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Comparison of the effects of PBL in 3D virtual environment and F2F on learning and spatial skills

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Abstract

This study aimed to juxtapose the impacts of the Problem-Based Learning (PBL) methodology implemented within a three-dimensional (3D) virtual environment against PBL in a conventional face-to-face setting, along with a control group, on students' learning performance, conceptual comprehension, and spatial aptitude. The investigation concentrated on the structure of matter within a seventh-grade science curriculum, encompassing a cohort of 79 students enrolled in the course. The study was conducted under a mixed methods experimental design and comprised three distinct groups: two experimental groups (E1; E2) and one control group (C). The instructional intervention in the E1 group involved utilizing a 3D virtual environment grounded in the problem-based learning method, whereas the E2 group underwent face-to-face instruction employing worksheets derived from problem-based learning. In contrast, the control group received traditional direct instruction from the science teacher through lectures, demonstrations, and question-and-answer sessions, all focusing on the same topic. Pretests and posttests were administered to the participants before and after the experimental interventions, assessing conceptual understanding, spatial visualization, and mental rotation. Additionally, learning tasks completed by the E1 and E2 groups were evaluated using rubrics to assess learning performance. Subsequent to the post-test, individual semi-structured interviews were conducted with randomly selected students from the E1 group. The results indicated that instruction within the problem-based 3D virtual environment significantly enhanced students' learning performance, conceptual understanding, spatial visualization, and mental rotation skills compared to the other instructional conditions.

Keywords PBL · 3D virtual environment · Spatial visualization · Mental rotating · The structure of matter · K12

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1 Introduction

New and emerging technologies bring new opportunities for enhancing teaching and learning. It is possible to think about more effective teaching and learning processes with them, but we need systematic implementations and evidence of their effectiveness in real-life settings. Virtual learning environments like Second Life, Active Worlds, Alice, and Metaverse offer opportunities for instructional designers and teachers to design and use new learning environments for students to explore and understand abstract and complex concepts in subjects such as the structure of matter. Learning the structure of matter, specifically atoms and molecules, can be enhanced through immersive experiences in 3D virtual environments. These environments provide immersive and interactive experiences that help students visualize and understand atomic and molecular structures more effectively.

Learning in 3D virtual environments and the metaverse offers several benefits and opportunities for enhancing education. 3D virtual reality (VR) environments provide features not available in the real world, such as the ability to position oneself in any environment and communicate using avatars. These environments are more effective than two-dimensional learning environments and can also be used in online education (Çoban & Göksu, 2022). Moreover, virtual environments can simulate real-world scenarios, making the learning experience more engaging and relevant to students. They can be particularly beneficial in Problem-Based Learning (PBL), where students apply their knowledge to solve real-life-like problems.

PBL is a learning method that encourages students to learn by solving problems and reflecting on their experiences. It engages students effectively, promotes deep, multidisciplinary learning, and fosters critical thinking, problem-solving, teamwork, and leadership. In the context of learning the structure of matter in K-12 education, PBL can be combined with 3D virtual environments to create immersive, interactive learning experiences. These virtual environments can also support the integration of STEM education, promoting spatial awareness and offering benefits to gifted and talented students (Rodger et al., 2010).

Learning the structure of matter in K-12 science education can be challenging due to the abstract concepts involved. Students often struggle with understanding the particulate nature of matter, including the concepts of atoms, molecules, and the different states of matter (Singer et al., 2003). The employment of direct instruction in science courses leads to learning only the operations (procedures) and rules (Tobin et al., 1994). Students memorize these in science courses without assigning meaning to knowledge and cannot associate the concepts instructed in the class with daily life (Ünal & Ergin, 2006). In science courses taught with direct instruction, the students are given known problems that could be solved with a single method instead of real problems (Fortus et al., 2005). However, science education does not mainly aim to memorize scientific knowledge but allows the students to acquire the necessary scientific attitudes and skills to access information and solve daily-life problems using learned knowledge (Kaptan, 1998). Thus, problem-based learning (PBL) is a prominent instruction method based on the constructivist approach that could allow students to use the knowledge they learn in science courses in daily life to overcome these problems (Hung et al., 2008; Kaptan & Korkmaz, 2001; Wood, 2003).

PBL enables students to connect new and prior knowledge and suggest solutions to real-life problems (İnel, 2012; Koçakoğlu, 2010) and improves the learning capacity of students (Çelik et al., 2012) and their ability for learning to learn (Akınoğlu & Tandoğan, 2007). By employing real-life scenarios, this approach promotes research, learning, discussion, selection of the most adequate solution, and application of the learned knowledge (Yurd & Olğun, 2008) as they are like scientists (Boran & Aslaner, 2008). In problem-based learning, students actively collect data, draw conclusions, make decisions about complex real-life problems, and acquire real experiences by reaching beyond the classroom (Akçay, 2009). Thus, students could acquire reasoning, analysis, synthesis, and interpretation skills while solving real-life problems (Yurd, 2007).

Traditionally, PBL is conducted face-to-face in classrooms prominently (Hung et al., 2008; Jonassen & Hung, 2012). Hopefully, it is possible to transfer the PBL into a virtual setting (Parson & Bignel, 2017). Thus, investigation of the impact of PBL in 3D virtual environments and the additional opportunities that these environments provide when compared to face-to-face environments is necessary (Göktaş, 2017). 3D virtual learning environments could be utilized in actual classrooms to safely experience dangerous conditions, expand the visual reality that could not be achieved with two-dimensional materials, concurrently access data from various sources, implement scientific methods and develop process skills, and interact with unfamiliar environments using micro-worlds (Kennedy-Clark, 2011). Three-dimensional virtual learning environments help students explore the context of the presentation, develop ideas about the problem, test these ideas, generate hypotheses, and find solutions (Phillips & Ball, 2011, as cited in Soleimani, 2013). Thus, it allows the development of the students' problem-solving skills and in-depth learning. In-depth learning, since most concepts in the science course are theoretical and abstract, rendering these concepts difficult to learn, additional learning resources and materials, especially visualization, are required to facilitate learning (Tekbıyık & Akdeniz, 2010). To meet this need for visualization, abstract and hard-to-understand concepts could be concretized with 3D virtual environments in the science course (Kandi, 2013). Virtual learning environments allow realistic and accurate reconstruction of concepts with 3D representations. The students can also analyze problems more concretely by visualizing these concepts holistically (Chittaro & Ranon, 2007). Realistic and reliable experiences are provided in virtual learning environments by simulating complex or dangerous experiments (Barab et al., 2000; Kwon et al., 2002; Song & Lee, 2002). The effects of a PBL designed with these features provided by three-dimensional virtual learning environments and face-to-face should be compared.

According to Jamaludin et al., (2009) and Dickey (2003), virtual worlds are the most adequate environment for the comprehensive application of constructivist learning (Girvan & Savage, 2010). A meta-analysis of studies assessing the impact of VR training on student learning and skills development found that students exposed to virtual reality training are more efficient in using inputs and time and/

or avoiding performance errors than students receiving traditional training (Angel-Urdinola et al., 2021). The 3D virtual world could be an excellent environment for comparing various instructional strategies and developing an interactive multi-user classroom environment (Shudayfat et al., 2012). Studies demonstrated that constructivist 3D virtual environments promote interaction, commitment, motivation, active learning, experiential learning, and cooperation (Barab et al., 2005; De Jong et al., 2005; Dickey, 2005b; Minocha & Roberts, 2008; Omale, 2010). 3D virtual worlds provide a realistic, shared, and immersive space where students can explore, interact and implement changes with their avatars (Bell, 2008; Calongne, 2008; Dalgarno & Lee, 2010; Dickey, 2005a; Girvan & Savage, 2010; Ibáñez et al., 2011). 3D virtual worlds allow individuals to interact with objects and settings that they could not interact with in real life, and they are excellent for working on phenomena that are quite expensive in real life but critical for learning (Shudayfat et al., 2012). The most popular problem-based educational 3D virtual environments include River City, Quest Atlantis (QA) (Barab et al., 2007; Dieterle & Clarke, 2007; Ketelhut et al., 2006; Nelson, 2007), and Alien Rescue (Liu et al., 2002). Studies demonstrated that the QA environment significantly contributes to learning (Arici, 2008; Barab et al., 2007). Ketelhut et al., (2006) argued that 3D multi-user virtual environments such as River City were more effective than traditional methods in instructing complex research skills in biology. Liu et al., (2011) reported a positive correlation between students' motivation and science achievement test scores in a study conducted on Alien Rescue. Horton (2014) argued that Alien Rescue contributed to the students' scientific problem-solving skills and learning. These scenario-based 3D virtual learning environments promote scientific research, arouse curiosity among students, and improve their motivation to learn (Kennedy-Clark, 2011).

