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Contribution of 3D modelling and printing to learning in primary schools: a case study with visually impaired students from an inclusive Biology classroom

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ABSTRACT

Contemporary education adopts various new visualisation techniques for content to be learned. Recently, research on the application of 3D modelling and printing (3DMP) has been expanding. However, as the latest literature reviews indicate, little research is available on the contribution of 3DMP to learning of students with blindness (SWB) and students without disabilities (SWOD). This research aims to fill the gap through an exploratory case study, conducted in an inclusive Biology classroom in a primary school. Eight SWOD and four SWB (12 years old) participated in the study. The focus of the research was on pre-interventional and post-interventional students' knowledge about cells, and students' views on using 3DMP in Biology education. The data was analysed using Grounded Theory. The results indicate that 3DMP contributes to students' learning by improving the ability to enumerate, describe, and visualise the cell and its parts, by remediating some of the students' misconceptions and by increasing communication within a classroom. In terms of encountered obstacles, SWB noted that the quality of 3D models could cause new misconceptions. Adjusting the ratio, positioning and scaling of printed objects, inaccuracy in printing, and long printing process, are some of the problems which students encounter in 3DMP.

KEYWORDS

Students with blindness; inclusion; 3D modelling and printing; misconceptions; Biology

Introduction

There is a degree of complexity to natural sciences which brings certain problems for learners, and consequently for teachers, to tackle. For instance, some of the issues in Biology studies include plentiful species diversity and their shapes in nature, natural hierarchy from molecular to ecosystem levels, and almost an unlimited number of natural processes within and between different entities. Various teaching methods are used in Biology, whereas some, such as verbal-textual methods are common to other school subjects. However, dissection, experiments with living organisms, and microscopy are unique to Biology. In almost every instance of Biology education, problems encountered include misconceptions (Coley and Tanner 2012), unwillingness to participate in certain activities with living animals (Tomažič, Pihler, and Strgar 2017), and inability to connect knowledge of related topics at different hierarchy levels (Šorgo and Šiling 2017), to name but a few. With increased necessity for the inclusion of students with disabilities into an everyday classroom,

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and additional teaching obstacles arising, for which Biology teachers are usually not prepared, the need for contemporary research in the field increases as well.

There are approximately 36 million people with various degrees of blindness in the human population (Bourne et al. 2017), who receive different levels of support to overcome private and professional obstacles. The scope of this concern is backed by the fact that *Universal Eye Health: a Global Action Plan 2014–2019* created a proposal under the guidance of the World Health Organization, calling for all member states to ensure that people with visual impairment have access to educational opportunities and for disability-inclusion practices to be developed, realised and evaluated. Governments should support and assist actions to overcome the barriers that visually impaired people face in accessing public services, education, healthcare, employment, and mobility in their environments (WHO 2013). In the opinion of people with blindness, special attention of researchers should be paid to the following topics: environmental access, access to information, education, civil rights, social and financial support (Duckett and Pratt 2001). Unfortunately, traditional science teaching still generally relies on visual imagery, which is only rarely adapted to the blind (Jones et al. 2006; Beck-Winchatz and Riccobono 2008). A recognised problem of Biology in relation to education of SWB is that exercises focus on microscopy, dissection, and other laboratory techniques where most of the measuring tools, observation methods, and experiments rely on vision (Caldwell and Teagarden 2007). Essentially, it is not that teaching of Biology/Science is completely absent and unavailable to SWB. Nevertheless, it can easily be recognised that some topics are underrepresented or even completely missing in teaching Biology to SWB. In addition, there is an evident shortage of research which explores the adaptation of Biology learning materials to the visually impaired (Anđić et al. 2019; Fraser and Maguvhe 2008). Some of the contemporary technologies, such as haptic devices and 3D printing, promise potential for more inclusivity of SWB in Biology classrooms. As 3D printers have become cheaper and more accessible to schools, their presence in inclusive education with SWB has also increased. However, there is still a lack of research exploring the contribution of 3D printers to students' acquisition of Biology knowledge in primary schools (Hansen et al. 2020; Monkovic et al. 2021). Our paper strives to contribute to the knowledge in this area and explore the after-effects of 3DMP usage on SWB and SWOD learning outcomes.

3D modelling and printing in Biology education – literature review

3D modelling and printing has been used in Biology education in different areas and contexts, from Biochemistry to Anatomy, primary schools to universities. This section reviews research on 3DMP at all levels of education in Biology.

Garas et al. (2018) explored possibilities for using 3D-printed models as an Anatomy educational tool at university level. Within the study, a pre-test and post-test research design was used to explore the contribution of using the 3D-printed, wet and plastinated specimens of organs to develop the students' knowledge. The results indicate the students who used 3D-printed models achieved better knowledge in Anatomy than the students who used wet and plastinated specimens. In addition, students regarded 3D anatomical models as a usable tool for identification of anatomical structures and chose them as preferred tools for learning. The results from that study are supported by other similar research (Li et al. 2018; O'Reilly et al. 2016) which examines 3D printing in Anatomy at a medical faculty. Similarly, Keaveney et al. (2016) explore 3DMP in Biology education using the anatomy of corallite and crab specimens. In their research, a different approach to 3D scanning, modelling and printing diverse corallite and crab species was applied, where produced artefacts are used in education and research. The conclusion was that the produced 3D models effectively represent morphological and anatomical taxonomical features and could be successfully used for species, gender and age identification. In line with these are the results of Qing (2015) which concluded that 3DMP could be used for producing models of nematodes in the Biology classroom. It is to be noted that the research of Keaveney et al. (2016) and Qing (2015) primarily focused on the

