

The use of 3D-printed instructional materials in active learning activities within science lessons

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Highlights

- Active learning with 3D-printed materials significantly improved students' academic achievement in science lessons.
- Students reported better conceptual understanding through enhanced visualization and tactile interaction.
- Despite some technical issues, students overwhelmingly preferred lessons involving 3D-printed materials.
- 3D-printed materials were especially effective for teaching abstract and spatially complex scientific topics.

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Keywords: 3D printers, 3D-printed instructional materials, science education, active learning, academic achievement

Abstract

This study aims to investigate the effect of active learning activities utilizing 3D-printed instructional materials on students' academic achievement and to explore their perceptions of these activities in science lessons. Specifically, the research focuses on the 6th-grade unit "Systems in Our Body and Health," where 3D-printed instructional materials were produced and integrated into classroom activities. The study was structured as a "sequential mixed research design" since qualitative and quantitative data were collected one after the other. The experimental group, which received the intervention, comprised 30 students, while the control group, which underwent the conventional science lesson process, included 28 students. Students who engaged in active learning activities utilizing 3D-printed instructional materials in the science lessons demonstrated higher academic achievement compared to their peers who did not participate. In the semi-structured interviews, the experimental group students commented that the activities helped them understand the subject because 3D materials allowed them to see and touch the content from different angles.

1. Introduction

Expository teaching strategies, a conventional method for teaching fundamental concepts in science courses, remain prevalent. Conventional teaching approaches are characterized by verbal communication (expository, didactic) and a formal structure, where the focus is on the teacher, who delivers lectures while students passively receive information (Zarotiadou & Tsaparlis, 2000). A substantial body of research indicates that active, student-centered instructional methods outperform teacher-centered approaches in fostering conceptual understanding (Cohen, 1992; Hockings, 2009). Numerous scholars advocate for the essential shift from teacher-centered to student-centered teaching methodologies (Agrahari, 2016; Awacorach et al., 2021). In the student-centered pedagogical method, the student actively engages in course activities. Engaging students in activities that facilitate active participation will concretize abstract scientific concepts, which are often unobservable in daily life. This approach will enhance the ethicality of the course; heighten student interest and motivation, ultimately leading to improved learning outcomes. Nonetheless, factors such as large class numbers, inadequate resources and

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time, and instructors' deficiency in essential professional tools compel educators to implement expository teaching methods in science education. In the classroom setting, it is considered that instructional materials that facilitate the involvement of numerous students are cost-effective, readily accessible, and user-friendly for educators and can enhance the implementation of active learning activities.

Active learning activities utilizing three-dimensional (3D) instructional materials in the classroom setting for science lessons are believed to fulfill this objective. Students will have the opportunity to engage with 3D instructional materials through direct physical interaction during active learning activities, thereby facilitating a clearer explanation of abstract scientific topics that are typically challenging to comprehend, while promoting active student involvement. Nonetheless, these 3D educational materials are either unavailable or, if accessible, prohibitively expensive. 3D printers are anticipated to significantly aid scientific educators in the creation of 3D instructional materials. Currently, 3D printers have become prevalent even in educational institutions. Moreover, online 3D printing services are available at quite competitive pricing. An educator possessing the computer file of the 3D model for the required 3D-printed instructional materials can order and print it, hence facilitating prolonged active learning activities in their sessions.

The use of 3D instructional materials produced with 3D printers in course activities in which students actively participate has attracted the attention of researchers with the widespread use of 3D printers, but the instructional results of their use have not been sufficiently observed. Experimental research demonstrating the superiority of active learning activities with 3D-printed instructional materials compared to standard teaching techniques would facilitate the broader use of this approach in science courses. This study aims to determine the effect of active learning activities utilizing 3D-printed instructional materials on students' learning efficacy and to explore their perceptions of these activities in science lessons. In line with this purpose, the following research questions were sought to be answered:

- Is there a significant difference in the academic achievement of students who participate in active learning activities supported by 3D-printed instructional materials compared to those taught through conventional instruction in 6th-grade secondary school science lessons?
- How do students perceive the contribution of active learning activities supported by 3D-printed instructional materials to their learning and engagement in science courses?

2. Literature

Several educators state that incorporating 3D printing in educational settings connects the teaching of science, technology, engineering, and mathematics to real-world applications, fosters creativity, and promotes collaboration (Murray, 2013). However, research focusing on the instructional application of this emerging technology primarily remains at the theoretical and introductory stages. It was concluded that 12 studies on 3D printers in Turkey from 2003 to 2017 concentrated on instrumentation, science and technology, materials science/engineering, engineering, and physics, with no research addressing the educational impacts of 3D printers (Yıldırım et al., 2018). Numerous studies indicate that further applied and experimental research is necessary to enhance the effectiveness of 3D printers in educational settings (Demir et al., 2016; Karaduman, 2018; Kökhan & Özcan, 2018; Novak & Wisdom, 2018; Saorin et al., 2017; Sitompul et al., 2024; Yıldırım et al., 2018). Research involving 3D printers suggested examining the educational outcomes of materials created with these printers in science courses (Jo et al., 2016) and suggested the diversification of resources in Turkey, as the majority of 3D instructional material models are sourced from foreign websites (Karaduman, 2018). Many studies indicate the necessity of empirically exploring the impact of instructional materials created with 3D printers in educational settings. Consequently, the outcomes of this novel technology and its implementation, which is theoretically posited to yield beneficial effects on education, can be verified using empirical evidence.