Previous studies reported several contributions of problem-based instruction and the 3D virtual environment to science learning (Barab et al., 2007; Liu et al., 2011; Merchant et al., 2012; Reynolds & Hancock, 2010; Toprac, 2008). However, none of these studies tackled conceptual understanding, spatial skills and learning performances with a holistic approach, especially in problem-based 3D virtual learning environments instructing on the structure of matter. Imagining a difficult topic such as the structure of matter could be quite challenging in face-to-face instruction, while a virtual environment could be significantly advantageous in learning. It could also be suggested that working in a three-dimensional environment could further improve spatial skills compared to face-to-face learning due to higher interaction with models. However, the impact of these methods on student skills is also an important question. Thus, the present study aimed to compare the effects of the PBL method implemented in a 3D virtual environment on students' learning performance, conceptual understanding, and spatial skills with PBL in a face-to-face environment and a control group. Furthermore, the study also aimed to determine the students' views on the problem-based learning method implemented in 3D virtual environments.

Compared with the previous ones from the literature, this study distinguishes by exploring the effects of 3D PBL through 8 different learning tasks with students. The study involved the implementation of 3D PBL under the guidance of a science teacher and researcher guidance in a computer laboratory. Furthermore, it established three experimental conditions to determine the method's, environment's, and method-environment's joint effects, addressing learning in terms of both learning performance tasks and conceptual understanding and additionally examining the impact of the 3D PBL environment on spatial skills. The number of interventions may help reduce the novelty effect and a multi-comparison of the effectiveness by experiencing the method and the environment.

This research aims to compare and investigate the effectiveness of PBL in a 3D virtual environment for learning the structure of matter. In the study, there were three experimental conditions. Two experimental and one control groups were formed to determine the sole impact of PBL and the impact of 3D environment + PBL. In the first experimental group (E1), problem-based learning was conducted in a 3D virtual environment. In the second experimental (E2) group, problem-based learning was conducted with face-to-face instruction using worksheets in the classroom. In the control (C) group, direct instruction included lectures, demonstrations, and question-and-answer sessions were used. The following research questions were investigated within this design.

1. Is there a significant difference between the PBL learning performances from the 8 learning tasks of the students from E1 and E2 groups?
2. Are there significant differences in the standardized post-test scores of the variables below between the students from E1, E2, and C groups when we control for their pretests?

    2.1. Conceptual understanding
    2.2. Mental rotation, and
    2.3. Spatial visualization.

3. What are the views of E1 group students about problem-based learning in the 3D virtual environment?

2 Methodology

In the methodology, first we introduced the model and the study participants. After that, we explain how we designed a 3D virtual learning environment using the ADDIE instructional design model. Thirdly, we described data collection instruments. After the instruments, we presented data collection procedures and analysis.

2.1 Model

In this study, we developed and implemented PBLs for learning 7th class structure of matter subject in a new sophisticated 3D virtual environment and also traditional face-to-face environments and investigated their effects on students' learning (conceptual understanding and PBL learning tasks) and spatial skills in a mixed methods experimental research (Creswell & Clark, 2018). In mixed methodology research, researchers employ qualitative and quantitative approaches (qualitative and quantitative data collection, analysis, and inference) to achieve a comprehensive and in-depth understanding (Johnson et al., 2007). The aim is to combine the quantitative and qualitative data, to complement the weaknesses of one data collection method with the strengths of the other to provide a full understanding of the research problem (Creswell, 2013). Qualitative data are collected to supplement and improve the quantitative data in mixed methodology experimental studies. In the present study, the findings were improved by participant views after the experimental procedures were completed. Experimental conditions could not be assigned randomly. We used intact groups because we could not assign the students to classes. We could choose randomly the experimental 1, experimental 2, and control group among classes; thus, a quasi-experimental design was achieved (Fraenkel & Wallen, 2000; McMillan & Schumacher, 2010). In this design, there were three conditions, two of which were experimental, and one was control. The students in the first experimental group (E1) were instructed in the 3D virtual learning environment with a problem-based learning method. In the second experimental group (E2), the students were instructed with the problem-based learning method using worksheets in the classroom environment. In the third group, the control group (C), the teacher directly instructed the students using lecture, demonstration, and question-and-answer techniques. All of the three interventions have the same learning outcomes. E1 and E2 conditions had the same method (PBL) but different environments (3D virtual and classroom). E2 and C had the same environment (classroom) but different teaching and learning methods (PBL and teacher-centered methods). C, as a control group, represented the common and regular method and environment in schools when the interventions were being done.

2.2 Participants

The study was conducted with 79 students attending the 7th-grade science course. The study established three groups, two experimental (E1; E2) and a control (C) group. The groups were assigned randomly to the conditions. In the study, 24 participants were in the E1 group, 20 participants were in the E2 group, and 35 participants were in the control group. Seven participants from the E1 group were randomly selected to participate in semi-structured interviews.

2.3 Development of problem-based learning in 3D virtual and face-to-face environments

In the present study, ADDIE, a popular instructional design model, was employed to develop the 3D virtual learning, and face-to-face learning environments with the problem-based learning method.

2.3.1 Analysis

Three steps were performed in the analysis stage. Firstly, the subject of "Structure of Matter", which students have difficulty in learning due to the presence of abstract concepts, has been determined. In the middle school curriculum, the "Structure of Matter" topic is instructed in the 7th grade. Therefore, secondly, it was decided to form a target group of 7th grade students. In the final step, an analysis of the need was conducted. A literature review was conducted to determine the common issues experienced by the students and misconceptions about the topic of the structure of matter in science courses (Griffths & Preston, 1992; Lee et al., 1993; Papageorgiou & Johnson, 2005; Papageorgiou & Sakka, 2000; Tokatlı, 2010). The course content was developed based on these misconceptions and the objectives determined in the science curriculum. In this process, expert opinions were obtained from two professors and two teachers in science education.

2.3.2 Design

In the design stage, the 3D virtual learning environment and face-to-face environment were designed based on the data collected during the analysis stage. Based on expert opinion, it was decided to instruct the topic that included predetermined objectives and concepts in a 3D virtual learning environment with experiments, videos, animations, visuals, 3D objects, and written texts. In the face-to-face PBL environment, it was determined to instruct the topic with worksheets and experiments that employed visuals, videos, and written texts. Afterward, the design of problem-based 3D virtual and face-to-face learning environments was initiated. In the study, 3D virtual environment storyboards were developed based on design principles, macrostructures, and instruction strategies determined by Kapp and O'Driscoll (2010). In the design stage, the 3D virtual environment storyboards and face-to-face instruction worksheets were planned to be developed based on the views of two educational technology and four science education specialists.

2.3.3 Development

In this stage, the storyboards developed during the design stage were converted into a 3D virtual learning environment. The 3D virtual learning environment included three sections: the entrance, the museum, and the laboratory. The entrance was developed to allow students to collaborate using their avatars (Fig. 1). The virtual museum included 8 artworks modeled in 3D (Fig. 2). To implement the problem-solving process of the E1 and E2 group members, eight learning tasks were developed about these works of art. Both groups were assigned the same learning tasks. Learning tasks were developed to allow the students to learn the problems associated with the works of art and to respond to questions about solving these problems (defining the problem, problem clues, problem hypotheses, solution methods, and solution suggestions).

