APPLYING MERRILL'S FIRST PRINCIPLES OF INSTRUCTION IN VIRTUAL REALITY-BASED ASTRONOMY EDUCATION: A CASE STUDY OF "THE SOLAR SYSTEM'S MYSTERIES"

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Abstract: The study combines Merrill's First Principles of Instruction (task orientation, activation, demonstration, application, and integration) with the application of VR in the astronomy module of primary school science courses to construct an article specifically exploring the teaching design and practical effects of VR in science education. This study investigates the factors that influence primary school students' science learning in a Chinese primary school, aiming to establish a collaborative science learning environment for these students. This study aims to improve the science learning environment for primary school students, enabling them to engage in collaborative learning during the science learning process and achieve high-quality learning outcomes. This study is based on TICOL theory and Merrill's First Principles of Instruction. It employs quantitative research methods, with structural equation modeling (PLS-SEM) as the primary analytical tool. The study used purposive sampling, selecting an elementary school equipped with VR teaching resources and taught by teachers with relevant teaching experience as the research site. The study participants were students in grades four to six. A total of 433 paper questionnaires were collected, and after data screening, cleaning, and common method bias (CMB) processing, 376 valid questionnaires were obtained for deductive data analysis. The results indicate that immersive virtual reality (IVR) courses effectively enhance students' affective learning outcomes through interactivity, with Merrill's First Principles of Instruction and collaborative learning structures playing a significant role in this process. In conclusion, learners can benefit from immersive VR science courses, particularly in contexts with good interactive design and instructional guidance, where emotional engagement and learning outcomes can be significantly enhanced.

Keywords: Merrill's First Principles of Instruction, primary school, science education, PLS-SEM.

INTRODUCTION

In this paper, we have selected content for the elementary school science curriculum using teaching resources from the China Digital Science and Technology Museum, which are publicly available for educational use. The platform's terms of use integrate these resources into the curriculum, allowing them to be freely used for educational purposes without additional authorization. IVR classes were held once a week for 6 weeks; each class was 40 minutes long, and VR use was limited to 10-15 minutes per class.

Merrill's First Principles of Instruction, which is shown in Figure 2, offer a comprehensive framework for effective teaching and learning. These principles include: (1) Problem-Centered Learning, which promotes engagement through real-world problem-solving activities; (2) Activation of prior knowledge, enhancing the foundation for new learning; (3) Demonstration of new knowledge to the learner; (4) Application of new knowledge by the learner; and (5) Integration of new knowledge into the learner's world (Merrill, 2002). These principles are highly applicable to immersive virtual reality (VR) environments used in education, such as those facilitating interactive lessons or collaborative problem-solving tasks in subjects like science or mathematics. For instance, immersive VR can provide realistic simulations for experiential learning, where students reflect on their experiences to enhance motivation and achievement (Makransky & Petersen, 2019). Collaborative instructional strategies can also be effectively implemented in VR settings, where students engage in group tasks within shared virtual environments, promoting active learning and more profound understanding through social interaction (Pellas et al., 2021). Integrating techniques such as educational games, virtual field trips, observation, roleplay, and simulation within VR further enhances the learning experience by making it interactive, engaging, and reflective of real-world scenarios. This approach aligns with Merrill's principles by ensuring that learning is contextual, active, and collaborative, enhancing educational outcomes. Deng and Xu (2021, 2024) explored the application of VR technology in primary school education. Since the selected public school did not have internet access in the classrooms, and although the multimedia room was equipped with internet and computers, renting and applying for its use was required each time, the researcher eventually purchased two portable Wi-Fi devices online. Each portable Wi-Fi device can connect to eight devices. Since each public elementary school class has approximately 50 students, the students were divided into groups of four. The researcher rented 13 VR devices for teaching and research purposes and thus decided to purchase two portable Wi-Fi devices to meet the internet requirements. The following four lessons are designed based on Merrill's (2002) principles and Deng and Xu's (2021, 2024) research.

IMMERSIVE VR INTEGRATION IN PRIMARY SCIENCE EDUCATION

This study is guided by two core theoretical foundations: Immersive Cooperative Learning Theory (TICOL) and Merrill's First Teaching Principle. TICOL emphasizes the psychological mechanisms and social interactions of learners in an immersive environment. At the same time, Merrill's Teaching Principle serves as a structured instructional design framework, guiding the entire process of teaching activities from problem-based introduction to integration and transfer.