2.1. 3D Printing Process

With the decrease in the purchasing and printing costs of 3D printers, their use in daily life is becoming increasingly widespread. Any three-dimensional material that is desired to be obtained with three-

dimensional printers can be easily prepared in the desired dimensions by drawing it. Once the drawing of the material is made once, the desired number of materials can be reproduced at any time with the same drawing. It also facilitates and cheapens the production of many industrial and educational materials. In particular, open source technologies, which are highly developed today, provide important opportunities to overcome the cost factor, which is seen as a limitation in the use of 3D printers (Demir et al., 2016).

At the beginning of the 3D printing process, the design of the 3D object to be produced must first be prepared electronically. For this purpose, a 3D drawing of the object can be made using 3D design tools (SolidWorks, AutoCAD, SketchUp, Tinkercad, ...) or a similar object to be produced can be scanned with 3D scanners and transferred to electronic media. If a new design is not desired, a previously made design can be used. There are 3D material databases (www.artec3d.com, all3dp.com, free3d.com, nasa3d.arc.nasa.gov, etc.) containing these materials on the internet. The resulting design will be in .STL file format and the design can be reproduced at any time using this file. Then the object to be produced is divided into layers using slicing software (Cura, Craftware, Simplify3D, slic3r, Netfabb Basic...). Finally, the object is produced with the selected raw material with a 3D printer. Many different types of raw materials (PLA, ABS, PVA, PET, liquid resin, wood, silver, etc.) can be used for the desired properties of the 3D object to be produced. Raw materials are sold in filaments and loaded into the printer.

2.2. *The Use of 3D Printers in Education*

A literature analysis on the application of 3D printers in education revealed that 3D printing is utilized in six primary ways in education environments (Ford & Minshall, 2019):

1. In instructing students in 3D printing,
2. In instructing educators in 3D printing,
3. As an assistive technology in educational contexts,
4. In the creation of resources to facilitate learning,
5. In the advancement of assistive technologies,
6. Facilitating outreach initiatives.

3D printing facilitates the effortless production of prototypes or functional models for the examination or testing of various ideas, concepts, characteristics, or forms (Fernandes & Simoes, 2016). Consequently, it is feasible to run experiments on a given topic by changing several variables. One of the primary advantages of employing 3D printing technology in science education is that it enables students to investigate the interconnections among engineering applications, technological advancements, and scientific principles, thereby establishing new benchmarks for science instruction (Novak & Wisdom, 2018). Research indicates that 3D printing in science classes enhances students' motivation, interest, mathematical abilities, and practical skills (Kwon, 2017), along with their linguistic and spatial competencies (Barroso et al., 2017); markedly reduces their anxiety regarding science instruction; and elevates their effectiveness and enthusiasm for teaching science (Novak & Wisdom, 2018). Another application of 3D printing technology in scientific education is enabling students to design and subsequently fabricate 3D materials independently. The application of 3D printing technology in science education enhances creativity and efficacy in teaching, particularly when employed in collaborative and project-based activities that equip students with engineering design and problem-solving competencies (Kefalis et al., 2024; Wisdom & Novak, 2019). Educators regarded the incorporation of 3D printing as advantageous for K12 science students; however, they faced several obstacles, including logistical and technical difficulties, inadequate time and resources, insufficient proficiency in operating 3D printers and integrating 3D printing with curricula, as well as challenges in instructing students with diverse needs (Cheng et al., 2024; Khefrianti et al., 2024).

Research indicates that utilizing 3D instructional materials created with 3D printers enhances students' recall and comprehension, boosts concentration and attention during lessons (Jo et al., 2016), elevates motivation levels (Fernandes & Simoes, 2016), and improves academic achievement percentages (Lim et al., 2016; Saorin et al., 2017; Smith et al., 2018). The studies conducted revealed that bone models created with 3D printers enhanced students' comprehension of skeletal structure (Li et al., 2017).

Additionally, another study involving heart models demonstrated significant advancements in students' knowledge acquisition, reporting, and conceptualization skills (Costello et al., 2014). These findings indicate that 3D-printed models serve as a novel, precise, and effective alternative for teaching when real objects are unavailable (McMenamin et al., 2014). The primary advantage of utilizing 3D-printed models as educational tools is the ability to physically manipulate objects, allowing for the observation of features that may not be apparent through digital models alone (Horowitz & Schultz, 2014). The capability of physical 3D-printed instructional materials produced with 3D printers is regarded as a significant advantage compared to 3D digital models. The production of 3D instructional materials using 3D printers provides a cost advantage. 3D-printed models are 10-20 times less expensive than their plastic counterparts (Adams et al., 2015). This also enables students to analyze replicas of objects without harming the originals (AbouHashem et al., 2015).

