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Research article

Collaborative science experiments based on the educational metaverse: Research on the impact and mechanisms of collaborative science experiments on elementary students' creative thinking

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Abstract: Elementary science curricula play a crucial role in guiding students to actively learn science and in sparking their innovative potential. However, practical science instruction often faces challenges, such as difficulties in gathering materials and a lack of guidance, leading to a prevalent reliance on teacher demonstrations rather than hands-on student experiments. This approach fails to cultivate the innovative thinking that experimental teaching should promote. To address this gap, this study introduced a model based on social cognitive theory that examines the impact of collaborative scientific experiments within an educational metaverse on elementary students' creative thinking. The research involved two parallel sixth-grade classes, with the experimental group engaging in collaborative science learning on a virtual experimental platform in the educational metaverse, and the control group using physical scientific equipment in the classroom. Data on students' learning styles, creativity scores, creative output, and survey responses were collected before and after the experiment, yielding 88 valid questionnaires. Descriptive statistical analysis of the data indicated that the metaverse-based collaborative experimental teaching positively influences students' creative thinking. Further analysis confirmed the reliability and validity of the data and tested hypotheses on correlation, mediation, and moderation effects. It was found that a sense of belonging partially mediated the impact of online environmental support on collaborative quality, while learning styles moderated the relationship between online support and creative thinking. Based on these findings, the study offered recommendations for improving teaching practices.

Keywords: creativity, collaborative science experiments, educational metaverse, structural equation model

1. Introduction

Hands-on experiments in science classrooms are pivotal in sparking students' curiosity and fostering a desire to explore. These activities promote independent thinking and problem-solving skills, and encourage innovative and creative expression [1]. However, practical science education faces several challenges. Many experiments require materials that are difficult to collect or standardize, which can hinder their execution. Additionally, certain macroscopic and microscopic phenomena may not be clearly visible, thus failing to achieve the intended educational impact. Students also encounter difficulties in accessing timely and effective professional guidance when conducting experiments outside the traditional classroom setting. Collectively, these issues have led to a decline in students' interest in scientific inquiry [2].

In recent years, researchers have begun to employ virtual experiments to simulate operations that are impractical in the real world or to visualize phenomena that are difficult to observe. This approach allows learners to engage in virtual observation and interactive experiences, enhancing their comprehension and understanding of abstract concepts [3,4]. Notable initiatives include the Learn Anytime Anywhere Physics laboratory at the University of North Carolina and the Vlab virtual laboratory developed by the University of Oregon. These platforms provide virtual experiments in fields such as astrophysics, mechanics, thermodynamics, and environmental science, and are open to all users, offering extensive opportunities for interaction. However, these platforms often suffer from limited simulation fidelity and are primarily focused on demonstration, offering limited opportunities for immersive collaboration and inquiry.

Researchers generally believe that the high integration of visual immersion, tactile feedback, and information transmission technologies in the educational metaverse provides the potential to reshape teaching paradigms, reconstruct learning spaces, and rebuild educational settings [5,6]. These technologies not only expand learners' embodied cognition and situational awareness in virtual experiments but also facilitate the seamless transition between the laboratory and other learning environments. These advantages suggest that collaborative scientific experiments conducted within the educational metaverse could address the shortcomings of existing virtual experiment platforms [7]. However, most existing research on the educational metaverse remains theoretical, and the impact and mechanisms of collaborative scientific experiments in the educational metaverse on the development of students' creative thinking are still unclear.

Overall, this study aims to fill two research gaps: (1) What are the differences in fostering students' creative thinking provided by the educational metaverse platform? (2) What are the mechanisms by which collaborative scientific experiments in the educational metaverse influence the cultivation of creative thinking?

2. Research background and hypotheses

2.1. Research background

Creative thinking is a form of higher-order thinking that involves the ability to produce or propose learning outcomes that are both novel and appropriate [8]. It encompasses redefining problems and challenges, exploring different perspectives, and seeking multiple solutions [9]. In terms of influencing factors, the formation and development of creative thinking are also influenced by the family atmosphere, school education, individual cognitive style, and so on. According to the 3D model theory of creativity, the influencing factors of creativity include intelligence dimension, cognitive style, and personality dimension [8]. Collaborative learning is one of the most widely used models of creativity cultivation. Some researchers have found that collaboration helps students integrate knowledge from different fields to think and solve practical problems, and creative ideas are generated in collaboration [10]. In recent years, more and more researchers have turned their attention to the scene of the science laboratory. Some researchers have built a theoretical model of the learning activity organization program for primary school students to cultivate innovative thinking, and found that students have significantly improved in the dimensions of adventure, imagination, curiosity, and challenge in the creativity tendency test with the help of programming experiments [11].

With the advent of the Internet era, this mode of creative thinking training also faces some drawbacks. For example, the problem of "information overload" makes it difficult for students to effectively select and use information, which affects their cooperation and judgment. The Internet culture of "quick answers" makes students more inclined to pursue direct answers, while ignoring the importance of independent learning and expression. Some educators and schools at home and abroad have recognized these problems. Some scholars believe that virtual science experiment teaching in the educational metaverse can not only provide learners with more high-quality digital learning resources and more abundant knowledge application scenarios, as well as improve learning performance and their sense of gain, but also better create an equal learning environment, promoting effective communication and collaboration among learners [7]. However, most of the researches on how to promote students' creative thinking and other higher-order thinking with the help of collaborative scientific experiments in the context of the educational metaverse are still in the theoretical stage, with few practical cases.

American educators and psychologists Albert Bandura and Richard Wagner proposed social cognitive theory in the 1970s, which emphasizes that individuals construct knowledge and understanding through interaction with others and participation in social activities during the learning process. It holds that learning is a social process in which individuals not only acquire knowledge from teachers and textbooks, but also construct knowledge and meaning through cooperation, discussion, and reflection with others [12]. Individuals, behaviors, and environments interact with each other. Environments, behaviors, and people are causal to each other, and each of them has a two-way interaction and causal relationship [13].

Social cognitive theory provides the theoretical basis and practical guidance for the application and development of the educational metaverse. The educational metaverse is a learning environment based on technologies such as virtual reality, augmented reality, and mixed reality designed to provide immersive, personalized, and interactive learning experiences, while social cognitive theory provides the theoretical foundation for engaging learning and social interaction, which is aligned with the learning goals and environment in the educational metaverse. This provides a potential learning mechanism for the education metaverse to promote the development of students' creative thinking.