When E1 group members clicked on the artworks, they were led to the related problems. Sample 3D models of artworks and related problems are presented in

Fig. 1 General view of the entrance

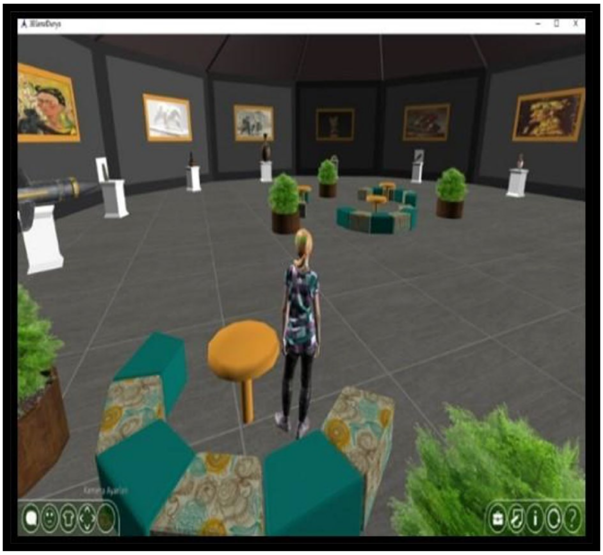


Fig. 2 General view of the museum

Figs. 3 and 4. After they learned about the problem and conducted research on that problem, E1 group members responded to questions about the problem-solving process using the "notebook" section in the 3D virtual environment. When the students in group E1 answered all questions, they completed the learning task for each work

Fig. 3 3D Model of the artwork 4

Fig. 4 The learning task that included the problem associated with the artwork 4

of art. A rubric and a panel were developed to allow the teacher and the researcher to score the learning tasks. Also, in the same panel, students could see their scores. In the E2 group, problems associated with eight works of art were developed in worksheets. After E2 group students learned about the problem and conducted research on the problem, they responded to the questions about the problem-solving process on the worksheet in writing. Similarly, E2 group students had to answer these questions to complete the learning task. A rubric was developed to allow the teacher and the researcher to score the learning tasks on the worksheets. The scores were discussed with the students in the classroom. The rubrics employed in the E1 group were also used in the evaluation. The development of the rubrics is detailed in the data collection instruments section.

The 3D objects, activities, and experiments in the laboratory were developed based on the objectives and content of the structure of matter topic in the science course curriculum. The laboratory included a 3D Bohr and Rutherford atom model, periodic table, pictures of scientists, interactive 3D models that depicted the transition of atoms to anion and cation states, molecular activities, compound activities, dissolution-evaporation-density difference-distillation experiments, and an analysis machine (Figs. 5 and 6). In the E2 group, topical details (Bohr and Rutherford atomic model, periodic table, information on scientists, and all other information) and molecular activity, compound activity, and analysis machine data are presented in text supported by visuals in the worksheet. The experiments were conducted in the classroom in the presence of the teacher, who provided the necessary materials for the dissolution-evaporation-density difference-distillation experiments.

2.3.4 Implementation

The developed 3D virtual learning environment was applied as a pilot study to 6 seventh-grade students. Before the pilot study, orientation was provided about the 3D virtual learning environment. Then, the students were asked to complete learning

Fig. 5 Rutherford atom model

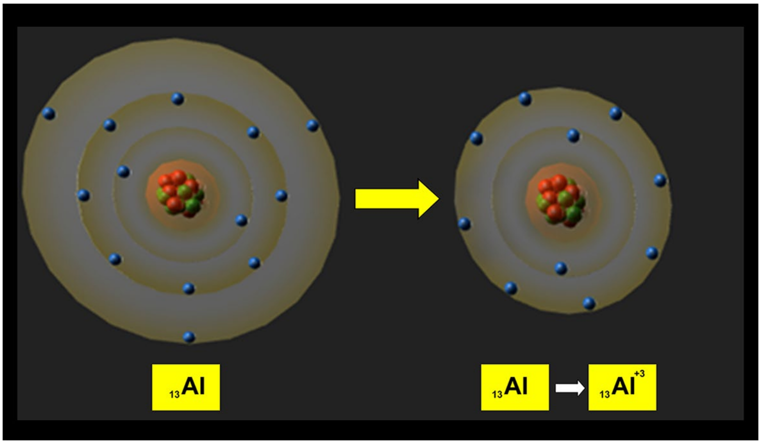


Fig. 6 Aluminum atom and aluminum cation

tasks 1, 2, and 5 in the environment. The face-to-face classroom environment worksheets were provided to 4 seventh-grade students. They were asked to complete the same learning tasks on the worksheet. Both processes in the two groups were observed by the teacher and the researcher.

2.3.5 Evaluation

The results of the pilot study were analyzed based on expert opinions (3 science education experts, 2 science teachers, 2 educational technology experts). The 3D virtual and face-to-face learning environment applications were revised based on expert views. Both environments were finalized for the experimental application.

2.4 Data collection instruments

To determine their learning performance, students were asked to complete certain learning tasks that included problem-solving processes, and the findings were analyzed based on the learning performance evaluation rubric developed by the researchers. The conceptual understanding of the students was analyzed with the conceptual understanding test developed by the researchers. Spatial visualization and mental rotation tests developed by Yıldız and Tüzün (2011) were employed to determine spatial skills. A semi-structured interview form developed by the authors was used to collect student views. These instruments are detailed below.

2.4.1 Problem-based learning performance rubric

Students were assigned learning tasks that included problem-solving processes to determine their learning performances. Rubrics were developed by the authors. In the study, eight rubrics were developed since there were eight learning tasks. The rubrics used to evaluate the learning tasks in the E1 and E2 groups were the same. The rubrics included 6 criteria to determine the problem-solving process. These criteria included understanding the problem, identifying the clues, determining the problem-solving strategy, the collected data during the solving of the problem, solution of the problem, and analysis of the problem-solving process. The first four criteria were scored between 0 and 5. The remaining two criteria were scored between 0 and 7, and 0 and 6 points. Thus, the highest possible learning score was 33. Each rubric was reviewed by 1 assessment and evaluation expert, 2 science teachers, and 2 science education professors. The eight rubrics were finalized after these expert views.

2.4.2 Conceptual understanding test

A conceptual understanding test was developed in the study to determine the impact of the experimental application on the conceptual understanding of the students. A two-tier conceptual understanding test was developed that included true–false questions in the first tier and open-ended questions were included in the second tier. The test was developed based on the steps determined by Treagust (1988). These steps included three main sections and further sub-sections: content determination, collection of the data on the issues experienced by the students, and test development. Experts were consulted during the development of the test, and the test was revised based on expert views. Then, a pilot scheme was conducted with 83 8th-grade students who were already instructed on the structure of matter. After analyzing the data, it was determined that the KR-20 coefficient of the test was 0.89. The first tier of the final test included 34 true/false and 5 matching questions, and the second tier included 8 open-ended questions.

An answer key was developed to score the conceptual understanding test. In the classification questions in the first test tier, correct answers received 1 point, and incorrect answers received 0 points. The open-ended questions in the second tier were evaluated with the "Numerical Concept Evaluation Chart" developed by Akpınar (2003). In this chart, the accuracy of the responses to the conceptual understanding test questions was awarded by 4 points for complete accuracy, 3 points for partial accuracy, 2 points for almost accuracy, 1 for little accuracy, and 0 for no response. For example, when a student's answer to a question in the first tier was "correct (1 point)" and the reason for this response was completely accurate (4 points) in the second tier, the student received 5 points from the question. The maximum possible score was 175 on the conceptual understanding test.