creation of 3D models which represented the taxonomical characteristics of different species of invertebrate, rather than focusing on practical utilisation of the models in the classroom. 3DMP also found a place in the teaching of students on plant anatomy and morphology at university level. McGahern, Bosch, and Poli (2015) were among the first researchers to analyse 3D printing usage in Botany classes. Their study showed that, in comparison to clay modelling, 3DMP contributed to better understanding of plant root anatomy, structure and ratio between different plant parts, in addition to the evident increase in students' digital competence. Several recent studies on the use of 3DMP have been carried out on biomolecules. Howell et al. (2019) dealt with visualisation of DNA and RNA structure through 3DMP. In their approach, they used flexible strings for 3D printing and connected them to magnets in the model to get flexible and assembled models for student tasks and activities. The students used 3D-printed models during the lesson activities by working in small groups. The results of their research indicate that 3D-printed models help in addressing misconceptions held by undergraduate Biochemistry students. Additionally, pre and post-performance results show that 3D-printed models significantly contribute to the students' knowledge on DNA and RNA structure, transcription factor-DNA interactions, and DNA supercoiling dynamics, and increase their abilities in transitioning between 2D and 3D learning objects. The study reports that the students consider 3D models beneficial to their learning. Researchers Lohning, Hall, and Dukie (2019) conducted a student-focused longitudinal study aiming to explore 3D printing and cheminformatics (software for molecular modelling) effects on students' visual-spatial ability and knowledge of protein molecules, and student perceptions of these technologies. The students used cheminformatics to model monomer molecules which contained a ligand binding at the surface. Afterwards, the model was converted to .stl format and printed using 3D printers. The collected data on students' experience highlights both technologies had a positive impact on learning outcomes, visual abilities and understanding of protein structure. However, the results illustrate that students had a slight preference for using cheminformatics to 3D printers. As a possible reason for this, the authors cited higher resolution of models produced by cheminformatics than by 3D printing. Nevertheless, the students believed 3D printers should be included more in Biochemistry education.

More recent evidence provided by Monkovic et al. (2021) suggests that 3D printers could successfully be used in Biology classes at a high school level. They conducted research on the use of 3DMP during a *Homoeostasis and Immunity* teaching unit, with high-school students. A design-experimental group used 3D printed antibody kits for learning activities, while a control group used 2D learning materials (photos) for the same activities. The results analysis indicates the experimental group achieved better knowledge on the topic of *Homoeostasis and Immunity* than the control group. 3D printing encourages student participation in learning activities that leads to better knowledge and understanding of the same concepts. The students from the experimental group considered using 3D prints more enjoyable than the traditional way of learning, irrespective of effects which it has on knowledge acquisition. The authors Monkovic et al. (2021), believe that students would need more sustained work with these teaching aids for them to become aware of acquired skills and knowledge.

Vones et al. (2018) developed a creative approach to 3DMP use in primary school while teaching environment and social sustainability. Wishing to clarify the environmental problem with plastic to the students, the following steps were undertaken: the students went to the beach to collect plastic (fishing rope, nylon) that had been washed up; then the students revealed individual strands of plastic and used them as materials for producing PLA filaments for 3D printing. The students were given the freedom to print whatever they wanted from the produced filaments. The students printed various things – from toys to scientific objects. In this way, the students understood the process of recycling better. More recent evidence (Kwon, Lee, and Kwon 2020) confirms that 3DMP could successfully be used in Ecology education of primary school students. Kwon, Lee, and Kwon (2020), examined the effects of 3DMP while the students were taught the topic of *Natural Selection*. The students, third to sixth grade of primary school, used 3DMP to create a bird's beak for feeding at

tidal flats. The printed 3D beak models were used for simulation of food snatching from different tidal flats. These practical activities helped the students to understand the connection between beak size and shape and birds catching prey, and to understand what happens if the conditions for food accessibility change. In conclusion to the research, Kwon, Lee, and Kwon (2020), suggested the following steps for introducing 3D printing and modelling in Biology education of primary school students: learning about 3D printing and modelling; presenting and exploration of the taught topic; modelling and printing the 3D model connected to the taught topic and interacting-simulating with models.

While inclusive classrooms do not represent the majority of research on the topic, such research has become more prevalent recently. Díaz-Navarro and Sánchez de la Parra-Pérez (2021) explored the contribution of 3D printed models to the learning outcomes of students with blindness through human evolution. Díaz-Navarr and Sánchez de la Parra-Pérez (2021), used 3D printed replicas of crania which represented 11 of the most significant Hominidae species in evolution. Students with blindness had the chance to explore the models in a multisensory way and learn about human evolution. The researchers pointed out that all the students considered 3D printed models useful or essential for learning. The students gained the knowledge necessary to identify the main cranial traits that differentiate 11 3D printed replicas of crania. Karbowski (2020) conducted a research project that aimed to model and print specifically for people with blindness. For Biology, models of a leaf with caterpillar eggs, caterpillars, and similar were printed. In the opinion of students with blindness who used the 3D models, the models helped them to visualise the object and perceive it more realistically. Marenzi, Danese, and Gandolfi (2018), explored the possibilities for 3D printing of microscope slides and using them in medical education of students with visual impairments. As a starting point for their research, they used micrographs of different tissues. The micrographs were converted into .stl printing files and printed. They concluded the 3D printed models obtained in this way can be reproduced with a high level of precision and can be useful in medicine education of students with visual impairments. They tested the 3D models with students with residual visual ability, and concluded the models contributed to the students' ability to distinguish details on tissues more than with 2D material. Ramirez and Gordy (2020) conducted several workshops with teachers in inclusive Biology education. They indicated the following barriers which could occur in 3DMP in the inclusive classrooms: access to 3D printers and training for their use; a long time for modelling and printing of models; high procurement cost of printers and filaments for schools; high level of technical skills required from the teacher, pedagogical training for constructivist learning, 3DMP requires longer time for realisation in the classroom than traditional teaching. These are but some of the obstacles that students and teachers deal with when it comes to education supplemented by 3D printing and modelling in both regular and inclusive classrooms.

