The cube is the basic solid in the case of constructing the cubic solids. The cubes are entered using the coordinates of the vertices lying diagonally on one of six faces of a cube and setting the high of the cube. In doing this, the user

- must determine how the particular cube is oriented with respect to the orientation of his own body. It means he must realize the directions of the axes of the Cartesian coordinate system used in the Rhinoceros with respect to the orientation of his own body and consequently, enter the correct coordinates of the vertices of the modelled cube as well as the appropriate value of the high of the cube. (usage of **A1**)

- is able to visualize the cube together with its parts following correctly the particular steps of setting by entering the required information (coordinates of vertices and high). (usage of **A2**)
- is able to realize if the virtual model of the cube that appeared in the scene of the software corresponds to the model of the cube. It means if the created model satisfies all the properties of a cube. He verifies if the exact part of a spatial object, e.g. the exact face of the cube is in the required position with respect to the reference plane or coordinate system. (usage of **A4**)
- is able to verify if the virtual model of the cube is located in the Cartesian coordinate system as it was mentioned. (usage of **A5**)

There are two possibilities for further modelling the cubic solid virtual model. Once, the user can create the basic solid (the cube) repeatedly. In this case, the user must consider the coordinates of diagonally opposite vertices for each newly created cube. This way is error-prone. Secondly, **duplicating a solid** (the cube; usage of **C5**) is another opportunity. The process of duplicating is the same as in every application. After duplicating an object, both objects are in the same position in the scene. A user can verify the creation of the duplicated object by marking it. Being two objects in one position, their edges/reference curves are lighted in pink colour instead of in a yellow one. No particular aspect of spatial ability is necessary for this step. The duplicated cube must be relocated in the next step. There is a special command for **relocating objects** (usage of **C3**) in the Rhinoceros software. The user should follow the particular steps that appear step by step in the command line of the software. Being relocating the duplicated cubes (see Figure 1), a user has to find out the coordinates of one of the vertices of the newly placed cubes.

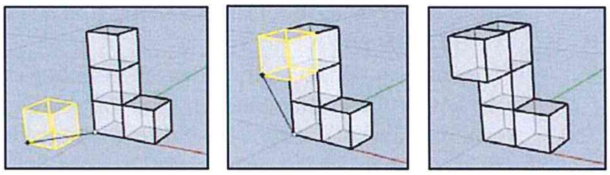

Figure 1: Process of the relocation of the cube in modelling the cubic solid

In relocating a duplicated solid, the user

- realizes the correct relation between the created solids. In the case of the cubic solids, i.e. the placement of the neighbouring cubes. It means, they must touch each other only by their touching faces. It is impossible to one cube is partly situated into a second one. (usage of **A1**)
- is able to visualize the cubic solid together with its unit cubes so that all the unit cubes are situated on their correct positions to create together the required cubic solid. (usage of **A2**)
- is able to imagine the relation of the particular unit cubes in the cubic solid, e.g. to find out parts of their contact (faces, only edges or nothing between the unit cubes of the cubic solid). (usage of **A4**)
- is able to verify how the particular unit cubes of the cubic solid are located in the Cartesian coordinate system. (usage of **A5**)

The Rhinoceros software allows the execution of Boolean operations such as union, intersection, and difference. It means that connecting solids (usage of C6) is possible to do in the Rhinoceros. Using the command of Boolean union, the particular unit cubes are united into the compact cubic solid. The user can verify the correctness of the used command by marking the cubic solid. If the edges of only one cube are in yellow colour (see Figure 2 on the left), the command of the Boolean union didn't work well. All the edges of the compact cubic solid must light in yellow colour. (see Figure 2 on the right)

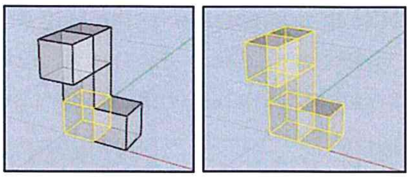

Figure 2: Process of the Boolean union of the unit cubes of the cubic solid

When connecting solids, the user

- realizes and distinguishes if the edges of only some unit cube or of all the unit cubes of the cubic solid are yellow lighted. (usage of **A1**)
- is able to visualize either the particular unit cubes of the cubic solid or the compact cubic solid in the scene of the Rhinoceros software. (usage of **A2**)
- must imagine if the command Boolean union is able to use for uniting the particular unit cubes for formatting the compact cubic solid. E.g. when two unit cubes don't touch themselves anywhere and no other solid is between them, the command Boolean union doesn't work. (usage of **A4**)

When creating the virtual model of the cubic solid, a user can use **zooming in** or **zooming out** (usage of **C7**) or **rotating the whole scene** (usage of **C8**) in the perspective window of the Rhinoceros software. Both mentioned categories are used to overview the parts or the complete constructed virtual model or for taking control of the correctness of the created particular steps of modelling.