3D-printed materials are utilized in various instructional contexts, including the creation of model race cars in design courses (Chien, 2017), architectural models (Leach, 2017), and anatomical models such as the heart, kidney, and digestive system (Bialy, 2016). The application of 3D design and printing in special education is structured around three primary objectives: Enhancing 3D design and printing skills promotes engagement in STEM activities, facilitates access to course content for students with disabilities, and enables the production of specialized adaptive materials for these students (Buehler et al., 2014; Lau & Sun, 2022). In Turkey, research on 3D-printed teaching materials has been conducted in mathematics (Yıldırım & Keşan, 2022; Yılmaz & Algil, 2018), social sciences (Aktın et al., 2023), STEM (Güleryüz et al., 2019), and science education (Karagöz & Çakır, 2020). The prevalence of 3D instructional materials in science is attributed to their ability to provide realistic replicas of objects that are challenging to view in reality inside the classroom setting. To properly incorporate these 3D instructional materials into classes, they must be utilized through suitable teaching methods and strategies. Students should be encouraged to engage with 3D instructional materials extensively during the lecture. Active and collaborative learning activities are the most successful pedagogical approaches for the efficient utilization of 3D instructional materials in instruction.

2.3. Active Learning Activities

Active learning is a pedagogical approach that empowers learners to make decisions regarding many facets of the educational process, necessitating the engagement of their cognitive faculties throughout the learning experience (Açıkgöz, 2003). Active classroom experiences are recognized to positively influence learning by enhancing engagement, altering attitudes towards education, boosting self-efficacy, and promoting interaction (Baeppler & Walker, 2014; Chiu & Cheng, 2017; Meyers & Jones, 1993; Park & Choi, 2014; Salter et al. 2013). Abstract conceptualizing results in retention of merely 20% of information, whereas concrete experiences yield a retention rate of 90% (Stice, 1987). This is particularly applicable to abstract physical concepts that are challenging to comprehend, and the utilization of physical models in active learning activities enhances learning (Lipson, 2007).

In science courses, 3D-printed instructional materials can facilitate active learning activities and the implementation of collaborative learning methodologies among students. Consequently, it is possible to integrate the capabilities of 3D printing technologies to enhance the efficacy of science education with the beneficial impacts of active learning methodologies on instruction (Schelly et al., 2015). Research on the application of 3D printing technology for educational purposes (Eisenberg, 2007; Hatch, 2013; Schneider, 2006) indicates that students exhibit significantly greater concentration during courses when they engage actively rather than only reading or listening. It is recommended to use the workflow given in Fig 1. below in the use of instructional materials printed with 3D printers in active learning activities (Addy et al., 2018).



Fig. 1. Basic workflow for active learning with 3D-printed instructional materials in the classroom. (Addy et al., 2018).

The utilization of 3D printing as a collaborative learning instrument assists educators by facilitating the incorporation of various active learning activities into the educational process, particularly in courses rich in theoretical content (Fernandes & Simoes, 2016). The application of 3D printing technologies in conjunction with active learning activities warrants investigation; various activities should be devised, and outcomes should be assessed due to their potential to enhance teaching efficacy.

3. Methodology

3.1. Research Design

Mixed research method was used for data collection in the project. Mixed method can be defined as the use of qualitative and quantitative methods, approaches and concepts together in a study or in successive studies (Creswell, 2003). The study was structured as a “sequential mixed research design” since qualitative and quantitative data were collected one after the other (Mertkan, 2015). The objective of the quantitative dimension of the study was to statistically demonstrate the impact of the intervention on the participants. While broad conclusions can be drawn from the quantitative data collected, it is essential to incorporate qualitative data to gain a deeper understanding of the underlying reasons and details associated with the quantitative results. The sequence of research activities is determined based on the research question and the objectives of the study (Özden & Durdu, 2016). In the current study, quantitative data were collected initially, with qualitative data collected subsequently, as the qualitative data will be utilized to interpret the quantitative findings.

3.2. Data Collecting Tools

“Supervisory and Regulatory Systems and Sensory Organs (SRSSO) Achievement Test” (Kargin & Gül, 2021) was employed to gather quantitative data for the study. The SRSSO test was developed as an achievement test for the topics of regulatory and supervisory systems and sensory organs in the sixth grade science course ‘Systems and Health in Our Body’ unit. In the development study of the test consisting of 40 multiple-choice questions, the KR-20 reliability coefficient was calculated as 0.86. In the study where the achievement test was developed, the average discriminating value was calculated as 0.47. Based on this value, it was concluded that the test has high discriminating power and can distinguish between knowledgeable and unknowledgeable students at a very good level. Furthermore, although the average difficulty value calculated in the study is 0.61, which is close to the middle range, it means that the achievement test is easy in terms of student level. Two science education specialists checked the items for curriculum fit before administering the test. This was done to ensure test validity. However, due to the update in the curriculum, topics related to adolescence and individuals with disabilities were later removed from this unit. For this reason, the questions related to these subjects were canceled and 28 questions of SRSSO Achievement Test were evaluated. To allow sufficient time between the pretest and posttest, the pretest was administered in the first semester. Upon the completion of the Systems and Health in Our Body unit topics in both groups, a posttest was conducted.