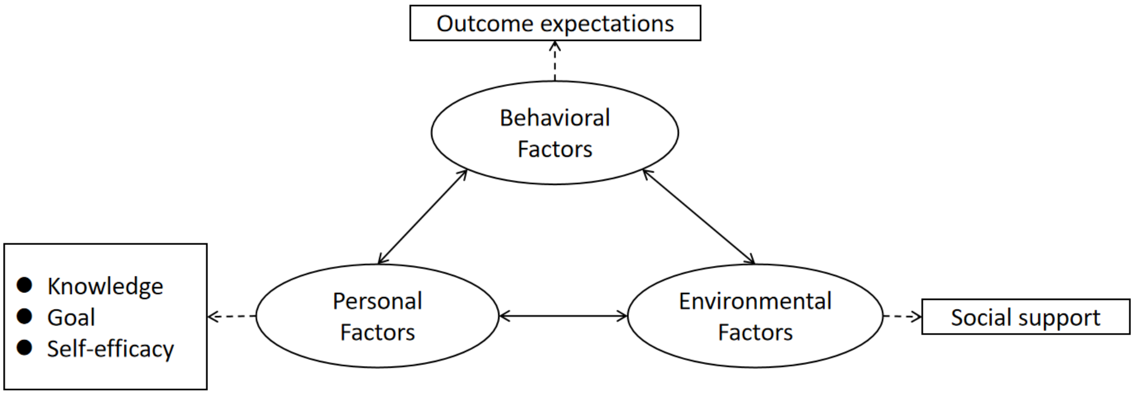

Figure 1. Determinants in social cognitive theory.

First of all, social cognitive theory emphasizes that learners' personal factors, such as personal self-efficacy, learning style, performance achievement, and surrogate experience, affect their learning behavior and environment, and determine the effectiveness and durability of learning. Through a personalized learning experience and feedback mechanism, the educational metaverse can meet the diverse needs of learners and promote the cultivation of their active learning and self-regulation abilities [14]. Second, social cognitive theory holds that individuals predict the possible results and feedback of performing a certain behavior, such as possible material rewards, sensory experiences, and spiritual rewards, and decide their next behavior according to their prediction. The immersion and interactivity of the educational metaverse complement the behavioral factors in social cognitive theory. Through virtual reality and augmented reality technology, learners can be placed in a virtual scene and interact with virtual objects to simulate the learning environment in the real world [15]. The real-time feedback and evaluation mechanism provided in the metaverse enables students to understand their learning progress and problems in time, adjust their learning strategies and methods in time through the objective results of online tests and the evaluation feedback of teachers, fill in the gaps, and improve their learning results. In addition, social cognitive theory holds that online environments can provide social support for learners, such as through discussion forums, online team projects, etc., enabling students to communicate, sharing experiences and perspectives with other students and teachers. This kind of social support helps students feel that they are cared for and supported, and improves the learning effect [16].

Based on the analysis above, the educational metaverse holds tremendous potential and promising prospects for fostering students' creative thinking. However, current research primarily remains at the stage of theoretical debate and basic application, and empirical studies on the educational metaverse's impact on nurturing students' higher-order competencies are urgently needed for deeper practical exploration and discussion.

2.2. Research hypothesis

Effectiveness hypothesis

Based on existing research on the neurocognitive basis and formation mechanisms of creative thinking, researchers generally believe that a feasible approach to cultivating creative thinking is to allow students to engage in timely and effective interactions and collaborations with team members or other collaborators while addressing complex real-world problems, drawing on interdisciplinary knowledge, experiences, and skills. This process gradually fosters innovative thinking abilities [17]. Therefore, theoretically, the educational metaverse, with its embodied practical advantages, positively promotes the cultivation of creative thinking. Moreover, research has also shown that virtual experiment systems and collaborative learning have a positive impact on learners' competency development [4]. For instance, collaborative knowledge learning construction activities that include the four stages of “knowledge sharing–knowledge negotiation–knowledge construction–knowledge integration” can significantly enhance students' creative works and levels of creative thinking [18]. Based on the above analysis, the following research hypothesis is proposed:

H0: Collaborative science experiments based on the educational metaverse have a positive impact on elementary school students' creative thinking.

Impact mechanism hypothesis

(1) Support level of the online environment, quality of collaboration, and creativity

The support level of the online environment refers to the degree of support and convenience provided to users by online tools, platforms, or systems. The quality of collaboration generally refers to the interaction and cooperation quality among team members. Social cognition theory believes that the degree of social support can have an impact on learners' cognition and behavior. Previous studies have also suggested that the support level of the online environment has a significant positive impact on the creative thinking of children and adolescents. In a qualitative interview study involving 16 middle school students, it was found that the support from significant others and the ease of access to resources and technology provided the behavioral basis and psychological conditions for students' creative learning [19]. Therefore, this study proposes the following hypotheses:

H1: The support level of the online environment has a positive impact on the quality of collaboration.
H2: The quality of collaboration has a positive impact on creative thinking.
H3: The support level of the online environment has a positive impact on creative thinking.

(2) Sense of immersion, sense of belonging, and quality of collaboration

In the context of the educational metaverse, the sense of immersion refers to the vividness of the virtual environment presented by the system and the degree to which it isolates the external world. The sense of belonging refers to an individual's identification and sense of belonging to their team or organization. Researchers tested the levels of immersion, sense of belonging, and learning motivation among 128 university students in a VR course on fire safety, finding that high levels of immersion in learning help enhance students' sense of belonging and learning motivation [20]. The sense of immersion may also have a positive impact on the quality of collaboration. When team members feel immersed during the collaborative process, they are more likely to focus their attention on participating in collaborative activities. Similarly, the sense of belonging may also positively influence the quality of collaboration. When team members have a strong sense of belonging to the team, they are more willing to invest energy and resources, participate in, and support the team's collaborative activities, ultimately achieving better collaborative outcomes. Therefore, the following research hypotheses are proposed:

H4: The sense of immersion has a positive impact on the sense of belonging.

H5: The sense of immersion has a positive impact on the quality of collaboration.
H6: The sense of belonging has a positive impact on the quality of collaboration.

(3) Support level of the online environment and sense of belonging

When users feel that the online environment provides adaptive and personalized functions and services that meet their needs and expectations, they are more likely to develop a sense of belonging to that online environment. Moreover, a sense of belonging can encourage users to be more loyal, engaged, and actively participate in the online environment, which in turn affects the support level of the online environment. Therefore, the following research hypothesis is proposed:

H7: The support level of the online environment has a positive impact on the sense of belonging.