Merrill (2002) proposed that effective teaching should follow a five-stage principle: problem-centered learning, activating prior knowledge, demonstrating new knowledge, practical application, and integration and transfer (see Figure 2). TICOL, on the other hand, emphasizes the role of social and physical Presence in immersive virtual environments in promoting learning motivation, cooperative interaction, and cognitive engagement.

In this study's IVR teaching design, Merrill's five-stage structure assisted in designing the teaching activity process. At the same time, TICOL theory enhanced learners' immersion and interactive experience through VR. These two approaches promote students' emotional engagement and cognitive construction in the virtual environment.

The core objective of this study is to explore how Immersive Virtual Reality (IVR) can enhance Collaborative Learning experiences by increasing learners' Presence. The four psychological factors of TICOL, Social Presence, and Physical Presence, are highly relevant to this study because they directly affect learners' quality of interaction, collaborative experience, and immersion in a virtual learning environment. Social Presence refers to the ability of learners to perceive and interact with others in a VR environment. In contrast, Physical Presence reflects whether or not learners feel that they are indeed 'in' the virtual environment. Enhancing learners' sense of Presence has increased their motivation to collaborate in VR classrooms (Makransky & Mayer, 2022).

In contrast, Body Ownership and Agency primarily concern an individual's sense of identity and control over a virtual body. They are less directly related to Collaborative Learning. Body Ownership emphasizes whether the learner sees the virtual character as part of them. At the same time, Agency refers to whether the learner feels free to control their behavior in the virtual environment. These two factors are typically associated with immersive gaming experiences, motion simulation, or physical interaction rather than VR instructional environments centered on collaborative learning (Slater & Sanchez-Vives, 2016). Therefore, this study focuses on Presence in TICOL theory, excluding body ownership and autonomy as research variables to ensure a focused scope and to explore more precisely how VR classrooms can facilitate collaborative learning through enhanced Presence.

Figure 1.
TICOL Framework (Makransky & Petersen, 2023)

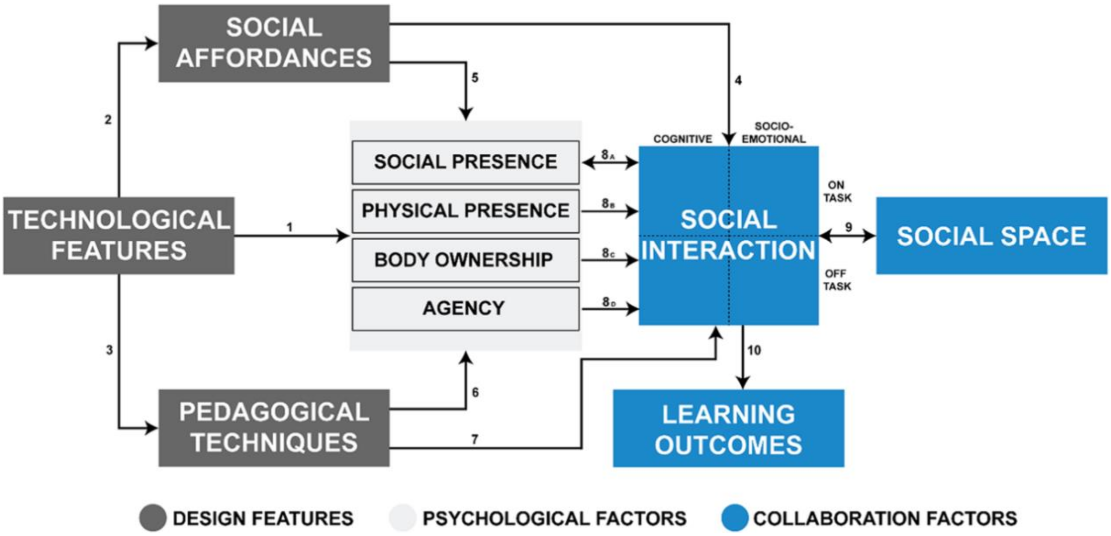
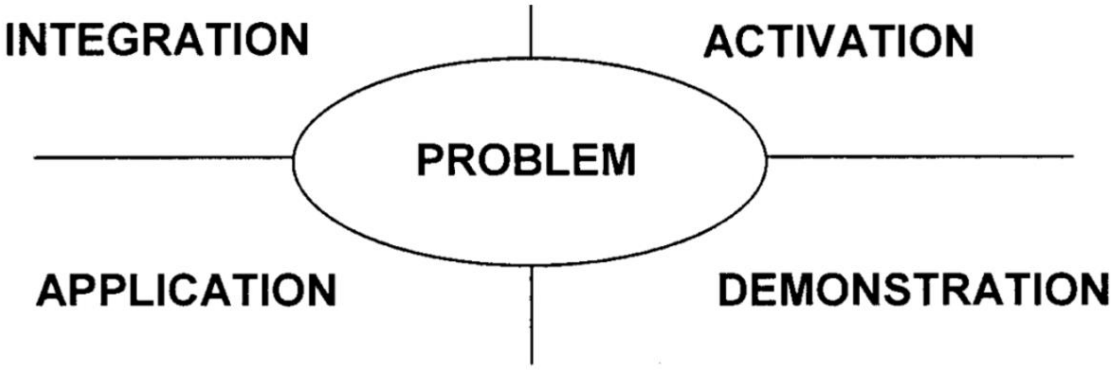