Qualitative data were obtained via semi-structured interviews with 11 students from the experimental group. Semi-structured interviews were conducted to gather comprehensive data regarding the utilization of 3D-printed instructional materials and to explain the quantitative findings of the research. The interview form, comprising five questions, was developed in accordance with the study questions and related literature. Prior to the interviews, the form was prepared including the insights of two subject matter experts and one linguist. The interview questions are as follows:

1. Did the use of 3D instructional materials in science classes help you understand the topics better? If so, could you explain how it contributed?

2. Can you describe the problems you encounter when using 3D instructional materials in your lessons?
3. Do you think the chosen subjects are appropriate for use with 3D instructional materials? What additional subjects might we cover with 3D instructional materials?
4. Do you believe that employing 3D instructional materials in science classes encourages students to participate more? In this sense, would you contrast traditional science lectures with those that make use of 3D materials?
5. Would you prefer traditional science classes or classes that use 3D materials? Why do you prefer one over the other?

3.3. Sampling or Study Group

The participants of the study were 58 6th grade students studying in a secondary school in the city center of Nevşehir in Turkey. The primary objective of the research was not to generalize the findings, but to gain a deeper understanding of the potential correlations between variables. Consequently, the convenience sampling methodology was selected as the preferred method. Consequently, 30 out of 58 students were assigned to the experimental group (EG), whilst 28 were allocated to the control group (CG). Table 1 shows the distribution of the groups according to gender.

Table 1.

Study groups

Groups	Male	Female	Total
Experimental	17	13	30
Control	15	13	28

While it is commonly believed that control and experimental groups should be of similar size in experimental research, this is not always feasible due to factors such as participant availability and the demographics of the study population. Since the study was conducted with two different classes, the group numbers were formed from the students of the classes who fully participated in the activities and assessments.

3.4. Data Analysis

The quantitative data of the study was analyzed using SPSS 22 software. The statistical analysis of the data acquired from the “Supervisory and Regulatory Systems and Sensory Organs (SRSSO) Achievement Test” commenced with an assessment of the normal distribution of the data. Table 2 presents the values of skewness and kurtosis, together with the results of the Shapiro-Wilk test.

Table 2.

Data on normal distribution of SRSSO achievement test scores

Groups	Tests	Skewness	Kurtosis	Shapiro-Wilk*
Experimental	Pretest	.198	-1.116	.107
	Posttest	-.518	-.597	.110
Control	Pretest	-.332	-.374	.330
	Posttest	-.626	-.277	.138

* $p < .05$

One method to comprehend the normal distribution of data is to examine the skewness and kurtosis values. If these values fall within the range of ± 2 , it indicates that the data have a normal distribution (George & Mallery, 2010). Furthermore, the normality assumption of the CG and EG data was evaluated using the Shapiro-Wilk test, revealing that the distribution of pretest and posttest scores at this significance level did not significantly deviate from normality ($p < .05$). Consequently, upon examination of the data in Table 2, it was determined that the data exhibited a normal distribution, allowing the use of parametric methods for the analysis of the scale-derived data. The assumption of homogeneity of

variances was evaluated for the pretest ($F(1,56)=.387$, $p=.536$) and posttest ($F(1,56)=.092$, $p=.763$), with both tests meeting the criteria as determined by Levene's F test.

ANCOVA was employed to ascertain the significance of the score differences between the SRSSO achievement test for the EG and CG students, while controlling for pretest scores. In all analyses performed in the study, a p-value of less than .05 was accepted as statistically significant.

For the purpose of analyzing the semi-structured interviews, the content analysis method was utilized. According to Yıldırım and Şimşek (2006), content analysis is a process that involves the collection of specific data pertaining to specific concepts and themes, and then presenting this information in a manner that is easily comprehensible to the reader. Following the completion of the content analysis, which was carried out independently by the researcher and an expert, the reliability of the analysis was evaluated by comparing the results of the two content analyses. It was determined that a value of 88% was achieved by employing the method developed by Miles and Huberman (1994), which states that reliability is equal to agreement divided by agreement plus disagreement.

3.5. Research Procedures

During the study, the EG engaged in active learning activities, whereas the CG followed the conventional instructional method, consisting of lectures and problem-solving sessions. Five active learning activities were carried out with 3D-printed instructional materials in the unit of systems in our body and health. The reason for limiting the number of applications in the unit to five is that active learning activities require much more class time than the lecture strategy through presentation. In case the number of activities is increased more, teachers will have problems in completing the content of the sixth grade curriculum within the year. There are a total of three hours allocated for activities in the classroom. The class will be divided into five groups for active learning activities. Each group performed the activities with the given 3D instructional material. After the activity was completed, the instructional material was transferred to the other group so that all groups had the opportunity to perform the activities. The printed 3D materials were used in active and collaborative learning activities in group work and alternately among students. A Human spine model, brain model, eye model, middle ear bones model (3 bones) and tongue model were used in the activities.