(4) The moderating effect of learning style

Learning style refers to the preferred ways and strategies individuals use during learning and cognitive processes. In the ternary interaction determinism of social cognition theory, learning style, a personal factor, can interact with both the learners' behavior and their environment. Research has found that individuals with different learning styles have varying impacts on the support level of online environments and the development of creative thinking [21]. Individuals who prefer an active learning style tend to favor learning through self-exploration and participation; they are more likely to benefit from the various resources and tools provided by online environments, thereby enhancing their creative thinking potential [22]. For individuals who prefer a guided learning style, the positive impact of a good support level in online environments on the development of creative thinking is relatively limited. Therefore, the following research hypotheses are proposed:

H8: Learning style plays a moderating role between the support level of the online environment and the quality of collaboration.
H9: Learning style plays a moderating role between the quality of collaboration and creativity.
H10: Learning style plays a moderating role between the support level of the online environment and creativity.

Impact mechanism hypothesis model

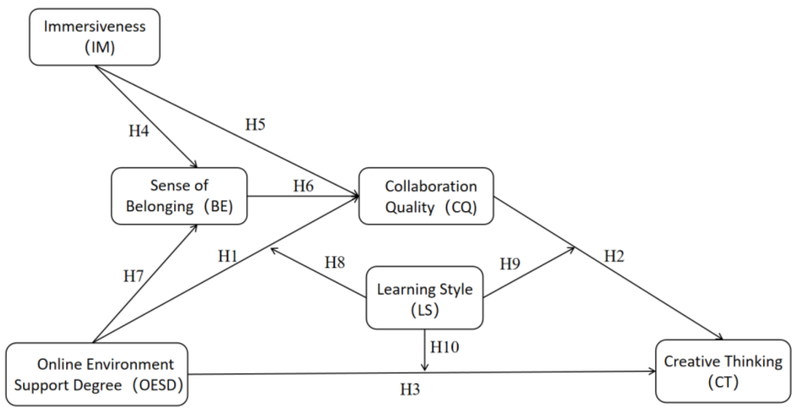

Figure 2. Impact mechanism model of collaborative science experiments based on the educational metaverse on creative thinking.

Based on the above analysis, this study constructs an impact mechanism model of collaborative science experiments on creativity based on the educational metaverse (as shown in Figure 2), exploring and explaining the transformative relationships and effects among the online environment (OESD), immersiveness (IM), sense of belonging (BE), collaboration quality (CQ), learning style (LS), and creative thinking (CT).

3. Platform development and design

This study established a virtual simulation experiment platform based on Unity3D technology to meet the comprehensive needs of the experiments. During the development of the platform, we thoroughly considered various functionalities such as user registration and login, campus scene navigation, experimental simulation operations, and social interaction. By integrating front-end display, back-end logic processing, and database storage design, the platform not only meets the needs of educational practices but also collects a variety of data generated during use, especially dynamic data from teacher and student interactions. Furthermore, the management platform effectively expands the functionalities for user roles and platform usage, fulfilling comprehensive system monitoring, flexible adjustments, and continuous optimization by administrators to ensure the platform's long-term stability and ongoing innovation. The main aspects of the platform development and design process include front-end development, back-end development, and database development.

3.1. Front-end development and design

Development of a virtual community for multiple scenarios: This research is dedicated to building specialized virtual communities based on different scenarios, successfully integrating theories of computer-supported collaborative learning and project-based learning methods to create various learning environments including campus navigation, virtual simulation experiments, virtual discussions, and online lectures. The platform not only provides rich learning resources and diverse functionalities but also supports collaborative learning among users through innovative design. Upon logging in, learners can easily switch between different scenarios, catering to diverse needs beyond virtual simulation experiments, greatly enriching the user experience, promoting innovative learning methods, and enhancing learning outcomes.

Development based on digital avatars: To provide an immersive experience for teachers and students, the platform utilizes advanced model generation technologies such as intelligent algorithms, 3Ds Max, and Avatar SDK to create virtual avatars. Initially, two-dimensional images are converted into three-dimensional models using deep learning algorithms, followed by the use of convolutional neural networks (CNN) to analyze the 2D images, and finally, the platform automatically creates highly realistic digital avatars for teachers and students. This process supports multimodal interactions in virtual spaces, thereby enhancing communication and collaboration.

Development of audio-visual and other social features: To meet the communication needs of students during group collaborations and to cater to diverse community activities in other scenarios, the platform integrates audio-video calling and screen-sharing functionalities in seminar settings. This enables real-time, efficient discussions and information sharing. Additionally, in the campus scenario, features like friend requests and text chatting are included to provide a richer social experience, fulfilling the social needs of students outside of learning activities. These features help create an open, interactive, and creative learning environment, allowing students to overcome geographical barriers for remote communication and collaboration, thus fostering a spirit of teamwork and cooperative skills.

3.2. Back-end development and design

Implementation of data transmission based on WebSocket technology: For large-scale, multi-user data transmission between the front end and back end, this study employs the WebSocket protocol on HTTP servers to introduce a bi-directional communication mechanism, enabling large-scale online open learning. With high concurrent connections and substantial client-server interaction load, WebSocket technology significantly reduces network bandwidth consumption and supports real-time synchronization of massive model data across the platform, meeting the needs of multi-user collaborative learning. This efficient data transmission ensures continuity in learning and enhances the learning experience for teachers and students.

Resource deployment based on cloud servers: To meet the needs of a large number of users online simultaneously, the platform is designed and deployed using cloud servers, reducing local storage pressure and enhancing the platform's operational fluency. Cloud server deployment offers several advantages: quick deployment and start-up of services, enabling rapid resource retrieval by users and meeting the fast online needs of the business; flexible resource scaling according to application demands; simplified maintenance procedures, reduced operational costs for businesses; high availability and disaster resilience of cloud servers ensure continuous and stable platform usage even in the event of hardware failures; cost-effective resource utilization with pay-per-use options allowing for adjustments based on actual business needs; and typically, cloud service providers' usage of clustered architectures and load-balancing mechanisms to ensure high service availability and data security.

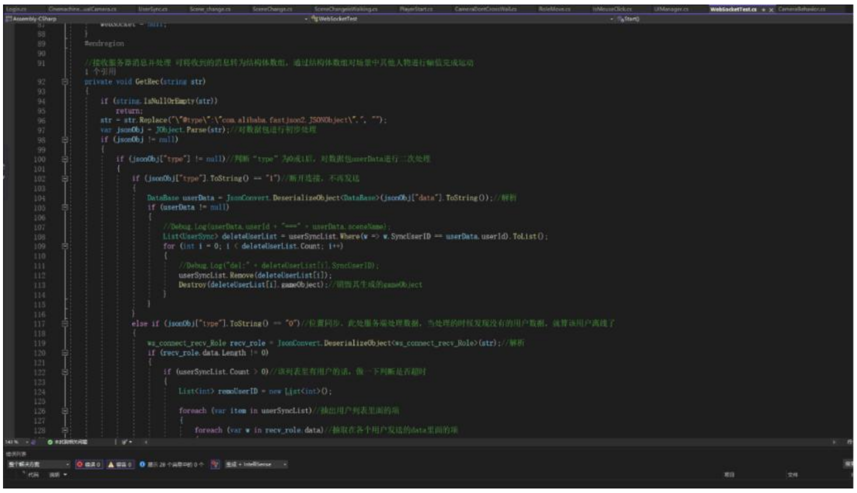

Figure 3. Diagram of the proprietary data transmission code based on WebSocket technology.