For the inter-scorer reliability of the test, the correlation coefficient was calculated. Students' answers were evaluated by one researcher and two teachers with the answer keys. Pearson correlation analysis revealed that there was a significant, positive, and high correlation (Can, 2013) between the conceptual understanding pre-test and post-test scores assigned by the researcher and the teachers: for pretests: 0.91, 0.94, and 0.92; for posttests: 0.88, 0.93, and 0.94.

2.4.3 Spatial visualization test

In the study, Lappan et al. (1986) "Spatial Visualization Test (SVU)" was employed to determine the visualization skills of the students within Middle Grades Mathematics Projects. This test was developed for 6th, 7th, and 8th-grade students and includes 32 5-point multiple-choice questions. In the study, the test adapted to the Turkish language by Yıldız and Tüzün (2011) that included 15 multiple-choice questions was employed. Cronbach's alpha coefficients were 0.679 ($N=161$) and 0.971 ($N=108$) from the two different applications used to calculate the reliability of the test. The Turkish version included questions about the isometric right, left, front, and rear views of unit cube structures, and "mat plan" questions that included the special coding for the bird's-eye view of the cube structures.

2.4.4 Mental rotation test

In the study, the "Mental Rotation Test (RTV)" was used to measure the ability of the students to rotate 3D objects mentally. The test was initially developed by Vandenberg and Kuse (1978) and modified by Peters et al., (1995). The test requires the students to rotate the objects not around a single axis mentally but around several axes (left/right, up/down) concurrently (Aykan, 2013; Peters et al., 1995). The test was adapted to the Turkish language by Yıldız and Tüzün (2011). The adaptation preserved the original version of the test, and no questions were added or removed. In the two applications conducted to calculate the reliability of the test, Cronbach's alpha coefficients were 0.712 ($N=161$) and 0.661 ($N=108$). In the present study, unlike the original application, each correct answer was scored with 1 point, and the highest possible test score was 48. Thus, students received 1 point for each correct answer.

2.4.5 Semi-structured interview form

Interviews were conducted to determine the experiences, views, and perceptions of the students in the E1 group about the 3D virtual environment and problem-based learning method. The interview form was developed based on the literature review. The interview form included open-ended questions such as "What do you think about the instructional method employed in the course?", "Did the instruction method allow you to learn better when compared to the other methods employed by the teacher?", "What were the contributions of the 3D objects?" Experts were consulted to review the interview form questions, and the interview forms were revised and finalized based on these reviews.

2.5 Data collection and interventions

The conceptual understanding test, the spatial visualization test, and the mental rotation test were applied as pre-tests to all participating students before the interventions. The meetings were done with the school staff for orientation to the method, environments and procedures by the researchers.

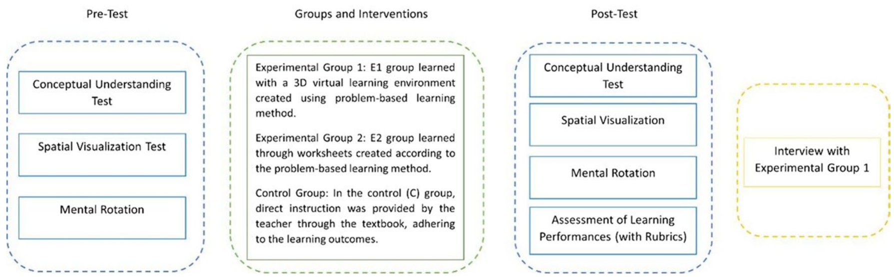


Fig. 7 Research design

The interventions lasted eight weeks and 32 class hours. Data collection and experimental design are presented in Fig. 7. During the interventions, the E1 group was taught by the problem-based learning method by the teacher using the 3D virtual learning environment in the computer lab., while the E2 group was taught by using the worksheets developed with the problem-based learning method in the classroom. In the control (C) group, the direct instruction method was used by the teacher using the lecture, demonstration, and question-and-answer techniques based on the textbook in the classroom. The same science teacher taught all groups. Students in all groups learned the same topical content on the structure of matter based on the learning outcomes and concepts mentioned in the 7th-class science curriculum. During interventions, students in E1 and E2 groups completed 8 learning tasks about eight artworks. The learning task 3 (Medallion) is presented in Appendix 2. In addition, the PBL process related to learning task 3 is provided as an example in Appendix 1. In the control group, however, the teacher continued to lecture with direct instruction (an explanation was provided in Appendix 1). After completing the interventions, the conceptual understanding test, spatial visualization test, and mental rotation test were reapplied as post-tests. Additionally, student reports for the PBL tasks by the E1 and E2 groups were scored with rubrics to have learning performance scores. After the post-tests, individual semi-structured interviews were conducted with randomly selected students from the E1 group.

2.6 Analysis

2.6.1 Analysis of quantitative data

We used descriptive and inferential statistics for analyzing quantitative data. Addressing the first research questions of the study we used an independent t-test to compare students' PBL performance scores, obtained from the rubrics, between E1 and E2 groups. For the second research question, there were three sub-questions. The pretest–posttest control group quasi-experimental design was utilized in the study. We used ANCOVA for examining them where the pretest is taken as a covariate, and standardized post-test compared to statistical control of the pre-experimental conditions, is the most adequate statistic when the researcher focuses on the effectiveness of the experimental procedure (Büyüköztürk, 2011). Before inferential analysis, the statistical assumptions were checked and confirmed.

The significance level was accepted as 0.05. A statistically significant difference between the groups does not necessarily mean a significant effect; thus, effect sizes were also calculated (Field, 2009; Fraenkel et al., 2012). Cohen (1988) reported proposed specific formulas to convert d to η^2 (eta square) and interpreted an eta square of 0.01 as a weak effect, an eta square of 0.06 as a moderate effect, and an eta square of 0.14 as a large effect (Tabachnick & Fidell, 2007). These limits proposed by Cohen are valid for partial eta squares as well as eta squares (Huck, 2012). In the study, partial eta squares (η_p^2) calculated on SPSS software for ANCOVA and Cohen's d for t-tests were employed to determine the effect size (Can, 2013).

2.6.2 Analysis of qualitative data

The data collected from the interviews with the E1 group were analyzed with content analysis. The content analysis method allows the determination of prevalent words/concepts in a text or a set of texts, the correlations between these words, and inferences about their messages by analysis (Büyüköztürk et al., 2012). Direct quotes are also frequently presented to emphasize the views of the participants. To determine the reliability of the research, the answers of the students in the E1 group were reviewed by the author and a qualitative research expert, and the items that these parties agreed or disagreed on were determined. The formula [Agreement/(Agreement + Disagreement) X 100] suggested by Miles and Huberman (1994) was used to calculate the reliability coefficient. The coefficient for the E1 group was 82%. A coefficient over 70% indicates reliability (Miles & Huberman, 1994).

3 Findings

3.1 Quantitative findings

3.1.1 Problem-based learning performance findings

To assess students' problem-based learning performances, students were assigned learning tasks that involved problem-solving processes. These tasks were subsequently evaluated and scored using rubrics developed by the researchers. An independent sample t-test was conducted on student scores to investigate potential significant differences in their performances (Table 1).