Zooming in/out or rotating the total scene, the user

- is able to perceive the constructed virtual model of the cubic solid either in the total overview, in detail, or from various points of view. (usage of **A1**)
- visualizes e.g. a detail of the virtual model for creating small parts belonging to the 3D object, an overview of the virtual model to add some other parts to the scene, or another part of the object that wasn't seen from the starting point of view and is necessary to use it for the further steps of construction. (usage of **A2**)
- can rotate the virtual model of the cubic solid in the perspective scene of the Rhinoceros software and in his mind at the same time. (usage of **A3**)
- can analyze much better the spatial relations of all the parts and the whole created virtual model of the cubic solid with respect to the other created models, to the reference plane, etc. (usage of **A4**)
- is able to orient the virtual model of the cubic solid or its parts in the Cartesian coordinate system set in the Rhinoceros software. (usage of **A5**)

The categories **C2** and **C4** according to Dilling & Vogler (2021) weren't used in the process of creating the virtual model of the cubic solid in the Rhinoceros software. On the contrary, they will be used in setting the virtual model for 3D printing in the PrusaSlicer software.

Setting the visual model for 3D printing in PrusaSlicer

Before inserting the virtual model of the cubic solid onto the virtual printing bed of the PrusaSlicer software, it must be saved in the *.stl file in Rhinoceros. Having inserted the virtual model onto the virtual printing bed, it can be set for 3D printing using various tools of the PrusaSlicer software. The **parameters** of the model can be easily **changed** (usage of **C2**) via setting other percentages of its original sizes if we realize the printed model will be too small, or vice versa too large (see Figure 3 on the left). Spatial perception (a user perceives the location of the virtual model on the virtual printing bed, the size of the virtual model in comparison to the size of the grid drawn on the virtual printing bed) and spatial visualization (a user visualizes the virtual model on the virtual printing bed; having based on it, he decides if the model is printable without any extra supports) are used in this activity.

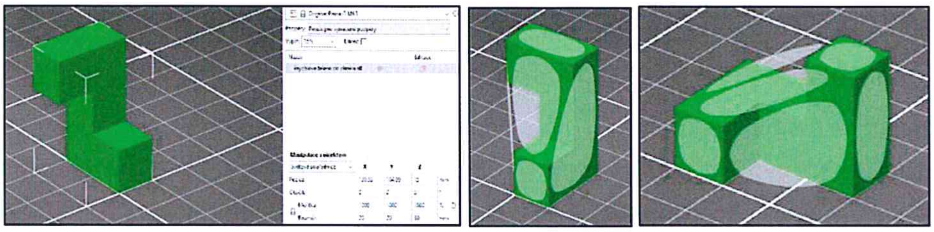

Figure 3: Changing parameters of the model and relocating the model on the virtual printing bed

The suitable location of the virtual model on the virtual printing bed is very important for 3D printing itself. 3D printing of a 3D object takes place in layers when the nozzle of the 3D printer places one layer of molten plastic on the other. Therefore, a user must modify the location of the virtual model on the virtual printing bed especially if the printed 3D object contains "overhangs". Sometimes it is possible to relocate or rotate the virtual model onto the virtual printing bed using the special tool of PrusaSlicer and marking the face of the virtual model onto which the virtual solid should be layn so that “overhangs” disappear in such a position (see Figure 3 in the middle and on the right). Rotation of the cubic solid (usage of **C4**) was done to the model is unproblematically printed on the 3D printer. If we take Maier’s (1994) aspects of spatial ability into account, the user is able to

- perceive the inserted virtual model on the virtual printing bed, he realizes its position with the respect to the Cartesian coordinate system and to the grid of the virtual printing bed. (usage of **A1**)
- visualize the inserted virtual model in the position which is the most suitable for the process of 3D printing and set the most appropriate parameters for the virtual model. (usage of **A2**)
- rotate the virtual model of the cubic solid onto the virtual printing bed so that the supports are not necessary to use in 3D printing. (usage of **A3**)
- analyze if the particular cubic solids are located separately without any contact with each other when inserting more than one cubic solid onto the virtual printing bed. (usage of **A4**)
- orient the virtual model on the virtual printing bed in such a way to it is parallel to the 3D printer arm so that 3D printing is of the highest quality. (usage of **A5**)