3.3. Database development and design

Database design based on data collection and embedding: Embedding is a data-collection technology primarily used to record and collect end-user behaviors. In applications, embedding can be understood as installing data collection points at critical operational nodes, similar to cameras, capturing user actions or events. When a user performs a specific action, such as entering a page or clicking a button, these points are automatically triggered, recording relevant data, which is then transmitted to the back end for analysis. Platform data, including embedded events, is stored in a MySQL database, accessible through Navi cat Premium for further data analysis.

4. Research practice

4.1. Instruments

This study primarily employs quasi-experimental design and survey methods. The research instruments include a creative thinking test, an evaluation of creative projects, and a learning style inventory. Statistical analysis methods were used to identify and verify the factors influencing creative thinking through collaborative scientific experiments in the educational metaverse.

(1) Creative thinking test

This study adopts the Torrance Test of Creative Thinking (TTCT), which includes three items of product improvement, unusual use and hypothesis conjecture and one item of graphic supplementary drawing [23], with a total of four questions (see Appendix 1). The students in the experimental group and the control group completed the questionnaire in the pre-test and post-test periods. According to the Torrance Test of Creative Thinking scoring manual, three science teachers with more than 10 years of teaching experience were organized to score each student on the three dimensions of the questionnaire flow: flexibility, flexibility and originality, and then the scores of the three teachers were averaged. The average score of each student in these three dimensions was obtained. The score values of fluency, flexibility, and originality of the questionnaire were obtained in the pre-experiment period, and the Cronbach's α coefficient values of each dimension were 0.879, 0.821, and 0.691, respectively, indicating good reliability and validity of the questionnaire.

(2) Creative project evaluation

At the end of each unit, students were required to complete a creative project evaluation. The tasks were related to the content of the unit. For example, after studying the Circuit unit, students were asked to use their knowledge of circuits to light up a model house in as many ways as possible using four batteries, two switches, several wires, and small bulbs. After the Light unit, students were tasked with improving the performance of a telescope based on what they had learned about optics. These tasks were project-based, encouraging students to creatively solve real-life problems within a set time frame. Both formative and summative assessments were conducted, evaluating students' design solutions and problem-solving processes. Evaluation participants included the students themselves, their group members, and the teacher, with scores assigned on a 100-point scale.

(3) Learning style inventory

The VARK learning style inventory, developed by Neil Fleming and Chris Mills in 1992, was used to assess learning styles. VARK stands for the four main sensory modalities: Visual, Aural, Read/Write, and Kinesthetic.

4.2. Participants

The participants in this study were 88 sixth-grade students from two parallel classes at a K–12 school in Binjiang District, Hangzhou. There were 44 students in both the experimental and control groups. Statistical analysis indicated no significant differences between the two groups in terms of gender distribution, age, or daily internet usage. Prior to the experiment, a pre-test on creative thinking and learning styles was administered to both groups. The pre-test results showed no significant differences between the two classes in creative thinking (p-fluency = 0.904, p-flexibility = 0.906, p-originality = 0.818), indicating that the two groups were homogeneous and suitable for experimental research.

In the experimental study, the experimental group carried out collaborative science learning in the educational metaverse virtual experiment platform, while the students in the control group used physical science equipment in the classroom to carry out collaborative science learning. Except for whether the metaverse platform was used for experimental exploration, discussion, and communication, the other teaching elements of the two classes were consistent, such as the teacher, teaching process, teaching content, and class time, so as to minimize the influence of irrelevant variables on the experimental research results.

Table 1. Basic information of the sample (*n* = 88).

	Frequency	Percentage
Gender		
Male	47	54.4%
Female	41	45.6%
Age		
11 years old	15	17.8%
12 years old	70	78.9%
13 years old	3	3.3%
Average daily Internet usage time		
＜1h	64	72.7%
1–2h	17	19.3%
2–3h	6	6.8%
3–4h	1	1.14%
＞ 6h	0	0.00%
Learning style		
Visual type	14	15.91%
Auditory type	22	25.00%
Reading and writing type	18	20.45%
Kinesthetic type	34	38.64%

4.3. Research procedures

This study spanned six weeks, encompassing a total of 12 class periods, as detailed in Figure 4. Students from each class were randomly divided into nine groups, with approximately five students per group. The experimental group conducted their learning within a metaverse virtual experiment platform. Throughout various stages of the teaching, all students in the experimental group were immersed in the metaverse virtual experiment settings, using virtual experimental materials to conduct inquiries, draw conclusions, and engage in discussions within the virtual discussion spaces of the educational metaverse. Conversely, the control group was situated in traditional classroom settings, using real experimental materials and tools to perform experiments, derive conclusions, and engage in face-to-face discussions. Both groups covered the same content during each class, were taught by the same teacher, and followed a collaborative experimental learning process structured into four phases: knowledge sharing, collaborative design, cooperative inquiry, and integration of results. This structure was designed to minimize the influence of extraneous variables on the experimental outcomes.

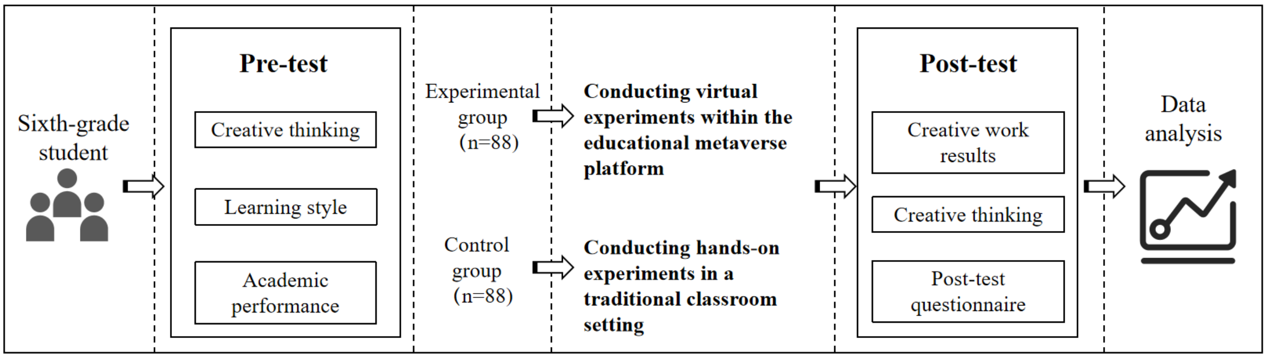

Figure 4. Research process flowchart.