The analysis revealed a significant difference in scores between Task 6, Task 7, and Task 8 for the groups [($t_{(17)} = 2.38$, $p < 0.05$); ($t_{(17)} = 3.32$, $p < 0.05$); ($t_{(17)} = 2.76$, $p < 0.05$)]. Specifically, in Task 6, the mean learning performance of the E1 group ($\overline{X}$=24.33) was higher compared to the E2 group ($\overline{X}$=20.60). Similarly, in Task 7, the mean learning performance of the E1 group ($\overline{X}$=22.78) surpassed that of the E2 group ($\overline{X}$=17.80). Task 8 also exhibited a higher mean learning performance for the E1 group ($\overline{X}$=22.89) compared to the E2 group ($\overline{X}$=17.20). Although there was no significant difference between the effect sizes, the effect sizes for the 2nd, 3rd, and 4th tasks were approximately 0.80, indicating a relatively high magnitude. In contrast, the effect sizes for the 1st and 5th tasks were below 0.30, suggesting a low

Table 1 Descriptive statistics and t-test results of PBL performance

Learning Task	Group	N	$\overline{X}$	S	t	df	p	d
Task 1	E1	9	12.11	4.73	0.37	17	0.713	0.17
	E2	10	11.30	4.72				
Task 2	E1	9	20.56	6.15	1.95	17	0.067	0.90
	E2	10	15.90	4.15				
Task 3	E1	9	21.67	4.74	1.69	17	0.109	0.78
	E2	10	18.80	2.90				
Task 4	E1	9	23.78	4.97	1.90	17	0.074	0.87
	E2	10	18.80	6.27				
Task 5	E1	9	19.67	4.77	-0.55	17	0.587	0.26
	E2	10	20.90	4.91				
Task 6	E1	9	24.33	3.46	2.38	17	**0.029**	1.09
	E2	10	20.60	3.37				
Task 7	E1	9	22.78	3.46	3.32	17	**0.004**	1.53
	E2	10	17.80	3.08				
Task 8	E1	9	22.89	4.83	2.76	17	**0.013**	1.27
	E2	10	17.20	4.16				

E1: 3D Virtual Learning Environment, E2: Face-to-Face Learning Environment

magnitude. Notably, the effect sizes were high in the 6th, 7th, and 8th tasks, where significant differences were observed. Consequently, it can be suggested that the 3D virtual environment significantly and positively influenced students' problem-based learning performance when studying the structure of the matter topic compared to face-to-face instruction, especially in the latter three tasks.

3.1.2 Conceptual understanding findings

Table 2 displays the descriptive statistics, estimated posttest scores, and ANCOVA results for comparing the impact of interventions on conceptual understanding scores of the E1, E2, and C groups.

The results indicate a statistically significant difference between the mean post-test conceptual understanding scores of the E1, E2, and C groups, adjusted for pre-test scores ($F_{(2–75)} = 24.67$, $p < 0.01$), (Table 2). Also, it was observed that there was a

Table 2 ANCOVA results for conceptual understanding

Group	*N*	Pretest		Posttest		Est $\overline{X}$	$F_{(2–75)}$	*p*	η^2	Pairwise Comparison
		$\overline{X}$	S	$\overline{X}$	S					
E1	24	38.67	10.32	101.98	18.16	97.00	24.67	0.00	0.397	E1 > E2, E1 > C, E2 > C
E2	20	36.62	11.68	82.25	16.88	78.91				
C	35	25.89	7.11	54.43	20.08	59.74				

E1: PBL with 3D- Virtual; E2: PBL with F2F; C: Teacher Directed with F2F significant difference between the conceptual understanding levels of all groups. The analysis of the mean posttest scores adjusted for pretest scores showed that the E1 group had a higher mean score ($\overline{X}$ = 97.00) compared to the E2 group mean score ($\overline{X}$ =78.91) and the C group mean score ($\overline{X}$=59.74), while the mean score of the E2 group was higher compared to that of the C group. The effect size calculated for the significant difference was 0.397, indicating that the impact of the intervention on conceptual understanding was high ($n_p^2 > 0.14$). The results indicate that the problem-based learning method in the 3D virtual environment had a significant positive impact on the conceptual understanding of students in the science course on the topic of the structure of matter, comparing with other groups. Additionally, the face-to-face problem-based learning has also yielded better results than direct instruction in face-to-face teaching.

3.1.3 Mental rotation skill findings

Based on the results of the ANCOVA conducted to examine the impact of interventions on mental rotation skills, Table 3 provides the standardized posttest scores for the E1, E2, and C groups, adjusted for their respective pretest scores.

In Table 3, a statistically significant difference is evident in the mean posttest scores for mental rotation skills when comparing the E1 group with the E2 and C groups after adjusted for pretest scores ($F_{(2–75)} = 7.47$, $p < 0.01$). Conversely, no significant difference was observed between the scores of the E2 group and the C group ($p > 0.05$). The posttest scores, adjusted for pretest scores, indicate that the average score of the E1 group ($\overline{X}$=38.43) exceeded those of the E2 group ($\overline{X}$=34.19) and the C group ($\overline{X}$=33.15), highlighting a notable difference in mental rotation skills attributed to the intervention. The calculated effect size for this significant difference was 0.166, indicating a high impact ($n_p^2 > 0.14$) of the intervention on mental rotation skills. According to the results, there is a significant and positive impact of the 3D virtual environment on mental rotation skills compared to the face-to-face settings.

3.1.4 Spatial visualization skill findings

Based on the results of the ANCOVA aimed at comparing the impacts of interventions on spatial visualization skills, Table 4 displays the standardized mean posttest scores for the E1, E2, and C groups after adjusting for the pretest scores.

Table 3 ANCOVA results for mental rotation

Group	*N*	Pretest		Posttest		Adj $\overline{X}$	$F_{(2–75)}$	*p*	η^2	Pairwise Comparison
		$\overline{X}$	S	$\overline{X}$	S					
E1	24	35.67	6.23	39.94	6.65	38.43	7.47	0.001	0.166	E1 > E2, E1 > C
E2	20	33.45	5.99	34.35	5.31	34.19				
C	35	31.32	6.77	32.03	6.70	33.15				

E1: PBL with 3D- Virtual; E2: PBL with F2F; C: Teacher Directed with F2F

Table 4 ANCOVA results for spatial visualization

Group	N	Pretest		Posttest		Adj $\overline{X}$	$F_{(2-75)}$	p	η^2	Pairwise Comparison
		$\overline{X}$	S	$\overline{X}$	S					
E1	24	7.63	3.17	9.33	3.14	8.30	6.75	0.002	.153	E1 > E2, E1 > C
E2	20	6.09	2.67	6.77	2.39	6.64				
C	35	4.53	2.89	5.40	2.41	6.17				

E1: PBL with 3D- Virtual; E2: PBL with F2F; C: Teacher Directed with F2F

As seen in Table 4, there was a statistically significant difference between the mean posttest spatial visualization skill scores of the E1 group and the E2 and C group scores adjusted for the pretest scores ($F_{(2-75)} = 6.75$, $p < 0.05$). No significant difference was determined between the E2 group and the C group scores ($p > 0.05$). The mean posttest scores adjusted for the pretest scores demonstrated the mean E1 group score ($\overline{X}$=8.30) was higher when compared to the mean E2 group ($\overline{X}$=6.64) and the C group ($\overline{X}$=6.17) scores, demonstrating that spatial visualization skills of the students differed significantly based on the experimental procedure. The effect size for the significant difference was 0.153, demonstrating that the experimental procedure had a high effect ($n_p^2 > 0.14$) on spatial visualization.

3.2 Qualitative findings

The interviews were conducted with seven students from the first experimental group (E1), who were instructed using the problem-based learning method within the 3D virtual learning environment.

3.2.1 Views of the students on PBL in 3D virtual environment

The primary question in the interview was "What are your views on the problem-solving activities conducted within a 3D virtual environment?". It was intended to assess the students' opinions regarding the problem-based learning method in a 3D virtual environment with the question. The categories and subcategories identified through the analysis of answers are displayed in Fig. 8.