In summary, two basic principles of 3D printers in Biology education are common: interaction solely with previously 3D-printed models and modelling and printing of models by students during the lesson. In both cases, literature shows that 3DMP places students into an active role of a producer, which leads to better understanding, describing, and applying of knowledge (Fidalgo et al. 2019; Loy 2014; Rias et al. 2017). However, research focuses more on pedagogical value and effectiveness of a learning process, rather than on the benefits to students' knowledge. This is in line with recent literature review on 3D printers in Biology education (Hansen et al. 2020).

Research goals and questions

The purpose of this study is to explore the influence, usefulness, and contribution of 3DMP to students' Biology learning outcomes on the topic of *Cell Structure*, in an inclusive classroom. In addition, this study wants to give recommendations for future research on this innovative practice of integrating 3DMP in inclusive Biology education. In line with the research goal, this research addresses the following questions:

(1) What are the effects of 3DMP on sixth grade (12 years), SWB and SWOD knowledge acquisition on the topic of *Cell Structure* and students' abilities to:
   (a) enumerate parts of a cell and its organelles;
   (b) describe parts of a cell and its organelles.
(2) What are SWB and SWOD views on 3DMP in learning?
(3) Which obstacles do SWB and SWOD face when using 3DMP in learning about *Cell Structure*?

Methodology

To understand how 3DMP influences and contributes to knowledge and the learning process in inclusive classrooms, we conduct an exploratory case study. Yin (2018) suggests an exploratory case study should be used if the researchers want to answer 'who', 'what', 'where', 'how', and 'why' questions. According to Cohen, Manion, and Morrison (2002) and Yin (2018) an exploratory case study should be used where there is not enough published previous research. They suggest that the exploratory case study needs to specify the data collecting and processing procedures so that they could be used in future research. To our best knowledge, there is no published research that explores the contribution of 3D printing and modelling to students' Biology knowledge in a primary school inclusive classroom, which was the primary reason for choosing an exploratory case study for our research. The second reason for the employment of the exploratory case study is the fact that the exploratory case study has a long tradition in science education when examining student learning outcomes (Mills, Durepos, and Wiebe 2009).

Research design

Our exploratory case study aimed to examine 3DMP contribution to students' knowledge and opinions about the learning process. This research was conducted in the 2019–2020 school year, through the following phases:

Phase 1: *Teachers' workshops* on using 3D printers. All teachers who participated in this research attended a one-day workshop on 3D printers. This workshop was divided into several parts, such as: theoretical part on 3D printing, technical part on 3D printing, presentation of free 3D modelling software and practical work of participants – modelling and printing of 3D models.

Phase 2: *Students 3D printing workshops.* Students' workshops were organised as extracurricular activities, and they were held by their teachers. These workshops lasted four school classes, organised in a span of two weeks. The teachers dedicated one school lesson to each of the following topics: technical characteristics of 3D printers, software for 3D modelling, practical activities in 3D modelling, and practical activities in 3D printing. In addition to these four classes, the students were given the opportunity to practise 3DMP on their own at school, as much as they wanted. Additionally, they could practise 3D modelling from home, due to an existing online platform. The main goal of these workshops was to get the students acquainted with 3DMP before its use in Biology classes.

Phase 3: *Teaching about the cell.* During the four school classes, the teachers taught *Plant and Animal Cells*. The students worked in groups, using textbooks, workbooks, microscopes, microscope onion slide preparation, Braille worksheets, and standard 3D models. The main activities encompassed: analysing texts on *Cell* given in textbooks, discussing the topic, completing tasks in student workbooks, preparing of an onion microscopic slide, observing and drawing the cell. In this way, the students included all the activities envisaged by the national Biology curriculum. In accordance to the Montenegrin National Curriculum, teaching topic *Plant and Animal Cells*, is taught in the sixth grade. After completing the classes, the students should have achieved the following learning outcomes: ability to define a cell, understand the diversity of cells in terms of shape and size, knowledge about what cellular organelles are, ability to describe and distinguish

cellular organelles and different cell parts, ability to distinguish plant from animal cells. The students learn to recognise, denominate and describe the following 13 cell parts: cell wall, cell membrane, cytoplasm, nucleus, nucleolus, mitochondria, centrioles, endoplasmic reticulum, golgi apparatus, lysosome, ribosome, vacuole and chloroplast. According to the Montenegrin National Curriculum, sixth-grade students do not learn about the role and functions of organelles. These topics are covered in seventh grade.

Phase 4: *Pre-interventional students' knowledge testing on the topic – Cell.* The students were asked to enumerate parts of plant and animal cells and describe the cell parts, which they enumerated. In addition, the students were asked how sure they are about the accuracy of their answers (enumerations and descriptions). Through testing the knowledge in this way, we tried to adopt the suggestions of previous researchers who educated blind students about the *Cell* (Jones et al. 2006), as well as students without disabilities (Huk 2006). The basic principles of three-tiered tests for diagnosing students' misconceptions about the *Cell* were included (Suwono et al. 2021). The SWOD answered in written form, while the SWB answered orally and their answers were recorded. All of the students were given the time to think about the questions and come up with an answer. It was also emphasised to them that they could always go back to the previous question to correct their answer or to supplement it.