Table 2. Teaching design of collaborative science experiments.

Unit name	Name of the experiment (expected class period)	Learning target	Creative task
《Circuit》	Switch (1 class period)	Understand the function of a switch, comprehend the positions of conductors and insulators when making a switch, and be able to create a switch to control a simple circuit.	Use circuit knowledge to simulate lighting up a household circuit in as many ways as possible.
	Series Circuit (1 class period)	Understand the definition and characteristics of a series circuit, and be able to light up a small bulb using a series connection.	
	Parallel Circuit (1 class period)	Understand the definition and characteristics of a parallel circuit, and be able to light up two or more small bulbs using a parallel connection.	
《Light》	Light Travels in a Straight Line (1 class period)	Through experiments, recognize that light travels in a straight line and will be partially or completely blocked when encountering obstacles.	Design and improve a telescope.
	Refraction of Light (1 class period)	Master the concept that light refracts when it enters water from the air, be able to observe the refraction phenomenon through experiments, and understand common refraction phenomena in daily life.	
	Reflection of Light (1 class period)	Understand that the change in the direction of light when it encounters mirrors and other objects is called reflection, learn the laws of light reflection through experiments, and list reflection phenomena in daily life.	
	Dispersion of Light (1 class period)	Observe the dispersion of light through a prism experiment, and understand the principles behind dispersion and the formation of rainbows.	

Combining the advantages of the educational metaverse and the characteristics of primary school science experiment teaching, this study carried out the collaborative science experiment teaching based on the educational metaverse in four stages: knowledge sharing–collaborative design–cooperative inquiry–outcome integration, including two units on circuits and two units on light (as shown in Table 2).

Knowledge-sharing stage

The knowledge-sharing stage is the preparation stage for the generation and development of creative thinking. Teachers need to arrange preview materials for students in advance and ensure that students are familiar with relevant knowledge before class. Through the preview, students can have a preliminary understanding of what they are about to learn, laying the foundation for subsequent class discussions and the development of creative thinking. In the pre-test, the teacher assesses the students' initial understanding and mastery through questionnaires, quizzes, or short answer questions, and then explains the task requirements and experimental precautions in detail to ensure that students pay attention to safety and details during learning and experiments. In this stage, both the experimental group and the control group were conducted in the classroom environment.

Collaborative-design stage

Students digested and absorbed the relevant data obtained, and defined the experiment tasks. This stage is a critical stage for students to think and create. Under the guidance of the teacher, students need to propose various possible experimental schemes and make experimental guesses. At the same time, teachers set up intra-group and inter-group competition mechanisms to help students expand and imagine through supportive tools and activities, such as SWOT analysis and 635 brainstorming, to stimulate their creativity. Students may encounter difficulties and doubts in the process of thinking and creating, and their thinking may become blurred or interrupted. In this case, teachers provide teaching scaffolding to help students solve problems, such as leading questions: "How do you guess…", "What is your reason…", "Can you give an example…", etc., in order to encourage students to re-clarify their thinking and express their ideas. In this stage, learning for students in the experimental group was carried out in the metaverse platform and guided by the virtual digital teacher. The control group took part in the classroom.

Cooperative-inquiry stage

The cooperative-inquiry stage is the key process of verifying the effectiveness of cooperative knowledge and demonstrating the hypothesis of the research experiment. First of all, teachers need to explain to students and guide them in how to summarize the experiment steps. This helps students to sort out their thinking and clearly understand the importance and operating points of each step. Next, students can conduct collaborative research according to the experimental steps and precautions provided by the teacher. In the process of inquiry, students can talk freely with other students, learn from others' opinions, and constantly revise and improve the model of the experimental scheme. When students are confused or need help, teachers give guidance and reminders, such as "Are there any better ideas?", "Do you think there's another way?", and “Let's wait.” This can inspire students to rethink and try new directions to continue their inquiry.

In this stage, learning for the experimental group is carried out in the metaverse platform, and students can discuss, share, question, and think in the discussion room of the virtual experiment platform. At the same time, they can also view the learning support such as the introduction of experimental equipment and the suggestion of experimental steps in the platform. After the experiment is completed, the students in the group will discuss and fill in the experiment record together and draw the conclusion or discovery of the experiment (as shown in Figure 5). The control group’s learning takes place in the classroom.

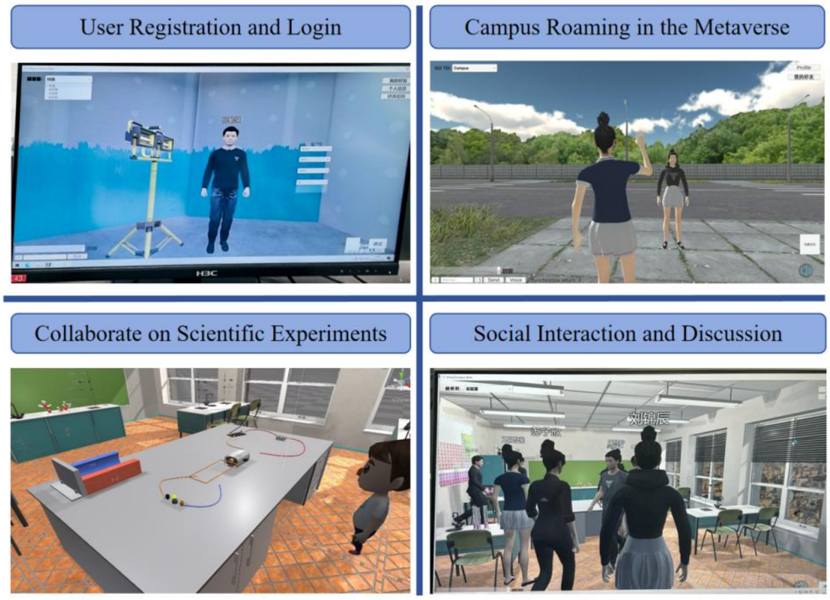

Figure 5. Educational metaverse-based collaborative science experiment teaching practice.