As a result of the interview analysis, it was revealed that the positive opinions of the students were higher than their negative opinions (Fig. 8). The "course process" was the most frequently mentioned category by the students with positive views. In the interviews, almost all students mentioned that the instruction was quite good and entertaining:

"At first, it appeared to be more enjoyable than traditional instruction. I believe that we can enhance our learning and articulate our thoughts more effectively through improved problem-solving. Personally, I found satisfaction

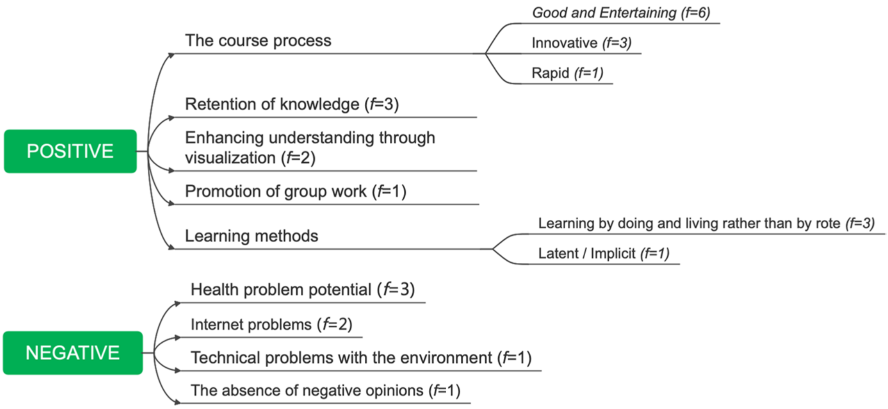


Fig. 8 Qualitative results on the PBL in the 3D virtual environment. **f: The repetition count of a sub-category*

in solving problems as it contributed to a better understanding." (Student 2/ "Good and entertaining")

Generally, the results indicate that students have positive views on problem-based learning in a 3D virtual environment.

3.2.2 Comparison of the PBL in the 3D virtual environment and the direct instruction method based on learning

The second question in the interview was "Did problem-based learning in the 3D virtual environment improve your learning compared to direct teaching?". This question aims to assess students' experiences and opinions regarding whether problem-based learning implemented in the 3D virtual environment enhances their learning for the topic of the structure of matter compared to direct instruction used by their teachers in previous topics. The categories and subcategories identified through the analysis of answers are displayed in Fig. 9.

Some student opinions, along with the respective categories, are provided below:

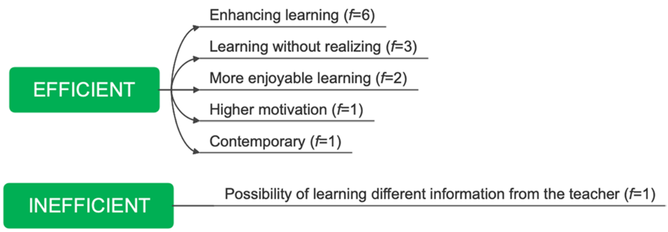


Fig. 9 The views on the efficiency of PBL in the 3D virtual environment compared to the direct instructional method in learning. **f: The repetition count of a sub-category*

The teacher used to present lectures, had us summarize, and made us write. I believe I achieved better learning outcomes with this method (Student 5/ "Enhancing learning")

When the teacher lectured, we had to memorize it. Here we learned without realizing it. (Student 4/ "Learning without realizing")

The analysis of the second interview question revealed that the students considered the problem-based learning method in the 3D virtual environment more efficient when compared to the direct instruction by the teacher. The students pointed out enhancements in their learning, emphasized the lack of necessity for rote memorization, and expressed enjoyment in the learning process facilitated by this method. According to the results of the analysis, it can be said that students generally found PBL in the 3D environment effective.

3.2.3 Contributions of 3D objects

The second question in the interview was "What were the contributions of working in a 3D environment for you?". The aim was to determine the students' views regarding the impact of 3D objects on the learning process. The categories and subcategories identified in the analysis of the answers are presented in Fig. 10.

Based on the analysis of the interview data, the most frequently mentioned category by the students was the contributions of the 3D objects to "visualization". The 3D atomic, anion, cation, and molecular models in the structure of matter topic allowed concretization of these abstract concepts, leading to better knowledge retention. The students stated the following about visualization:

"First, it was easier for me to visualize. Understanding, transferring it to my brain." (Student 2/ "Visualization").

"When we think about them in terms of form, 3D objects, for example, the atom, it helped me to visualize the atom model more easily because it was visual. It made the formation of anions and cations fit more comfortably in my brain." (Student 3/ "Visualization").

The analysis of the responses to the third interview question revealed that, according to the students, 3D objects contributed to the visualization of the concepts, allowing them to learn easily.

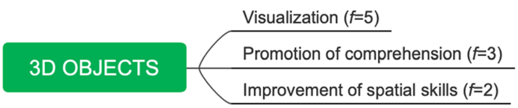


Fig. 10 The views regarding the impact of 3D objects on the learning process. **f: The number of times the category was mentioned*

4 Discussion and conclusion

The present study aimed to compare the effects of the PBL method implemented in a 3D virtual environment with PBL in a face-to-face environment, and a control group on students' learning performance, conceptual understanding, and spatial skills in teaching the "structure of matter" topic in the 7th-grade science course.

Students' performances from the E1 and E2 groups were similar in the first five learning tasks but significantly differed in favor of E1 in the last three. This result could be explained by the fact that the E1 group students oriented the PBL method and the 3D learning environment more by time than the F2F group students. They possibly engaged more in the task with higher interest and motivation until the end of the learning task. E1 group students stated that they considered problem-based learning method in the 3D virtual environment more effective on motivation and more enjoyable when compared to instruction by the teacher in the classroom. Furthermore, it was observed that the E1 group considered the instruction method "good and entertaining". Similar to these qualitative findings, Kimmons et al., (2012) and Liu et al., (2011) reported that "fun" was the most frequently mentioned word about the 3D virtual environment by 6th-grade students. Kennedy-Clark (2011) demonstrated that students had positive views on virtual worlds, positively affecting academic achievement and motivation. Huang et al., (2010) reported that virtual worlds motivated students to learn and positively affected the permanence of learning. Toprac (2008) determined that most students considered learning science in a problem-based virtual environment more interesting when compared to learning in the classroom, and the method improved their willingness to learn. However, Aslan (2019) reported that virtual learning environments designed with the problem-based learning approach did not affect student motivation; more studies from the literature support the opposite view, and the present study confirmed that PBL in 3D virtual environment positively affected students' perceptions on their motivation also related variables such as performance and conceptual learning.

The participants from E1 had significantly higher conceptual understanding scores when compared to the other groups. Also, E2 was significantly higher than the control group. These results allow us to draw two conclusions. First, the problem-based learning (PBL) method used in both the 3D virtual environment and the face-to-face setting has been more effective in enhancing students' conceptual understanding compared to direct instruction in the learning structure of matter. Second, conducting PBL in a 3D virtual environment has increased students' conceptual understanding compared to PBL with face-to-face instruction and direct instructions. This conclusion was also corroborated by the qualitative findings of the present study. Students from the E1 group asserted that they found the problem-based learning method in the 3D virtual environment to be more effective in fostering learning, as compared to instruction by the teacher in the classroom. In parallel with our initial conclusion, when the literature is examined, many studies have been encountered that demonstrate the positive impact of problem-based learning on conceptual understanding compared to traditional instruction (Çoban & Erol, 2020; Nangku & Rohaeti, 2019; Simanjuntak et al., 2021). PBL enhances students' conceptual understanding and problem-solving skills (Mancera-Olive, 2022) while utilizing real-world problems as a context for acquiring fundamental knowledge and concepts related to the subject matter. PBL shifts the traditional classroom dynamic by placing students in an active role, where they actively engage with problems, conduct research, and apply critical thinking skills to find solutions. On the other hand, 3D virtual learning environments, similar to the problem-based learning method, played a key role in learning. 3D virtual worlds are an effective tool to enhance students' understanding (Barab et al., 2000). According to the qualitative results of the present study, students in the E1 group stated that visualizations of 3D objects significantly enhanced their comprehension. When PBL is combined with a 3D virtual environment, it creates a dynamic and engaging learning experience. PBL in 3D virtual environments provides students with a platform to explore concepts, conduct experiments, and engage in activities that might be challenging or impossible in a traditional setting. It provides a safe and controlled environment for students to engage in collaborative and immersive learning activities (Parson & Bignell, 2011). The problem-based 3D virtual environments encourage students to learn by active participation, develop individual problem-solving skills, and share their ideas with peers (Phungsuk et al., 2017). Using a 3D virtual environment in science education has positive effects on student learning outcomes (Shudayfat & Alsalhi, 2023). Similar to our second conclusion, Aslan and Duruhan (2021) found that virtual learning environments designed based on the problem-based learning approach are more efficient in enhancing students' academic success and problem-solving skills compared to traditional methods in science lessons. In addition, Dede et al., (2005) demonstrated that the problem-based 3D virtual environment increased the biology knowledge of the experimental group students by 32% to 35%, whereas it increased by 17% for the control group students. It also provided complex inquiry skills better than good traditional approaches do. In the literature, there are also some studies indicating that problem-based learning does not have an impact on conceptual understanding (Dobbs, 2008; Mungin, 2012; Şendağ & Odabaşı, 2009). The conclusion of the present study is in favor of the positive effects of PBL in the 3D environment on conceptual understanding related to the topic of structure of nature.