Phase 5: *Practical activities – collaborative 3D printing and modelling*. During the following four weeks (eight classes), the students collaborated in groups at first to model, and then print 3D cell models. For 3D modelling, students used Tinkercad software. The students developed cell models from scratch. In this process, the students were instructed on the importance of collaborative work. From it, SWOD explained the modelling steps to SWB and discussed potential solutions and future steps in the modelling process. The designed models were printed with Creality Ender 4 3D Printer.

Phase 6: *Post-interventional students' knowledge testing on the topic – Cell.* During this phase the students were asked the same question as in phase 3, just the questions were in different order. The same principle for answering and collecting the data was employed.

Phase 7: *Questionnaire – Interview.* In the end, each class researcher conducted a short, mini interview with students. All the students were asked the same five questions: *What were the positives of today's class? What were the negatives of today's class? Describe your interactions with your classmates; Describe your participation in the task; What could be improved for the future use of 3D printers in inclusive classrooms?* The students on average spent around 5 minutes answering the questions. The main aim of short questions was to explore students' opinions and impressions immediately after the team work in 3D modelling and printing.

Data processing

The data obtained on pre-interventional and post-interventional testing was analysed with descriptive statistics (mean). The descriptions of cell organelles and cell parts by students were coded by three researchers with a background in Biology education and three experienced Biology teachers and then marked as correct or as incorrect. A similar approach for students with blindness was used in other studies (Anđić et al. 2019; Jones et al. 2006), and equivalently for students without disabilities (Knight et al. 2015). The answers from short-interviews were coded by the same researchers and Biology teachers. The audio recorded material collected from SWB during the description of cell parts and mini-interviews of all students was transcribed at first and then combined with the written responses of SWOD from pre- and post-interventional testing.

The transcribed material was read and re-read to provide insight into the whole material, to the researchers and Biology teachers. After that, the material was coded by each member of the research team independently. Grounded Theory was used for coding (*Strauss and Corbin 1990*). Grounded Theory is preferable when there has been no research done in a particular field, or the available research is scarce (McCann and Clark 2003). Grounded Theory was recommended for the use in data processing in Biology education in previous researches (Anđić et al. 2021; Sung, Swarat, and Lo

2020). The coding process was done manually and organised in three stages: a) open coding, b) axial coding, and c) selective coding. In the first stage of open coding, the data was organised into smaller parts, which were analysed in detail and coded. During the process of separating the transcriptions into the smaller parts, the following questions were asked: *what, who, how, when, why, what for*, recommended by Böhm (2004), Mey and Mruck (2011). The reasoning was to obtain a wealth of initial codes, which clearly and accurately represent the data. In vivo, open coding was used, which means the initial codes were derived using descriptions directly from the data. In the second stage of open coding the small parts were compared. At the basis of similarities small part – initial codes are tagged with the same final code. The codes obtained in open coding represented the basis for axial coding. The intent of axial coding was to investigate the relationships between codes according to causes, strategies, consequences, and to developing the categories. The categories created in axial coding were used in selective coding. The goal of selective coding was analysing, developing and linking the codes obtained in axial coding. The results of selective coding were theme-central phenomena, around which other categories revolve. After the process of coding, the formula of Miles and Huberman (1994) (number of agreements/(number of agreements + disagreements) × 100), was used to calculate the reliability of the obtained data. For the coding of descriptions of cell parts and organelles, the Miles and Huberman formula indicates high inter-coder consistency (93%). The same formula shows high inter-coder consistency for questions in the interview (89%). Due to these facts, the data obtained in the process of open, axial and selective coding could be considered as reliable.

Participants and treatment

Eight students without visual impairments (SWOD) and four students with visual impairments (SWB) from Montenegro participated in this study. All participants were 12 years old. One SWB had no light perception and three of them had light perception without the ability for independent object dissimilitude. None of SWB had any other disabilities except visual ones. The anonymity of all the participants was guaranteed. The principals of the schools, teaching and administrative staff were informed about the research and its purpose. Before the research commenced, a meeting with students' parents was held. The parents were informed about the research and all its phases and the children could participate.

The students were divided into two teams, both made of six students (4 SWOD and 2 SWB). Both teams were given the same task, to model and print a 3D model of a plant or animal cell of their choice. The students were directed that every member of the team should participate during each activity. The students had two weeks for modelling and printing, during eight school classes. During this period, the students had four Biology curricular school classes, but also the students were offered to work on their models in four extra-curricular school classes, if they considered it necessary. Each team was provided with a computer and 3D printer. The students collaborated on ideas, models and printing of their 3D cell models. In this process, teachers were included only to give advice and only when students required it. The students used Tinkercad software for modelling and Creality Ender 4 3D Printer for printing. Tinkercad is a free 3D modelling software that does not require a high level of computer skills. Tinkercad 2is also recommended for education in primary and secondary schools in previous research such as that undertaken by Coşkun and Deniz (2021), Trust and Maloy (2017). The model of 3D printer was selected using the following criteria: safety, quality of the model, price and affordability. The suggestions form two experts on 3D printers were acknowledged. We found that Creality Ender 4 3D Printer fulfilled all the requirements.

Results

Student knowledge on plant and animal cells before 3D modelling and printing

After the lessons and before 3D modelling and printing, the students were able to name 8.5 out of 13 cell parts on average. Most of the students (nine out of twelve), forgot to name the following cell parts: centrioles, ribosome, and lysosome. The students had a problem with enumerating mitochondria and vacuole in plant or animal cells where only six students gave the right answer. However, the students were less successful in the task of describing the cells and their parts and organelles. None of the students described all cell parts correctly. Twelve students described 13 cell parts or organelles, which amounted to 156 descriptions. From this number only 61 (39.1%) were correct. Parallel to it, the students were highly confident with the opinion that 118 (75.4) of their descriptions were right. This data indicates students' misconceptions on cells. In the process of coding, student misconceptions were categorised into three themes: misconceptions about the spatial interpretation of cell shape, misconceptions about the spatial cell parts and organelles, misconceptions about the cell part and organelles' positions and colours. All three themes of misconceptions were registered in both groups of students. The only difference was that SWB did not use colour in cell descriptions. For instance:

Ana (13 years old, SWOD) described the shape of cells in the following manner: "*The cells can be of different shapes, such as square, circle, and so on. They can also be reticulate in shape like the cells of onions which we observed under a microscope* ".