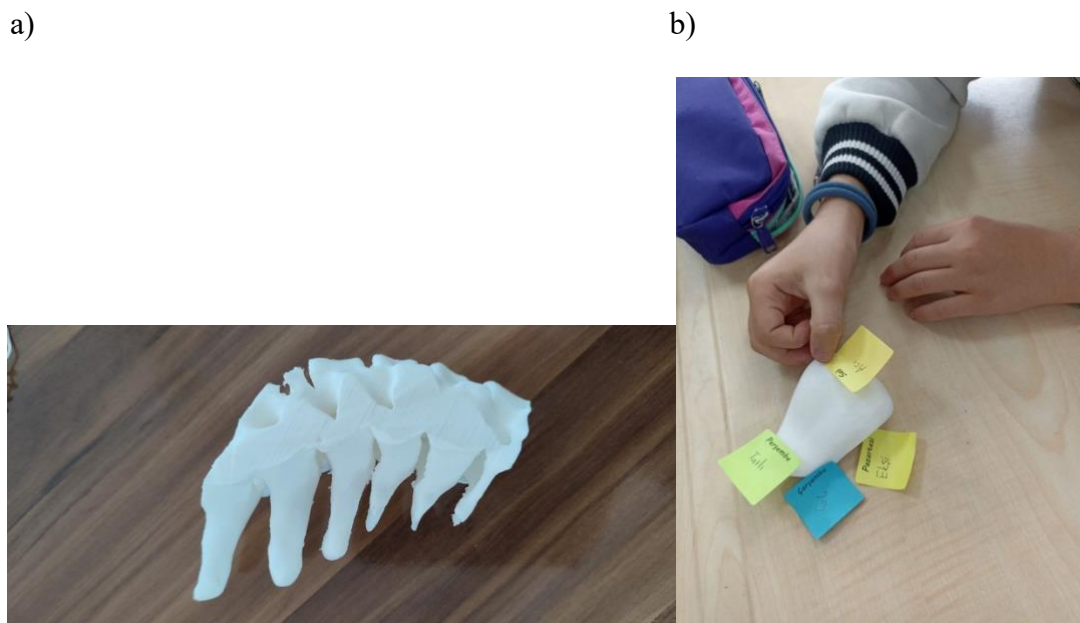


Fig. 2. a) 3D-printed human spine segment model b) Active learning study on human tongue model

Fig 2. shows examples of active learning activities in science lessons with 3D-printed models. In the human spine segment model activity, students were required to use colored Play-Doh to insert various tissues connected to the human spine in the appropriate locations on the model. In the human tongue 3D-

printed model assignment, students were required to use post-it notes to accurately name the sections of the human tongue that have diverse tasks.

4. Findings and Discussions

4.1. Findings from First Research Question.

The data acquired from the SRSSO achievement test were examined to address the first research question. An independent samples t-test was conducted to see if a significant difference existed between the pretest scores of the control and experimental groups. The analysis findings are displayed in Table 3.

Table 3.

Descriptive statistics and t-test results for SRSSO pretest scores of EG and CG groups

Group	N	Mean	Median	Mod	Min	Max	SD	Df	t	Sig.	d
Experimental	30	12.00	12.00	8.00	7.00	18.00	3.22	56	-3.84	.000	1.14
Control	28	8.89	8.50	8.00	2.00	14.00	2.91				

Table 3 demonstrates that the independent-samples t-test findings revealed a significant difference between the pretest SRSSO scores of the groups, $t(56) = -3.84$, $p < .05$, $d = 1.14$. The effect size for this analysis ($d = 1.14$) adheres to Cohen's rule (1988) for a large effect ($d \geq .80$). Since there was a significant difference between the pretest scores of the control and experimental groups, ANCOVA was preferred in the analysis of the difference between the posttest scores. The main advantage of ANCOVA is that it reduces the bias in the experiment when there are differences between groups at the beginning (Büyüköztürk, 1998). For this, firstly, an assessment was conducted to determine if the ANCOVA assumptions outlined by Frigon and Laurencelle (1993) were satisfied.

The normal distribution of pretest and posttest scores for the EG and CG, which constitutes the initial assumption of ANCOVA, was assessed, and the data confirming that this assumption was satisfied are displayed in Table 2. The regression line slopes of the groups were also examined. The "group x pretest" joint effect test indicated that the difference between the slopes of the lines was not statistically significant ($F(1, 56) = .34$, $p = .564$), suggesting that the assumption of homogeneity of regression slopes is upheld. The linear relationship between pretest and posttest scores, another assumption, was tested, resulting in $r = .48$ for the EG and $r = .53$ for the CG. Given that $r \geq 0.3$ for both groups, a linear relationship between the pretest and posttest scores was determined. Upon confirming that all assumptions were satisfied, ANCOVA was implemented.

Table 4.

Covariance analysis results of the CG and EG posttest scores corrected for SRSSO pretest scores

Source	SS	df	MS	F	p	η^2
Pretest (Covariate)	157.42	1	157.424	18.45	.000	.251
Group	124.51	1	124.509	14.59	.000	.210
Error	469.35	55	8.534			
Total (Corrected)	24791.00	58				

Table 4 indicates that ANCOVA revealed a significant difference between the posttest scores of the EG and CG after adjusting for the SRSSO pretest scores ($F(1, 55) = 14.59$, $p = .000$). This finding shows that the applied experimental procedure (utilizing 3D-printed instructional materials in active learning activities during secondary school science lessons) caused a significant difference in the students' academic achievement in the "Systems in Our Body and Health / Living Things and Life" unit subjects.