Outcome-integration stage

The result-integration stage is the key stage for students to condense their views and advance their thinking. In this stage, teachers organize students to report experimental results in the form of speeches and demonstrations. In the report, students need to explain in detail their findings in the experimental investigation, as well as the difficulties encountered in the process of the experiment and the solution. At the same time, students also need to reflect on what new knowledge and skills they have acquired in the learning process, what content they are still confused about, and the improvement strategies for subsequent learning. According to the assessment scale, teachers and students used self-evaluation, peer evaluation, and teacher comments to comprehensively evaluate the process and results of the group. In this stage, the experimental group conducted their discussion in the hall and discussion room of the metaverse platform, supporting multi-person interaction and voice and text communication. The control group's discussion took place in the classroom.

5. Data statistics and analysis

Reliability and validity testing of the questionnaire and analysis of variable correlations

This study was based on a hypothesized model for designing a survey questionnaire on collaborative scientific experiment learning, incorporating four latent variables: Online Environment Support Degree (OESD), Collaboration Quality (CQ), Immersion (IM), and Belongingness (BE). Each latent variable was assessed using three measurement items, making a total of 12 questions. Each item was rated using a Likert five-point scale ranging from "strongly disagree" to "strongly agree".

The measurement model was analyzed using SPSS 27.0 software for reliability and validity. The Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity indicated a KMO value of 0.85 (above 0.7) and significant Bartlett's test results ($P < 0.001$), demonstrating suitability for factor analysis. The factor loadings, Cronbach's alpha, composite reliability (CR), and average variance extracted (AVE) for each latent and observed variable are presented in Table 3. The results revealed all factor loadings greater than 0.6, Cronbach's alpha and composite reliability (CR) both above 0.7, and AVE all above 0.5, indicating good internal consistency and convergent validity.

Table 3. Factor analysis.

Latent variables	Observed variables	Factor loadings	Cronbach's alpha	CR	AVE
Quality of the collaboration	CQ1	0.743	0.905	0.940	0.840
	CQ2	0.719			
	CQ3	0.922			
Support level of the online environment	OESD1	0.849	0.708	0.839	0.635
	OESD2	0.626			
	OESD3	0.798			
Sense of immersion	IM1	0.816	0.768	0.866	0.684
	IM2	0.788			
	IM3	0.875			
Sense of belonging	BE1	0.857	0.837	0.902	0.754
	BE2	0.878			
	BE3	0.870			
Creativity	CT1	0.877	0.776	0.870	0.692
	CT2	0.811			
	CT3	0.693			

Table 4 displays the discriminant validity results within the measurement model, where the square root of the AVE for each latent variable on the diagonal is greater than the intercorrelations among the latent variables, confirming good discriminant validity.

Table 4. Means, standard deviations, and correlations.

	Mean (Means)	Standard Deviation (SD)	1	2	3	4	5
CQ	4.531	0.761	(0.917)				
OSED	4.759	0.381	0.925 **	(0.797)			
IM	4.575	0.515	0.885 **	0.895 **	(0.827)		
BE	4.705	0.532	0.918 **	0.915 **	0.862 **	(0.868)	
CT	4.683	0.170	0.869 **	0.860 **	0.865 **	0.867 **	(0.832)

** At the 0.01 level (two-tailed), the correlation is significant.

(Note: OESD is the support level of the online environment, CQ is the quality of the collaboration, CT is creativity, IM is the sense of immersion, BE is the sense of belonging.)

Testing of research hypotheses

The structural equation modeling (SEM) and testing of research hypotheses were conducted using Smart PLS 4.0 software, applying the PLS-SEM algorithm. The model's SRMR value was 0.096, below 0.1, indicating a good model fit. Using bootstrap analysis in Smart PLS 4.0 with a sample size of 2000, the following results were obtained (as shown in Table 5). Analysis showed that hypotheses H1, H2, H3, H5, H6, and H7 had T-values greater than 1.96 and P-values less than 0.05, and therefore, hypotheses 1, 2, 3, 5, 6, and 7 were supported. This means that the online environment support degree positively influences students' creative thinking and positively affects the quality of scientific experiment collaboration within the educational metaverse, and that the quality of scientific experiment collaboration in the educational metaverse positively influences students' creative thinking. Immersion and belongingness positively influence the quality of scientific experiment collaboration. The online environment support degree has a significant positive impact on belongingness. Hypothesis 4 was not supported, indicating that immersion does not significantly affect belongingness.

Table 5. Results of model hypothesis verification.

Hypothesis	**Path**	**Path Coefficient**	**Sample Mean**	**Standard Deviation**	**T**	**P**	**Is it valid?**
H1	OESD→CQ	0.267	0.249	0.109	2.459	0.014	Yes
H2	CQ→CT	0.506	0.549	0.155	3.256	0.001	Yes
H3	OESD→CT	0.388	0.348	0.159	2.439	0.015	Yes
H4	IM→BE	0.094	0.121	0.163	0.577	0.564	No
H5	IM→CQ	0.276	0.299	0.102	2.698	0.007	Yes
H6	BE→CQ	0.459	0.458	0.063	7.295	0.000	Yes
H7	OESD→BE	0.807	0.780	0.164	4.935	0.000	Yes

Mediating effect test

To explore the mechanisms by which collaborative scientific experiment learning on the metaverse platform impacts students' creative thinking, this study employed the complete bootstrap method in Smart PLS 4.0, setting the bootstrap sample size to 2000 and using the 2.5th and 97.5th percentile points as the 95% confidence interval for estimates. The research results indicated that the total effect of the pathway from the online environment support degree (OESD) to collaboration quality (CQ) to creative thinking (CT) was significant ($P < 0.001$), but neither the direct nor indirect effects were significant, with the confidence interval including zero. This suggests that there was no mediating effect, indicating that collaboration quality did not mediate the relationship between online environment support and creative thinking. However, the total effect of the pathway from OESD to belongingness (BE) to CQ was significant, with a significant indirect effect and a confidence interval not containing zero, showing that belongingness partially mediated the relationship between OESD and collaboration quality, accounting for 60.50% of the mediation effect.

Table 6. Mediating effect test.