Luka (13, years old, SWB) used this description for cells: '*Cells can be in the shape of a circle and they are mostly animal cells and in the shape of a square or irregular, they are most often plant cells*'. These and similar descriptions were classified in the theme misconceptions about the spatial interpretation of cell shape, because in these descriptions, students mostly described the cells as two-dimensional objects.

Most students described the cell parts and organelles as two-dimensional, for example: Ivan (13 years old, SWOD) described the cell wall as a "*thick line that surrounds the cell*", similarly Sara (13 years old, SWB) described the lysosome as "*small circles inside the cell*". These two-dimensional perceptions and descriptions of cell parts and organelles by the students are classified into the theme misconceptions about spatial cell parts and organelles.

The analysis of students' descriptions of cell parts and organelles indicates several misconceptions about cell parts' and organelles' positions and interrelations. For example, some students used the following codes in descriptions: '*cell wall and membrane are intertwined*', '*mitochondria are below the nucleus*', '*centrosome is close to the cell membrane*'. Most of the SWOD added colour to their description: '*mitochondria are orange*', '*nucleus is red*' '*Golgi complex is blue*'.

Student knowledge on plant and animal cells after 3D modelling and printing

Both groups of students modelled the cell for a total of eight school classes. After modelling, the process of printing a cell whose average dimensions were 6 cm × 7cm × 4 cm was between 5 and 6 hours. The printing process itself was organised as an extra-curricular activity and students had the opportunity to observe it. For the printing of the cell itself, a quantity of PLA printing material

Table 1. Differences in the students' achievements on pre-test (before 3D modelling and printing of the cell) and post-test (after 3D modelling and printing of the cell).

	Student achievement	
Student task	Pre-test	Post-test
Name cell parts (out of 13)	8.5	11
Percentage of accurately described cell parts	39.1	77.6
Percentage of incorrectly described parts of the cell	60.9	22.4
Percentage of students' confidence level in their punctuality of cells part descriptions	75.4	87.1

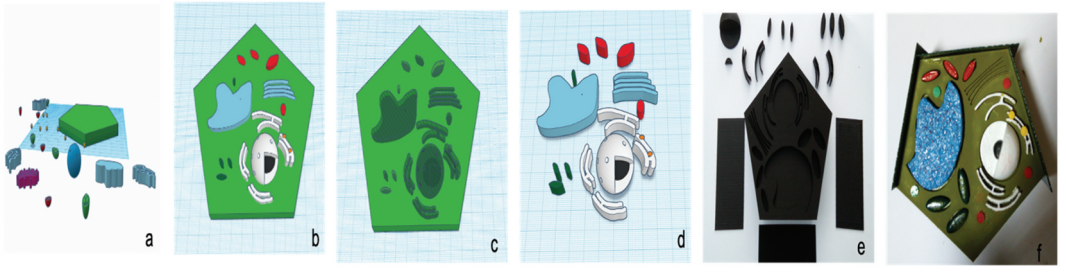


Figure 1. The process of developing a 3D plant cell model by students: a-d 3D plant cell modelling; e-f printed 3D model.

of about 5 Euros in value was used. After the printing process was completed, the students started the process of painting the cells, with this activity lasting for one class. After 3D modelling and printing of the cell, post-testing of students' knowledge was performed.

All the students achieved better scores on post-testing than on pre-testing, Table 1.

On average, the students were able to name 11 out of 13 cell parts and organelles. Seven students did not name the lysosome and ribosome as cell organelles. However, after studying supplemented by 3D modelling and printing, all the students could clearly separate which parts belong to plant and which to animal cells. The students' work in the process of 3D modelling, as well as the 3D printed model of the plant cell are shown in Figure 1. Both groups of students printed one model each, which they then painted with acrylic paints.

The students' abilities to describe the cell parts and organelles were increased after 3D modelling and printing. From the total of 156 student descriptions of cells and their parts and organelles 121 (77.6%) were correct. The students had a very high level of confidence in accuracy of their answers and considered a total of 136 (87.1%) of descriptions as right. Misconceptions on cells and their parts and organelles, after 3D modelling and printing and interacting with models, were categorised into two themes: misconceptions about the colours and misconceptions about texture. Misconceptions about the colours were registered only with SWOD and it occurred in two instances. First in the descriptions during the testing and then during the students' interviews. Filip (13 years old, SWOD) described the nucleus: '*The nucleus is a red ball*'. In a similar way, Ina (13 years old, SWOD), expressed in an interview: '*Today we decided to color our 3D model, it was good we could procure all the colors, which we should use to color the cell as it is in the textbook. The colored cell will be more beautiful than the black one*'. The misconception about the texture occurs only with SWB, and it is registered in their re-test descriptions. For example, Barbara (13 years, SWB), described the mitochondria as: '*Mitochondria are cylindrical structures with both sides with rounded ends, their length is two or three times their thickness and width. On the surface of the mitochondria, small lines as micro channels could be palpated*'. However, these lines are the consequence of 3D printer printing layer by layer, which can sometimes create