Table 5.

Groups' SRSSO posttest scores corrected according to pretest scores

Groups	N	Corrected Posttest	
		Mean	Std. Error
Experimental	30	21.85	.57
Control	28	18.55	.59

Table 5 indicates that the posttest SRSSO score, adjusted for the pretest, was $\bar{X}=21.85$ for the EG and $\bar{X}=18.55$ for the CG. It is seen that secondary school 6th grade students who participated in active learning activities using instructional materials produced with 3D writings in the subjects of “Systems in Our Body and Health / Living Things and Life” unit in science lessons had higher academic achievement than the students who did not participate. Upon examining the effect size ($\eta^2=.210$) value in table 4, it was determined that the effect size is small.

The study indicates that the academic performance of the CG, which employed solely teacher-centered and traditional instructional approaches such as lecturing and problem-solving, likewise improved as expected. However, the academic achievement in the EG was significantly higher than in the CG. These quantitative results of the study corroborate the findings of a great deal of the previous work on using 3D instructional materials in the classroom. As mentioned in the literature review the utilization of 3D-printed instructional materials enhances students' academic performance scores (Avinal & Aydın, 2022; Çoklar & Çekirge, 2020; Li et al., 2017; Lim et al., 2016; Saorin et al., 2017; Smith et al., 2018). The students in the EG engaged significantly more actively in class compared to the CG, when pupils exhibited passivity, and active learning activities were implemented in the courses. Another reason for this outcome favoring the EG should be the students' active engagement in the lessons. Previous studies evaluating the effects of active participation have observed consistent results regarding its positive impact on students' academic achievement (Baeppler & Walker, 2014; Chiu & Cheng, 2017; Park & Choi, 2014; Salter et al. 2013). Activities were designed to enable students to engage individually and collaboratively with the 3D-printed materials, rather than merely displaying them. This approach ensured the integration of the documented positive effects of active learning activities with the advantageous characteristics of 3D-printed instructional materials, including ease of production, low cost, accessibility, detailed material examination, and hands-on interaction. The study's quantitative results indicate that the use of 3D-printed materials in conjunction with active learning activities enhances learning effectiveness.

4.2. Findings from Second Research Question

To gain a deeper understanding of the quantitative findings of the study and to interpret these results more thoroughly, semi-structured interviews were conducted with 11 students who engaged in activities utilizing instructional materials produced by 3D printers. This section also addressed the second research question. The qualitative findings of the study were structured around two planned themes corresponding to the research objectives, along with eight emergent sub-themes derived from the analysis.

1. 3D-printed instructional materials
 - a. Ways to help enhance learning
 - b. Problems in using 3D-printed instructional materials
 - c. Choosing the right subjects to employ 3D-printed instructional materials in science lessons
2. Science lessons
 - a. Active participation in science lessons
 - b. Students' preference for science lessons

All (100%) of the students who participated in the interviews stated that the use of 3D-printed materials in science lessons helped them to understand the subjects better. In addition, these students explained how they helped them. The percentage value given in the tables of qualitative data (Tables 6, 7, 8 and 9) is the ratio of the total number of students to the number of opinions on the subject. The findings on how this happened are presented in Table 6 below:

Table 6.

Ways to help enhance learning

Ways to help enhance learning (N=11)	<i>f</i>	%
Enhanced visualization	9	81.8
Touching	5	45.5
Active participation	2	18.2

Table 6 indicates that nine students (81.8 %) reported that 3D-printed instructional materials in science lessons enhanced their comprehension of the subject matter by allowing them to view the content from several perspectives. In addition, five students (45.5 %) explained that they were able to understand the subject better because they could touch the objects that make up the subject content thanks to the 3D-printed instructional materials. Finally, two students (18.2 %) argued that active participation in the activities helped them understand the topics better. Interviewee #1 stated that “So it is better to see it in three dimensions than in a book. So it helps us to understand better by touching.” It is understood that 3D-printed instructional materials allow students to view and touch objects in greater detail than 2D representations in books, allowing them to better learn the subject. Interviewee #5 explained, “For example, when I was looking at the brain, I was able to divide it into parts like this. Compared to classical lessons, that’s why it happened. Yes, I mean, I can perceive it better after holding it in my hand in 3D and feeling it like this.” The student explained that he had the opportunity to examine the 3D-printed instructional materials in detail by touching them and thus better understood the parts of the human brain.

These results reflect those of Horowitz and Schultz (2014) who also found that the main benefit of using 3D-printed models in education is the capacity for physical manipulation, which facilitates the observation of features that may not be visible in digital models alone. Moreover, 3D-printed solid models contribute to the enhancement of various spatial abilities, particularly mental rotation and spatial visualization, as well as improved learning outcomes (Huang & Lin, 2017). 3D-printed models enable the materials that are important for understanding the subject to be observed from different perspectives, and it is also possible to better understand the relationship between other objects and concepts related to the material by combining them with the 3D-printed material. Students utilizing the human spine model applied play dough textures to the appropriate locations on the spine. Consequently, they gained a deeper understanding of the relationship between bones and tissues in the spine.