The results revealed that PBL in the 3D virtual environment has a significant positive effect on improving the spatial visualization and mental rotation scores compared with the other groups. No significant difference was determined between E2 and C groups. In the interviews conducted with the E1 group students, they mentioned visualization and improvement of their spatial skills. Spatial visualization and mental rotation are the foundations of spatial skills, and they play a critical role in daily or professional tasks (Zhou et al., 2022). Several activities, such as reading a map and self-orientation, are associated with spatial skills (Tito et al., 2021). Good spatial skills also positively affect learning achievements in science, technology, engineering, and mathematics (STEM) (Barrett & Hegarty, 2016; Merchant et al., 2012). Spatial skills education could help students make a difference in STEM (Stieff & Uttal, 2015). The most prominent and promising feature of 3D virtual environments is their capacity to promote spatial learning (Merchant et al., 2012). In these environments, learners could interact with various objects (images, sounds, and multimedia content) as they communicate and collaborate with other learners when they explore scenarios and solve various complex problems (Nelson & Ketelhut, 2007). Wang et al., (2007) reported that 2D and 3D media representations did not lead to a significant difference between the spatial visualization skills of undergraduate science students. But, certain authors reported that the 3D inquiry environment was more effective when compared to the traditional environment in developing spatial skills (Li et al., 2020). Zhou et al., (2022) reported that the spatial skills of the experimental virtual environment group (FORSpatial) exhibited significant improvement compared to the control group. Merchant et al., (2013) reported that students who were classified with low spatial skills exhibited significantly better performance when they conducted the same activities in a 3D virtual world when compared to students who only worked with 2D images in a study conducted with Second Life 3D virtual environment. Similarly, Lee and Wong (2014) reported that the performances of students with low spatial skills were more positively affected by the 3D virtual learning environment (V-Frog™) compared to students with high spatial skills. Spending more time and interacting in this environment improves participants' spatial skills (Yilmaz et al., 2015).

Based on the results of the study, we can conclude that the implementation of the PBL in a 3D virtual environment has led to significant improvements in students' problem-based learning performance, conceptual understanding, spatial skills, and their opinions toward it. The combination of PBL and 3D virtual environments, for teaching the structure of matter, provides a dynamic and engaging learning experience, allowing students to explore concepts, and engage in activities that might be challenging in a traditional setting. In traditional classroom settings, abstract concepts can be difficult for students to grasp. However, in a 3D virtual environment, these concepts can be visualized and manipulated in a concrete way. Moreover, the problem-based nature of this approach encourages students to actively engage with the learning material, rather than passively receiving information. By presenting students with real-world problems to solve, PBL prompts them to think critically, apply their knowledge, and make connections between different concepts. This active learning process can lead to a deeper understanding of the material, as students are not merely memorizing facts, but truly understanding the underlying concepts. As a practical recommendation, the study advocates for integrating 3D virtual learning environments alongside the problem-based learning (PBL) approach, particularly beneficial for subjects encompassing abstract concepts like the "structure of matter".

5 Limitations and future research

However, while the potential benefits of this approach are significant, some challenges need to be addressed. These include the cost and accessibility of 3D virtual environment software and programs, robust internet connections, technical support needs, and possible health problems because of improper use. Additionally, the success of this approach depends on the quality of the problem scenarios and the facilitation of the learning process. Educators must carefully design the problems to align with learning objectives and ensure students are guided and supported throughout the learning process. However, careful planning and consideration are required to overcome potential challenges and ensure the successful implementation of this innovative approach.

The study findings should be interpreted considering some limitations. First, the study was limited to a specific group of 7th-grade students, which may limit the generalizability of the results to other populations. Future studies could benefit from including a more diverse sample of students from different grade levels to better understand the impact of PBL in 3D virtual environments across a wider range of ages and educational backgrounds. Secondly, the study concentrated on the "structure of matter" topic within the science curriculum, potentially limiting its ability to fully elucidate the broader impact of PBL in 3D virtual environments across other learning domains. For future research, exploring the application of PBL in 3D virtual environments across various subjects and topics would be advantageous to ascertain its overall influence on student learning and engagement. Additionally, the study focused on a specific set of variables, including problem-based learning performance, conceptual understanding, spatial visualization, and mental rotation skills. While these are important factors to consider, future studies could benefit from exploring other variables, such as critical thinking skills, motivation, engagement, and satisfaction of students in problem-based 3D virtual environments. Another limitation is that the intervention period was limited to eight weeks. Extending the intervention duration and monitoring its long-term effects over an extended period may provide valuable insights into the sustainability and persistence of the observed positive outcomes. Moreover, the study did not explore the impact of previous spatial skills of students on learning in a problem-based 3D virtual environment. Future research could benefit from investigating the relationship between spatial skills and student learning outcomes to better understand the potential benefits of PBL in 3D virtual environments for students with different spatial abilities. Furthermore, 3D implementations were conducted in a computer lab. with using keyboards and mouses in this study. Future studies can be realized by using VR headsets and new immersive technologies. Finally, the study did not explicitly account for individual differences among students, such as level of intelligence/visual skills, diverse learning styles, or prior exposure to technology. Considering these individual factors in future research could contribute to a better understanding the differential impact of 3D virtual environments on diverse student populations. It is recommended to extend the investigation by incorporating assessments designed to differentiate among students based on their levels of intelligence and visual skills. Including instruments such as the GEFT (Group Embedded Figures Test) or other relevant measures can provide a more comprehensive understanding of the impact of problem-based learning in 3D virtual environments across varying cognitive and visual abilities. This approach will contribute valuable insights into how students with diverse skill sets respond to and benefit from the implemented intervention.