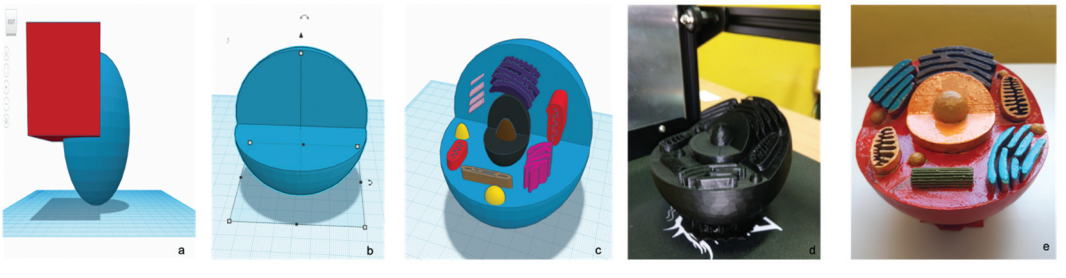


Figure 2. The process of developing a 3D animal cell model by students: a-c 3D animal cell modelling; d- the process of 3D model printing, e- 3D printed and coloured model.

a micro channel between two layers, and it is not a specific characteristic of mitochondria. The students' work in the process of 3D modelling, as well as the 3D printed model of the animal cell are shown in Figure 2.

Student views on the use of 3D modelling and printing

In the process of coding the students' mini-interview, 187 codes were extracted; these codes were classified into 9 categories, and at the basis of the links and dependencies between them into three core themes: a) contribution to learning outcomes, b) contribution to student communication, c) obstacles during 3D printing and modelling.

The theme *contribution to learning outcomes* consists of four categories: opportunities for practical activities, providing fast feedback, increasing the visualisation and spatial abilities and multiple representations of the learning content.

In students' opinion 3D printing and modelling contributed to their knowledge by providing practical activities. Luka (13 years old, SWB) after 3D cell model interaction said: '*Something really good in today's class was that I had a chance to explore something that was created by my friends and me. It is really cool to discuss, conceptualise and create this model for learning with my mates. During this process we learn a lot because we should not only memorise things but also build something*'.

It was important for students to get quick feedback and the ability to correct a mistake if they made it. It was also important for them to have the opportunity to discuss corrections and analyse different solutions and find the best one for correction during 3D modelling. This is reflected in Ana's opinion (13 years old, SWOD): '*I like the possibility that we can know what is good in our model during 3D modelling, while we observe it from a different perspective. When some mistake occurred, we first give our proposal for correction and afterwards discuss it and select the best solution for correction. The point is not that one solution is right and the other is wrong, the point is to choose the best from several good suggestions*'.

The students found the possibility to rotate and observe the models from different perspectives important. It helped them visualise and memorise how many sides a cell has. Barbara (13 years, SWB) said, '*And since I couldn't see the screen, it was very helpful that my friends from the group explained to me on the example of the book what can be seen. Just as two different ends of a book cannot be touched/explored at the same time with one hand, so parts of a cell cannot be seen on the screen at once*'. Filip (13 years old, SWOD) said '*A good thing about 3D modelling is the possibility to see what we did from a different point of view. When we model the cell something that looks connected from one side, is actually totally separated when we change the perspective. It's like . . . you can't see the man's belly if you look from his back'*.

Multiple representations of the learning content created by 3D printing and modelling provide additional contributions to the students' visualisation and spatial abilities. The students liked the possibility to observe a digital version of the model, print the physical one and compare it with information and pictures from the textbooks. Sara (13 years old, SWB) said '*It was good to explore the 3D printed model, because I wanted to explore how our idea about cells was realized. It was also interesting during the model exploration, to recall all modelling descriptions which my peers provided in the modelling process and have a look at the cell parts which are described in the textbook. This helped me to understand what the cell actually is*'. Ana (13 years old, SWOD) said '*It is interesting how the cell is differently represented in the textbook, in Tinkercad and as a printed model. I think all students should have the chance to learn from all three depictions of a cell because they provide different information. For example, I prefer the digital version of the model it is 3D and in color*'.

The theme *contribution to student communication* contains two categories: interaction during the modelling and interaction with the 3D printed model. SWB enjoyed both parts of model creation, because the peers described every step to them, but they had the feeling that explaining things makes the process of modelling a bit slower. Luka (13, years old, SWB) said '*I really liked it when my peers describe to me what they do during the modelling, usually, it doesn't happen during*

other class activities, it allows me to express my ideas. Maybe, it takes a longer time for model creation, but I like it'. Comparatively, SWOD liked to describe the process of modelling to the SWB, because during that process some new ideas were born. Filip (13 years old, SWOD) '*The description of the modelling process to Luka* (SWB), *was like thinking aloud and it helped us improve our ideas*'. Students liked the possibility to change their role in the description process when they interacted with a physical model. For instance, Ina (13 years old, SWOD) said '*It was amazing to hear how Sara (SWB), described the model to us, because we could check how good our description was in the modelling phases*'. This process was interesting for SWB, and they had the feeling of equality. Sara (SWB) said '*When my peers asked me to describe to them the 3D cell models I was really happy. It was like in the process of modelling they were leaders and in the model description, me and Luka took that role*'.