The second sub-theme identified as a result of the analysis of the semi-structured interviews is the problems that arise in the use of 3D-printed materials in science courses. Data on this sub-theme are presented in Table 7.

Table 7.

Problems in using 3D-printed instructional materials

Problems in using 3D-printed instructional materials (N=11)	<i>f</i>	%
Sharing materials		
-No problem	8	72.7
-Waiting too long for material	3	27.3
Difficulty in understanding the materials	7	45.5
Materials are too fragile	1	9.1

As seen in Table 7, students expressed their opinions about the practice of using 3D-printed materials jointly by students in lessons. Eight (72.7 %) students reported no issues with this practice, whereas three (27.3 %) students indicated that they experienced excessive wait times for access to the material. In addition, seven (45.5 %) students stated that they had difficulties in understanding the material for various reasons. The students said that the material was hard to understand because it was complicated, 3D printing mistakes happened, the material had no color, and there was a lot of misunderstanding. The comment made by Interviewee #3 on this issue is as follows: “Sometimes 3D printers make mistakes. For example, when it produces a shape in the ear model incorrectly, we can sometimes misunderstand it.” The

student indicated that comprehending the model was occasionally challenging due to flaws produced by 3D printers throughout the printing process. Interviewee #8 explained, “I found it difficult to comprehend due to some differences in a few areas. The variation depends on the image. It can be slightly confusing due to its differences.” The student expressed confusion due to the discrepancy between the 3D material and the drawing they had encountered in their books. At the conclusion of the process, he stated that he comprehended the material thoroughly. Finally, a student (interviewee #5) stated that he was worried about using the material because it was too fragile: “Due to its three-dimensional nature, it tends to be somewhat lighter and exhibits greater sensitivity.”

These results are in line with what other studies have said about the practical and pedagogical problems with using 3D-printed materials in the classroom. Cheng et al. (2024) and Khefrianti et al. (2024) say that teachers often have logistical problems, like not having enough time in the classroom, not knowing how to use technology, and not having enough resources. These problems may indirectly lead to longer wait times for shared materials and less effective teaching. So, the students' complaints about having to wait for access can be seen as a sign of these larger logistical problems that are common in schools. Also, the fact that students had trouble understanding the 3D-printed models because they were missing color, had printing mistakes, or were too abstract is in line with what Jo et al. (2016) found: that technical flaws in 3D prints, especially in anatomical or abstract models, can lead to misunderstandings and make learning harder.

The third sub-theme addressed the chosen subject for the application of 3D-printed materials in the sixth grade of secondary education, along with alternative potential subjects. Table 8 below presents data collected from semi-structured interviews with students regarding this issue.

Table 8.

Choosing the right subject for 3D-printed instructional materials

Choosing the right subject for 3D-printed instructional materials ($N=11$)	<i>f</i>	%
The chosen subject is suitable	11	100
Systems in our body	5	45.5
Solar system	5	45.5

The activities carried out with 3D-printed instructional materials were carried out in the subjects of the “Systems in Our Body and Health” unit, which is the 6th unit in the 6th grade secondary school curriculum. All students (100 %) who participated in the interviews considered the content of the selected unit appropriate for 3D-printed materials. In addition, five students (45.5 %) stated that the subjects of the “solar system” unit, which is the subject of the 6th grade curriculum, are also suitable for the use of 3D-printed materials. Likewise, five students (45.5 %) stated that they found the 2nd unit of the curriculum, the “Systems in our body” unit, appropriate and specifically mentioned the subjects such as movement and support system, circulatory system, respiratory system and digestive system in the unit. Interviewee #9 explained, “For example, in the nervous system, it can be like that when introducing such organs. Perhaps something similar might be done to display such joints in the movement system, specifically with bones.” Interviewee#2 made a very conscious comment about the science curriculum: “I think not only the sixth unit, but also the systems in our bodies in the second unit. It could also be on the planets. In other words, it can be to recognize the size, shape or shapes of the planets such as gas, solid, etc., their properties.” In his comment, he stated that both units recommended by other students were suitable for the use of 3D-printed materials.

This viewpoint aligns with the literature highlighting the significance of 3D-printed models in illustrating abstract and intricate scientific concepts. According to Horowitz and Schultz (2014) and Huang and Lin (2017), physical 3D models improve spatial visualization and enable students to analyze structures from various perspectives—advantages especially vital in anatomy-related subjects such as bodily systems. The current study indicates that students' appreciation of 3D representations for organs like the brain, eye, and middle ear corresponds directly with this educational benefit. In conclusion, these data indicate that students may identify curriculum areas where 3D-printed elements have the most significant instructional

influence, especially in units related to anatomical or spatial complexity. This reinforces existing recommendations in the literature to broaden the implementation of 3D printing in scientific courses and to utilize student feedback in identifying areas of application.