Appendix 1: PBL learning task sample: Learning experiences of the E1, E2, and C group students

	E1 Group	E2 Group	C Group
Session 1	The students were presented with the medallion problem about the work of art 3 as the 3D virtual environment learning task. In the learning task, the students were asked whether a medallion was fake or real in the virtual museum. To solve this problem, the students tried to use the clues available in the environment and determined individual methods to solve the problem	The students were asked to determine whether the medallion, the work of art 3, was fake or real in the learning task provided on the worksheets in the classroom environment. Students tried to find the clues to solve the problem with individual methods	The teacher conducted direct instruction based on the topical objectives. The teacher provided information and examples based on the course objectives, using the blackboard
Sessions 2 and 3	Students developed hypotheses to solve the problem. They analyzed the data, visuals, and 3D objects and employed the analysis machine to test their hypotheses The science teacher was always in the computer laboratory and guided the students when necessary	Students developed hypotheses to solve the problem. They examined the classroom resources, images, and the image of the structure of the medallion on the worksheet to test their hypotheses. The science teacher was always present in the classroom and guided the students when necessary	The teacher asked questions at the beginning of the session to remind the students about their prior knowledge. Later, the teacher instructed the new concepts directly with direct instruction
Session 4	According to the information they have acquired, the students developed solutions for the medallion problem When students answer the five questions in the 3D virtual environment related to the problem, the learning task (medallion) is completed. This learning task was scored by the authors using the rubric and provided feedback. These scores were also presented in the study findings	Based on previous findings, the students developed solutions for the medallion problem. They responded to questions about problem-solving on the worksheet and completed the learning task This learning task was completed at the end of the class, scored by the researcher using the rubric, and provided feedback. These scores were also presented in the study findings	The teacher completed the class by giving daily life examples about the instructed concepts and asked the students to give further examples

E1 Group	E2 Group	C Group
After the 4 sessions, E1-E2 and C group students learned the concepts of pure substances and elements, their significance in daily life, the elements in the periodic table, and their symbols. The E1 group employed the 3D virtual environment and the E2 group employed the worksheets to explore these concepts by solving problems. In group C, the teacher lectured using direct instruction, demonstration, and question–answer techniques		

Appendix 2: Learning task-3 (Medallion)

The following outlines the third learning task assigned to students, focusing on the medallion problem and the corresponding questions they addressed in the problem-solving process. The E1 group engaged with the medallion problem in a 3D virtual environment before responding to the questions presented. Conversely, the E2 group tackled the medallion problem within the F2F classroom setting and subsequently answered the questions outlined below. The learning task 3 concluded for both groups upon completion of their responses.

Medallion's problem:

The medallion, weighing 14.3 g and crafted from pure gold, representing the 'Karun Treasure,' was being exhibited in our museum. However, in a recent theft incident at our museum, it was noticed that this medallion had been replaced with a counterfeit copy. Through investigations, it has been determined that the medallion is currently in the country of Novantis. However, due to the lack of necessary analyses, there is no definite information on whether the medallion in Novantis is fake or authentic. Your task is to conduct the required analyses to prove whether this medallion is genuine or fake. If the medallion is genuine, we will do our best to bring it back to our museum.

Questions about the problem of the medallion:

Question 1: Could you explain the problem of the medallion?

Question 2: What are the clues in the problem of the medallion?

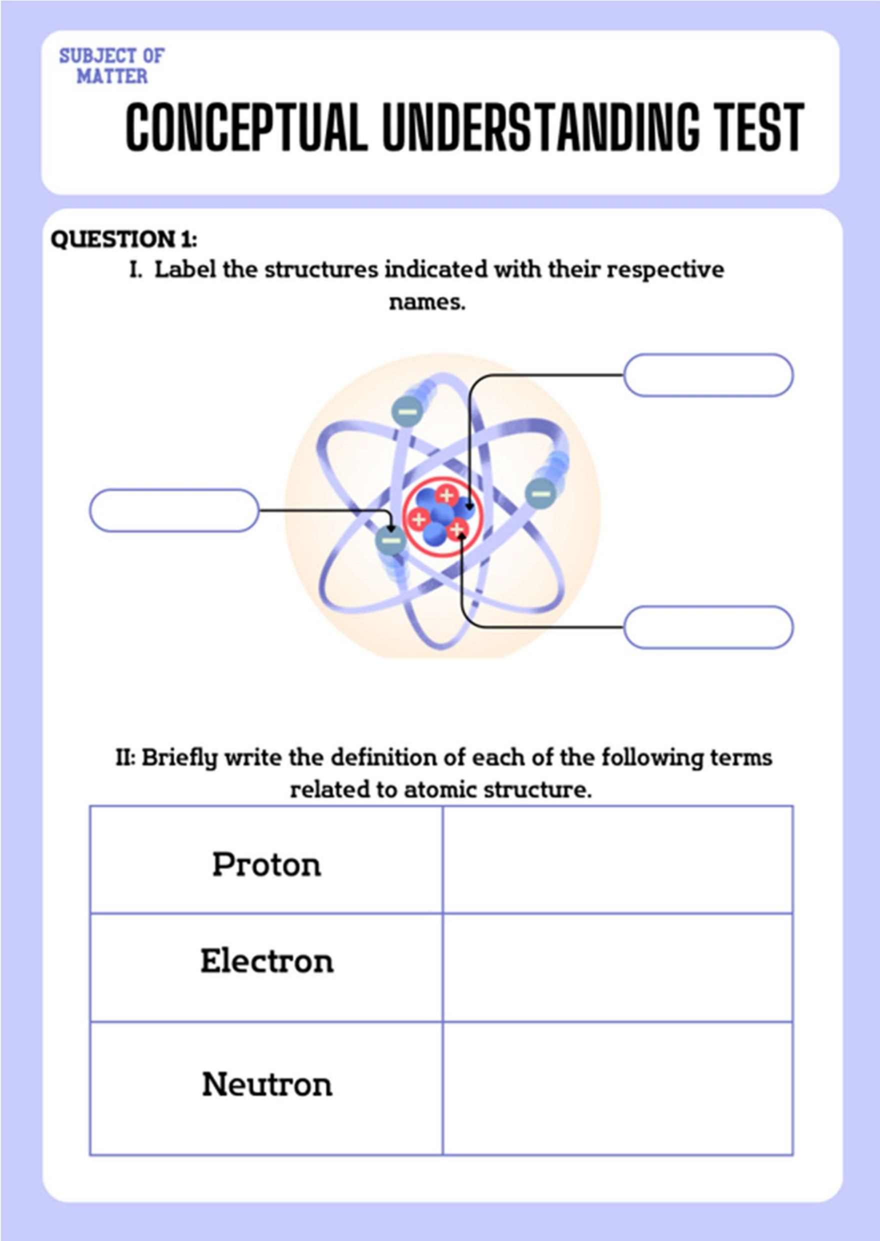
Question 3: Could you elucidate the steps you employed in resolving the problem associated with the medallion?

Question 4: During the process of addressing the medallion-related problem, what information did you access, and what did you learn?

Question 5: Do you think the medallion is authentic or counterfeit? Please explain

Appendix 3: Conceptual understanding test

A sample question for the conceptual understanding test is provided below.


SUBJECT OF MATTER

CONCEPTUAL UNDERSTANDING TEST

QUESTION 1:

I. Label the structures indicated with their respective names.

II: Briefly write the definition of each of the following terms related to atomic structure.

Proton	
Electron	
Neutron	

Appendix 4: A sample section of problem-based learning performance rubric

A section of the rubric-3 used for scoring students' responses to the medallion problem is presented below.

Question 1: Could you explain the problem of the medallion?

Criterion	Scores	Definition	Critical behavior
Understanding the Problem	5	Outstanding	The explanation is exceptionally clear, thorough, and demonstrates a deep understanding of the medallion problem. It includes all relevant details, and the response is well-organized
	4	Proficient	The explanation is clear and provides a good understanding of the medallion problem. It covers most of the relevant details, and the response is logically organized
	3	Basic	The explanation is adequate but may lack some clarity or depth. It covers the main aspects of the medallion problem but might miss a few details. The response is somewhat organized
	2	Limited	The explanation is limited in its clarity and depth. It may lack key details and understanding of the medallion problem. The response is poorly organized
	1	Inadequate	The explanation is unclear, lacking depth, and shows a minimal understanding of the medallion problem. It is disorganized and may not address the question adequately
	0	No response	No response is provided to the question

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Author contributions Şirin KÜÇÜK AVCI: Conceptualization, Investigation, Methodology, Data Analyze, Writing—original draft, Review & Editing.

Özcan Erkan AKGÜN: Supervision, Conceptualization, Methodology, Data Analyze, Writing-Review & Editing (Educational Technology).

Fatime BALKAN KIYICI: Supervision, Validation, Writing-Review & Editing (Science Education).

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare that they have no conflict of interest.

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