The theme *obstacles during 3D printing* has three categories: obstacles in 3D modelling, obstacles in 3D printing, and model quality. During the modelling phase, the students faced several obstacles: difficulty in settings the ratio scale and positions of all parts of the model from each perspective, problems with changing the scale of objects, and moving a part of the model instead of rotating the perspective. From the students' point of view, this could be tiring, time-consuming and disappointing. Ana (13 years old, SWOD) said '*Today was really a disappointing day. Yesterday, we spent the whole class adjusting several parts of the cell from a different perspective, and today we moved one by mistake and half of the class we spent on adjusting it again*'. The students mentioned two obstacles, which appeared in the process of 3D printing: pulling of the model during the printing and long time for printing. These obstacles were clearly presented in the narrative of almost all the students. Ana (13 years old, SWOD) said '*Today's class was really bad, after 15 minutes of printing, the printer started pulling the model around the surface, which destroyed the already started printing, which requires a long time anyway*'. The third obstacle which was classified in the category model quality was considered only from the side of SWB. For example, Sara (SWB) said '*During the exploration of the 3D model, I recognized that some of the cell parts have micro channels on their surface. My mates told me they appear because of the printing process. If it is possible to print a model without those micro channels it would improve the model for us who perceive it through touch*'.

Discussion and implications

The results of our research indicate that 3DMP could contribute to SWB and SWOD knowledge to name, visualise and describe cells and their parts and organelles. On average, the students were able to name 2.5 cell parts and organelles more after the process of 3DMP than before its use. Before 3D printing and modelling, seven students had problems classifying mitochondria and the vacuole in plant and animal cells. Most of the students (seven out of twelve) considered mitochondria as exclusively animal organelles and vacuoles as plant organelles. However, after 3D modelling and printing, all the students could successfully classify cell parts and organelles to the corresponding cell (plant cell, animal cell or both). These results coincide with the findings of Garas et al. (2018), which concluded that 3D printing contributes to the increase of SWB knowledge of Anatomy. Similar results were obtained in the research of Díaz-Navarro and Sánchez de la Parra-Pérez (2021), which claimed 3D printing and modelling contributed to the abilities of SWB to recognise and describe different replicas of crania of Hominidae species.

Perhaps more importantly, the results of our research indicate 3DMP contributed to the correction of student misconceptions about cells. Before 3D modelling and printing, most of the SWB and SWOD had misconceptions about cells and their parts and organelles, and considered them as two-dimensional objects, lines, squares or similar. Even though the teaching activities, teacher and textbooks (written information) provided correct descriptions (research phase 3) of cells and their parts, the students still developed misconceptions. One possible reason for the occurrence of the misconceptions could be how cells are depicted in textbooks. Our assumption is supported by the results of Kose, Pekel, and Hasenekoglu (2009), and Florax and Ploetzner

(2010), which indicate the two-dimensional depiction and schematic representation of Biology content in textbooks could be one of the reasons for student misconceptions. After 3DMP student misconceptions about the spatial interpretation of cell shape, cell parts and organelles were remediated. However, SWOD misconceptions about cell and organelle colours persisted. One team decided to colour their 3D cell model to look more beautiful than leaving it to be a black cell. A possible reason for persistent cell and organelles colour misconceptions is the mono-coloured (black) 3D model, which students produce, therefore rendering them unable to see colours on the model. Our assumption is supported by reports of McMenamin et al. (2014), which showed that coloured 3D printed anatomical models are more attractive and vivid teaching tools for the students than mono-coloured 3D models. However, previous research indicates contributions of 3D modelling and printing in remediation of SWB and SWOD misconceptions (Howell et al. 2019; Buehler et al. 2015). Students' misconceptions about cell and organelle colours and their prevention or remediation in future should be explored in detail. Teachers should bear in mind this misconception, and if students want to colour the 3D model they should explore the real cells' and organelles' colours, not only rely on textbook pictures.

It is surprising that the interaction and exploration of the 3D models created new possible misconceptions with SWB. During the interaction with 3D models, SWB perceived small 'micro-channels' on the model and considered them as a characteristic of cells, organelles and their parts. Previous research, which explored 3DMP for education of SWB, does not indicate a similar obstacle. One possible reason for overlooking this important information in previous research could be the tasks which SWB should perform when interacting with a 3D model. In most of the previous research, SWB had a task to recognise what the 3D model represents, but not to describe the model. We suggest several possibilities to prevent this misconception. Firstly, it is advisable to use a 3D printer of better accuracy for printing models in better quality for SWB. Secondly, providing additional information during the introduction of the process of 3D printing and modelling to the SWB, so they can be aware of the possible origin of this formation on the 3D printed model. As the third possibility, the use of easily available textures (e.g.a stone, sand and sanding, glass, pottery, etc.) can be considered for covering the imperfections of 3D printing and preventing the development of misconceptions in students with visual impairments. Another potential solution could be that SWOD model a cell in 3D software and SWB can model the cell using clay or plasticine. Future research could examine the effectiveness of the above proposals.

We summarised the contribution of 3DMP to the students' knowledge about cells and presented it in Figure 3.

To the best of our knowledge, there is no existing or ongoing research, which denies the contribution of 3DMP to students' knowledge. This and the results from our research encourage

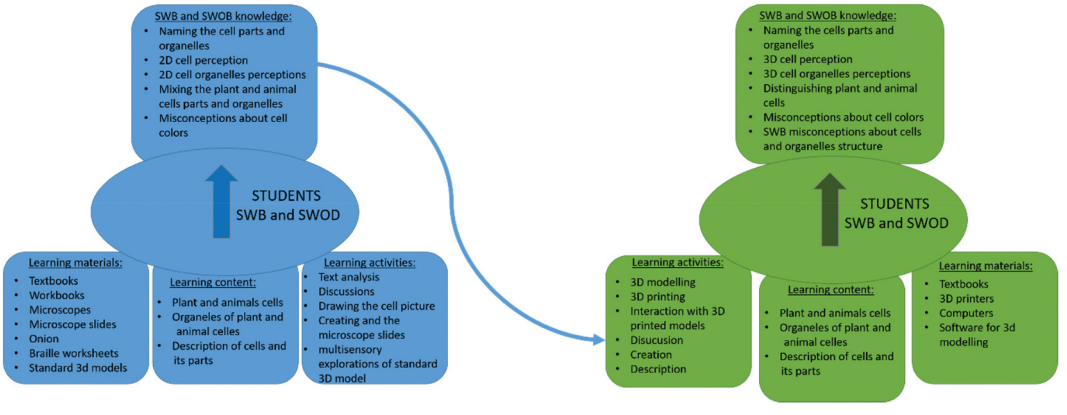


Figure 3. Contribution of 3DMP to the SWB and SWOD knowledge about cells.

us to recommend 3DMP for Biology education of SWB and SWOD, whilst having in mind the abovementioned shortfalls, which could be overcome.