The study aims to incorporate 3D-printed instructional materials into active learning activities. In other terms, students are expected to be active practitioners of the course activities rather than passive listeners. All students (100 %) reported their active participation in the lessons through the use of 3D-printed materials. Interviewee #3 stated that, “Indeed, engaging with my friends in real-life contexts made the experience more enjoyable and significantly enhanced our understanding of the subjects, as opposed to merely reading about them in textbooks.” Moreover interviewee #11 explained, “I was more engaged in the class, participated more actively, did not focus on questions, and consequently, learned more.” The comments indicate that student participation in the lessons was effectively facilitated as intended, and students expressed satisfaction with this arrangement.

Finally, the data regarding students' preferences for classical science courses versus those utilizing 3D-printed materials are presented. All students (100 %) who participated in the interviews expressed a preference for science lessons that incorporate 3D-printed materials. Table 9 presents data on the reasons students prefer courses that utilize 3D-printed materials.

Table 9.

Reasons for students' preference for science lessons with 3D-printed materials

Reasons for students' preference for science lessons with 3D-printed materials (N=11)	<i>f</i>	%
Better learning	9	81.8
More funny	6	54.6
More active participation	1	9.1
More interesting	1	9.1

When the data in Table 9 are analyzed, it is seen that nine students (81.8 %) preferred science lessons in which 3D-printed instructional materials were used because they learned the subjects better. In addition, six students (54.6 %) cited the fact that the lessons were more fun as the reason for their preference, while one student (9.1 %) each cited the fact that they participated more actively in the lessons and that the lessons were more interesting. Interviewee #6 stated that “Well, it's more fun and as I said, we don't get bored in class, at least. It has such an advantage.” According to interviewee #9, “I prefer 3D because it's more fun. I mean you can touch, you can understand. I understand the subjects better.”

The findings are well-supported by existing literature that highlights the motivational and engagement-enhancing features of 3D-printed instructional materials. Fernandes and Simoes (2016) and Novak and Wisdom (2018) reported that the integration of 3D printing in science instruction improves students' interest, enjoyment, and active participation. This study indicates that students' references to heightened “fun” and “interest” support previous findings and imply that the novelty and interactivity of the materials play a substantial role in affective engagement. The primary rationale provided by students for favoring 3D-enriched instruction was enhanced learning outcomes. The findings of this study indicate that students in the EG, utilizing 3D materials, achieved higher posttest scores compared to their peers. Additionally, it corroborates prior empirical findings indicating that 3D-printed models improve conceptual understanding and information retention (Lim et al., 2016; Li et al., 2017). The studies indicate that physical, interactive models enhance learners' capacity to visualize and internalize abstract scientific concepts, particularly in anatomical and spatial contexts.

These findings underscore the dual instructional benefits of 3D-printed materials: they enhance academic outcomes while also enriching the learning experience by fostering increased motivation, enjoyment, and agency. These attributes render 3D printing a valuable instrument for enhancing cognitive development and fostering sustained interest in science education.

5. Conclusion and Suggestions

This study investigated the effects of incorporating 3D-printed instructional materials into active learning activities in sixth-grade secondary school science classrooms. The research employed a sequential mixed-methods approach to assess both academic outcomes and student perceptions related to this instructional innovation. Quantitative results from the SRSSO Achievement Test indicated that students engaged in active learning activities with 3D-printed materials exhibited markedly superior academic performance relative to their counterparts receiving traditional teaching. These findings offer empirical evidence for the instructional efficacy of 3D-printed items, especially in enhancing conceptual comprehension of abstract topics like “Systems in Our Body and Health.”

In addition to these findings, qualitative data obtained from semi-structured interviews provided extra insight into students' learning experiences. Participants consistently indicated that 3D-printed instructional materials improved their understanding by facilitating multimodal interaction, particularly via visualization and physical exploration. Students identified various limitations, such as occasional challenges in interpreting the models due to printing problems, absence of color, and material fragility. Notwithstanding these limitations, students demonstrated a pronounced preference for classes that included 3D-printed models, attributing enhanced learning, heightened enjoyment, and augmented engagement as primary advantages.

The findings collectively highlight the educational potential of 3D printing technology in science education, while also indicating areas that necessitate additional improvement. In light of these findings, the following recommendations are put forth:

- Educators and curriculum designers should consider incorporating 3D-printed models into units involving abstract or spatially complex content, such as human anatomy or planetary systems, where physical representations can enhance comprehension.
- In the future, making models that last longer and are more detailed should be the top priority. Using better filament or post-processing methods, like color labeling or smoothing, may help make things easier to understand and use.
- Professional development programs should be broadened to help teachers choose models, edit fundamental 3D designs, and use printed materials in active learning in a way that works.
- In the future, researchers should look into how 3D-printed materials affect students' motivation, retention, and ability to transfer knowledge across different subjects over time. Comparative studies across multiple grades, subjects, and groups of students (including those with special needs) would add to the body of data and help us use it in more ways.

In conclusion, this study shows that 3D-printed instructional materials might be a great way to improve science education when they are used in student-centered and active learning contexts. Educators can use this new technology to help students learn more deeply and stay interested in school by solving the problems that have been found and carefully scaling up its use.

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