On the contrary, the rotation of the virtual model is not adequate in some cases. It means there is no chance to rotate the created virtual model of a 3D object into a position in which no overhangs appear. So-called “supports” must be used in such cases. Otherwise, the overhung parts of the 3D object hadn’t need to be printed well; a nozzle of a 3D printer could fall in the area of these parts. Consequently, there are two possibilities. A user can let set the supports by PrusaSlicer itself, or he can show the problematic details by drawing where the supports should be added (see Figure 4 on the left). Using the command “Slicing,” the software creates the individual layers of a virtual model and adds the supports if they seem to be necessary for safe printing (see Figure 4 in the middle). Having done slicing, a user can take control of the particular layers by using the unique slicer tool of the software (see Figure 4 on the right).

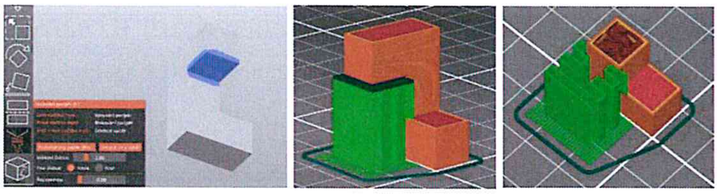

Figure 4: Process of setting supports into overhung parts of the cubic solid

The setting supports is a very responsible activity. If it is poorly done, 3D printing could crash in a better case, or a 3D printer could break down in a worse case. Thanks to that, a user has to use his spatial ability very carefully. Spatial perception and spatial visualization in the meaning of placing a virtual model onto the virtual printing bed in the adequate position are essential for visuospatial abilities as well as spatial relation when realizing whether there will be overhangs and mental rotation due to finding if it is not possible to prevent overhangs by another location of the object. If everything is set well, a user is able to save the created "project" as a so-called *.gcode file by pressing the appeared button. The *.gcode files communicate with 3D printers. So 3D printers reading those files are able to print 3D objects from corresponding virtual models.

Conclusion

Let's summarize, the attitudes of some researchers toward spatial were briefly described ability. The aspects of spatial ability according to Maier (1994) were mentioned. Categories of the identified actions of students when working with CAD software according to Dilling & Vogler (2021) were clearly written in a table and commented on. We described the creation of the relatively simple virtual 3D model of the cubic solid. By demonstrating its gradual modelling in the software Rhinoceros, we showed that in different steps of modelling, a user must involve various aspects of spatial ability. We have listed these aspects at each step and described them relating to the specific actions taken in each step. At the same time, we took over the relevant actions according to the categorization performed by Dilling & Vogler (2021). We found that in modelling the virtual 3D model of the cubic solid in the software Rhinoceros, six of eight activities mentioned by Dilling & Vogler (2021) were used. The remaining two activities can be used during the virtual setup of the 3D printed model in the PrusaSlicer software. The creation of a virtual 3D model of a 3D object in the software Rhinoceros and the setup of this virtual 3D model for 3D printing in the PrusaSlicer software themselves, e.g. according to a 2D drawing of the 3D model, affords users to develop their spatial ability. Students must transfer the 2D mapping of the 3D objects into the 3D scene of the software which helps to develop their spatial ability. We tested the modelling of cubic solids as parts of the so-called soma cube with students in the third year of the bachelor's cycle of the study program Mathematics for Education within the teaching of the course Geometric Software at TUL. Most of the students did make use of their spatial ability without any significant difficulty, even in the case when each of the students modelled their own cubic solids as part of the soma cube. One of the reasons could be the fact that they created the individual parts of the soma cube and their automatic com- and decomposition into soma cube in a dynamic applet in the freeware GeoGebra some weeks ago. More concrete details on findings of the suggested model in engaging students with spatial ability will be described after finishing the sharp testing of the model.

Our goal for the future is to use a case study to find out whether and how the use of the spatial ability in modelling virtual 3D models as a basis for 3D printing differs with the age of students, next, which aspects of visuospatial activities students use while creating virtual 3D models, and if students are able to construct 3D virtual models according to 2D drawings of the models.

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