According to students' feedback, 3DMP contributed to their knowledge through providing opportunities for practical activities, fast feedback, increased visualisation, increased spatial abilities and multiple representations of the learning content. This is in positive agreement with the results of research by Eisenberg (2013), Sullivan and McCartney (2017), which stressed that 3DMP enables students to turn theoretical knowledge into an actual object. This is especially important if we have in mind that science education is still often focused on theoretical knowledge rather than on practical student activities (Corum and Garofalo 2015). Students considered fast feedback which they got when rotating the prototype in a modelling process, feedback from classmates during the modelling and interacting with the 3D printed model, and possibilities to correct the models, as valuable for their knowledge. This substantiates previous findings in literature which indicate that through feedback and repetitive 3D modelling and printing, students can revise their ideas and achieve a better understanding of learning content and gain better knowledge (Huang and Lin 2017; Verner and Merksamer 2015; Wang et al. 2017). Our study expands on previous knowledge about the contribution of 3D modelling and printing to students' visualisation, spatial abilities and multiple representations of learning content (Huk 2006; Giraud et al. 2017; Howell et al. 2019; Bernard and Mendez 2020). In most previous studies, the contribution of 3D modelling to students' visualisation and spatial abilities was exclusively reserved for the students without sight disabilities. Additionally, previous research mainly examined the interaction of SWB with previously printed models. In comparison, our findings indicate the process of collaborative learning during the modelling process could contribute to the spatial abilities of SWB as well. According to the opinion of SWB, discussion with peers and descriptions of steps in modelling helped them in visualisation and spatial perceptions. This finding in turn led us to the next concept where contribution of 3DMP was present – communication.

According to the SWB and SWOD, communication between them was very helpful and amenable. SWOD considered the process of describing the steps, during the modelling of the 3D model, made them a bit slower, but it contributed to evolving their ideas. The most remarkable result about communication is seen in the opinions of SWB. They believe that during 3DMP they participate in the task as equals to SWOD. That is, the leadership in leading activities between these two groups of students alternated during the activities, which is not so common in an inclusive classroom. Our findings reinforce the results of previous research, which indicate that 3D printing and modelling helps in fostering meaningful communication and collaboration between SWB and SWOD (Usuda-Sato et al. 2019; Kostakis, Niaros, and Giotitsas 2015; Pantazis and Priavolou 2017).

Nevertheless, during the process of modelling, printing and interacting with the 3D model, students faced difficulties. Similar to previous studies (Nemorin and Selwyn 2017; Ford and Minshall 2019), in our study students struggled to adjust the models from different perspectives, change the scale and move one part of the model. Nemorin and Selwyn (2017) noted similar obstacles could lead to frustration in students. This is in line with the opinions of students who participated in our study. Taking into consideration that imperfections of 3D modelling software have been confirmed by multiple researchers, the developers of future software should consult with teachers and students. The students participating in this study had to overcome obstacles like long print times of between 5 and 6 hours, and a minor problem with printer accuracy. It is possible that these results are due to the use of an average 3D printer, but which is cheap and affordable for most of the schools. However, it should be emphasised that the total frame costs of 3DMP printing (PLA plastic strings and consumed electricity) are extremely low and in our case for a cell model measuring 6 cm x 7 cm × 4 cm it amounted to approximately 5 Euros. It is important to bear in mind that almost all the above-mentioned research pointed out that cheap and affordable 3D printers are most often present in schools. In relation to that, the future designers of 3D printers should consider improving the accuracy of 3D printers to increase their usability in education. SWB administered a suggestion for one more improvement in 3D printed model quality. They could

perceive the micro channels on the models which were a consequence of the way the models are printed in layers. However, teachers should have this in mind when it comes to the use of 3DMP in an inclusive classroom and try to overcome this with additional explanation and instructions. This imperfection of 3D printed models should be improved in collaboration between engineers, teachers and SWB.

Conclusion

The main goal of our study was to determine the contribution of 3DMP to the SWB and SWOD in Biology learning outcomes on the topic of *Cell Structure*, inside an inclusive classroom. The results of our study show that 3DMP contribute to the students' knowledge when naming the cell organelles, distinguishing plant and animal cell parts, visualising the cell and its parts, as well increasing student spatial abilities. Students had a positive attitude towards 3D modelling and printing. According to their opinion, this approach of learning helped them acquire more knowledge on cells through learning with practical activities, fast feedback, increasing the visualisation, spatial abilities and multiple representations of learning content. The students believed that 3DMP increased communication and created the atmosphere of equal participation. The students faced challenges in the process of modelling (setting the ratio scale, positions and scaling of the object), accuracy and long printing process. SWB perceived microchannels on the models, which would confuse them. These 3DMP imperfections should be reduced or eliminated in collaborative work between students, teachers, developers and engineers.

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Ethics statements

In accordance with the rules for educational research in Montenegro, in which this research was conducted, the approval of an ethics committee for this type of research is not necessary. Consistent with this, our study was undertaken in accordance with the British Educational Research Association's Ethical Guidelines for Educational Research.

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