Mediating Path	Effect Type	Effect Value	Proportion of Mediating Effect	Bias-Corrected Confidence Interval		P
				Lower Limit	Upper Limit	
OESD→CQ→CT	Total Effect	0.730	18.49%	0.374	0.852	0.000
	Direct Effect	0.388		-0.011	0.624	0.015
	Indirect Effect	0.135		0.017	0.245	0.021
OESD→BE→CQ	Total Effect	0.676	60.50%	0.415	0.822	0.000
	Direct Effect	0.267		0.025	0.461	0.014
	Indirect Effect	0.409		0.289	0.532	0.000

Moderating Effect Test

To understand whether learning styles play a moderating role between online learning support, collaboration quality, and creative thinking, the study treated learning style (LS) as a categorical variable and employed group regression analysis, dividing the sample into four groups based on learning style categories to regress creative thinking (CT) against online environment support (OESD). A significant difference in regression coefficients would indicate a significant moderating effect [24]. The analysis, conducted using the PROCESS plugin in SPSS, found that the model's R^2 value was 0.751. With different learning style values (1 = Visual, 2 = Auditory, 3 = Read/Write, 4 = Kinesthetic), the slopes of the independent variable on the dependent variable differed (2.56, -0.25, 0.35, -4.44, respectively), and significance was only observed when the learning style was visual ($P < 0.001$). This indicates that when students have a visual learning style, the impact of online environment support on creative thinking is significantly strengthened, confirming the existence of a moderating effect.

6. Research results and discussion

Relationship between collaborative science experiment learning and creative thinking

Regarding the effects, this study found that collaborative scientific experiments within the educational metaverse enhance students' levels of creative thinking, including fluency, flexibility, and originality. Compared to traditional collaborative science experiment teaching, there were no significant differences in the enhancement of students' creative thinking and creativity scores, indicating that both traditional and metaverse-based collaborative experiment teaching models effectively ensure students’ mastery of scientific knowledge and skills, and foster innovation in learning outcomes.

Influence mechanisms

The study identified that immersion, belongingness, and online environment support positively affect the quality of collaboration in scientific experiments conducted within the educational metaverse, and that online environment support significantly enhances belongingness. However, immersion did not significantly impact belongingness, possibly because students’ operations within the virtual science experiment platform are more distinct and continuous. The ability to manipulate objects in the environment, such as opening doors or moving experimental materials, and actively control their interaction with the environment to observe and listen creates a highly immersive environment that encourages some students to explore and complete tasks independently, thereby reducing their interaction with peers and sense of team belongingness.

Mediating role of belongingness

In the context of the educational metaverse, belongingness partially mediates the impact of online environment support on collaboration quality. This suggests that the metaverse's rich learning resources, accessible experimental materials, and effective content navigation enhance students' sense of belongingness, benefiting their perception of individual and group connections and emotional support. These factors collectively improve the quality of group collaboration and stimulate students' innovation, enabling them to apply theoretical knowledge in a focused and relaxed state.

Moderating role of learning styles

The study discovered that learning styles moderate the impact of online environment support on creative thinking, with visually oriented learners showing more significant enhancements in creative thinking compared to those oriented toward auditory and read/write styles. This may be due to the rich visual stimuli in the educational metaverse, which more strongly impact visual learners, aiding their understanding and creativity.

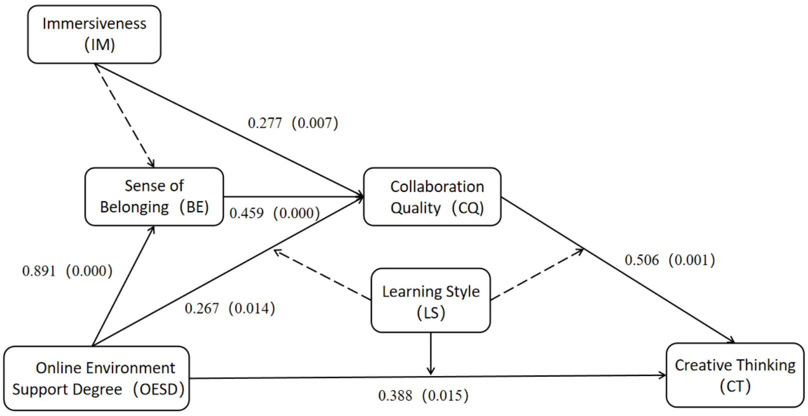

Figure 6. Mechanism model of the impact of metaverse-based collaborative scientific experiments on creative thinking (revised).

7. Research implications and future prospects

Reconstructing the learning environment: Using highly immersive situations to promote collaborative quality

Learning must be embedded in the actual situation, so that students can experience the complex process of thinking image construction from "representation" to "image", so as to make learning meaningful. At present, the common problem in various educational applications of virtual reality technology is that learners have difficulty perceiving the presence and assistance of peers in their environment, and this sense of loneliness will reduce the quality of cooperation and learning effect of students. The reconstruction of the learning environment based on the educational metaverse should pay attention to the sociality of the learning environment and create a group learning atmosphere with a high sense of presence and belonging.

Therefore, in education and teaching, we should promote the application of the education metaverse, use digital twin technology to generate a mirror of the real world, break the barriers between traditional classrooms, schools, and regions, integrate high-quality teaching institutions and social public resources, establish a digital innovation ecosystem, and provide students with highly immersive knowledge application and problem situations to help students establish the relationship between image and concept, knowledge, cognition, etc., and form the image of rational intuition in a higher form. For example, when teaching the "Universe" unit in the second volume of sixth grade, teachers can organize student groups to cooperate in virtual space travel, land on Mars to carry out geological exploration and other tasks, observe the changes of the moon phase in the metaverse space, or observe astronomical phenomena such as solar and lunar eclipses, so that students can understand the internal connection of things in the virtual world where reality is integrated and intelligence is open.

Reconstructing learning resources: Using targeted scaffolds to promote practical inquiry

With the rapid development of technology, the educational metaverse has built an immersive and interactive learning environment for us, and the introduction of learning scaffolding can further enhance students' learning experience and effect. These scaffolds are designed to be highly targeted and can be flexibly adjusted according to the individual needs and learning progress of students. By providing a clear learning path, specific problem-solving strategies, and real-time feedback mechanisms, learning scaffolding helps students better understand and master knowledge and improve their self-directed learning ability. Educational researchers and practitioners should design diversified and personalized learning scaffolds for learners, which can include virtual experiment guidance, simulated operation drills, question-answering prompts, and other forms. For example, in the educational metaverse, teachers can offer a variety of experimental projects and scenarios to meet the needs of students with different learning styles. For example, for students who like hands-on operation, you can design some physical experiment scenes; and for students who enjoy analog reasoning and problem solving, relevant virtual experiment simulations are available. The virtual laboratory in the education metaverse can also customize learning resources according to the learning style of students. For the different learning preferences of visual students and auditory students, we can provide a variety of learning materials, including but not limited to text materials, chart analysis, audio explanations, and video tutorials, to meet their respective learning needs. This approach is designed to ensure that each student finds the way that works best for them in the learning process, thereby improving learning outcomes.

In addition, attention should be paid to the interaction and feedback mechanism of the scaffold. The learning scaffold needs to be able to provide timely feedback and guidance according to students' operations and problems, helping them correct mistakes and deepen their understanding. At the same time, teachers can also introduce intelligent assistants or learning partners and other roles, so that students can feel the fun and challenge of learning through the interaction with the scaffold. Of course, all primary and secondary schools also need to pay attention to strengthening the training of teachers' educational technology literacy. Teachers are important participants in the design of learning scaffolding, and they should provide valuable suggestions for the design of scaffolding according to their teaching experience and professional knowledge, and then the technical personnel will transform these suggestions into practical and feasible learning scaffolding.

Reconstructing learning mode: Using deep collaborative interaction to achieve incremental thinking

In the educational metaverse, students can transcend the limitations of time and space and deeply collaborate with partners from different backgrounds and perspectives. This collaborative learning approach not only broadens students' knowledge horizons, but also stimulates their desire to explore the unknown. Learners can form interdisciplinary and transregional learning groups in the metaverse, and carry out in-depth communication and cooperation around common learning goals or project tasks. This collaborative learning model encourages students to think about problems from different perspectives, inspire each other, and solve problems together. By working with others, students not only learn new knowledge and skills, but also learn to listen, understand, and respect the views of others, developing their teamwork and social skills. At the same time, in the process of collaborative learning, students can constantly put forward new questions and ideas, and stimulate each other's questioning spirit and innovative consciousness. Embodied practice allows students to experience and operate in the metaverse with their own hands. By participating in the practical process, students can understand knowledge more deeply and face challenges more confidently. Embodied practice is an important means to cultivate students' high-order thinking quality in the educational metaverse. Through virtual experiments and simulation operations in the metaverse, students can personally participate in practical activities and experience the application process of knowledge. This hands-on approach to learning enables students to gain a deeper understanding of the nature and content of knowledge, while also developing their creativity and problem-solving skills.

In summary, this study comprehensively investigated the impact of metaverse-based collaborative scientific experiment learning on creative thinking and its mechanisms, proposing corresponding teaching improvement strategies. However, some limitations need addressing: In terms of content, due to constraints such as time and effort, the study did not explore other factors in collaborative scientific learning that might affect collaboration quality and creative thinking, potentially omitting some influencing factors. In terms of methodology, although quasi-experiments and surveys were used to explore the effects on creative thinking, these methods might not dynamically depict the progression of students' creative thinking. Therefore, future research could include interviews and expand the sample size to make the conclusions more convincing.

Author contributions

Xin Zhang: Conceptualization, Investigation, Data Collection and Curation, Result Analysis, Writing Original Draft; Longzhu Yi, Huikuan Chen, Jiayu Qian: Platform Development and Design, Review Original Draft; Xuesong Zhai: Methodology Creation, Resources, Funding Acquisition, Supervision, Writing—review and editing. All authors have read and approved the final version of the manuscript for publication.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors assert that they do not have any conflicts of interest.

Ethics declaration

The author declared that no ethics approval is required for the study.

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Appendix I: Collaborative Science Experiment Learning Survey Questionnaire

Survey Questionnaire

Dear students:

Hello! First of all, thank you very much for participating in this survey. This survey aims to understand your overall feelings about this virtual science experiment. This questionnaire does not involve personal privacy, please feel free to answer. We solemnly promise: This survey is for academic reference only and will never be used for any other purpose! We sincerely thank you for your strong cooperation!

Zhejiang University College of Education

Please evaluate each statement below based on your true situation (check the corresponding box).

Serial number	Item	Degree of agreement with the item				
		1	2	3	4	5
		Completely disagree	Disagree	Neutral	Agree	Completely agree
1	**Group members have relatively clear task divisions and systematically complete tasks.**	□	□	□	□	□
2	**Group members interact with each other in a high-quality manner, respecting and encouraging one another to work together and contribute their ideas.**	□	□	□	□	□
3	**Group members maintain a good mutual understanding of the problems that need to be solved.**	□	□	□	□	□
4	**The operations within the metaverse virtual science experiment platform are relatively obvious and continuous.**	□	□	□	□	□
5	**Within the metaverse virtual science experiment platform, I can change objects in the environment, such as opening doors, moving experimental materials, etc.**	□	□	□	□	□
6	**In the metaverse virtual science experiment platform, I can actively control my relationship with the environment, actively look at things, and listen to sounds.**	□	□	□	□	□

Serial number	Item	Degree of agreement with the item				
		1	2	3	4	5
		Completely disagree	Disagree	Neutral	Agree	Completely agree
7	**I feel that using the metaverse virtual science experiment platform has facilitated communication between my classmates and me.**	□	□	□	□	□
8	**I find it easier to become friends with those who use the metaverse virtual science experiment platform together.**	□	□	□	□	□
9	**The use of the metaverse virtual science experiment platform has made me more interested in this subject.**	□	□	□	□	□
10	**The content on the platform is well-organized and the navigation is clear, meeting my learning needs.**	□	□	□	□	□
11	**I can relatively easily find learning materials from the metaverse virtual science experiment platform.**	□	□	□	□	□
12	**The introduction of experimental materials and instructional videos provided on the platform has been very helpful to me.**	□	□	□	□	□

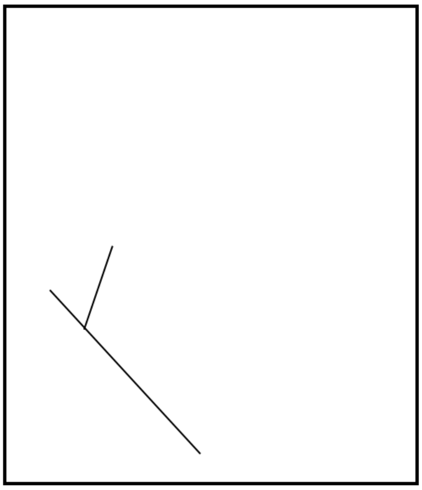
Appendix II: Creativity Test

Tests of Creative Thinking

During the completion of this test, please try to come up with as many ideas as possible, strive to think of ideas that others have not thought of, and provide details for your ideas to make them complete. If you have finished answering within the allotted time, you may continue to add details to your ideas or sit quietly. Please do not proceed to the next question without the teacher's permission.

1. What might happen if people could blink their eyes to transport themselves from one place to another? (Time: 5 minutes)

2. Complete the incomplete drawing below. Then use your completed drawing to tell a complete story and give your story a title. (Time: 10 minutes)



3. Can you think of how many uses a paperclip has? (Time: 3 minutes)

4. Puzzle: A magician claims he can throw a ping pong ball and then make it suddenly stop and return to his hand along the same path. He does not use any objects to bounce it back, nor does he tie it with a string. How is this possible? (Time: 2 minutes)