Figure 2.
Merrill's First Principles of Instruction (Merrill, 2002)



METHOD

This study employs a quantitative research method, specifically structural equation modeling, to explore the effects of IVR on students in cooperative learning activities in primary school science. The study employs a single-case study design, selecting an elementary school with suitable infrastructure for introducing VR teaching resources as the research setting to gain a deeper understanding of the interactive processes between students, teaching content, and immersive technology in a specific teaching context (Stake, 1995; Yin, 2018). Based on TICOL and Merrill's First Principles of Instruction, the conceptual framework and an a priori model are presented in the figure below.

This study is based on the TICOL theory and conceptual model, as shown in Figure 3, aiming to explore the impact of virtual presence and interaction on students' affective learning outcomes in an immersive virtual reality (IVR) learning environment. Based on this, the following research question is proposed:

RQ: How do virtual presence and interaction influence students' affective learning outcomes in an IVR environment?

To address the above research question, this study proposes the following hypotheses: virtual presence, interaction, and affective learning outcomes are higher-order models, and the sub-dimensions under each higher-order variable are shown in Figure 4.

H1: Virtual presence significantly positively influences student interaction in immersive virtual reality (IVR) learning environments.
H2: Virtual presence has a significant positive influence on affective learning outcomes.
H3: Interaction has a significant positive influence on affective learning outcomes.

Figure 3.
Conceptual Framework

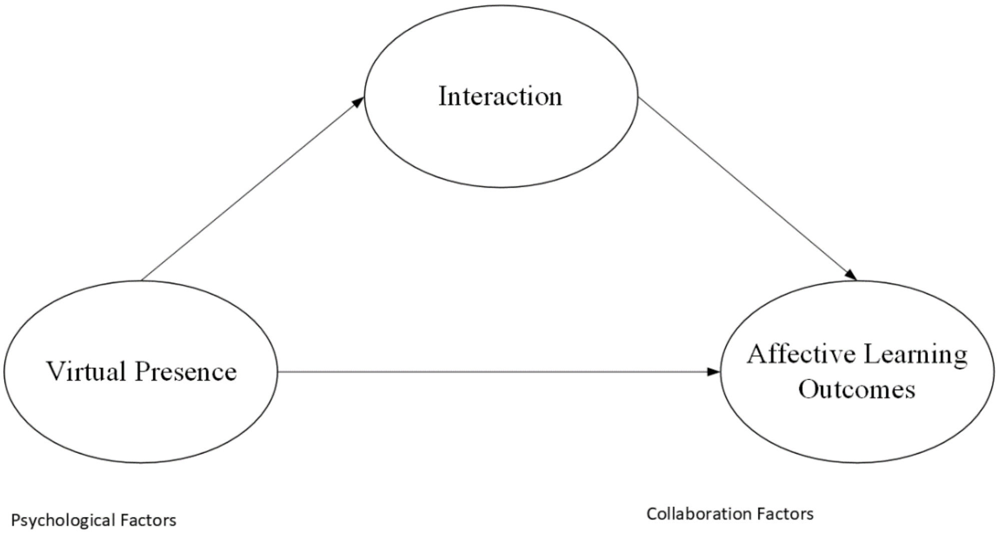
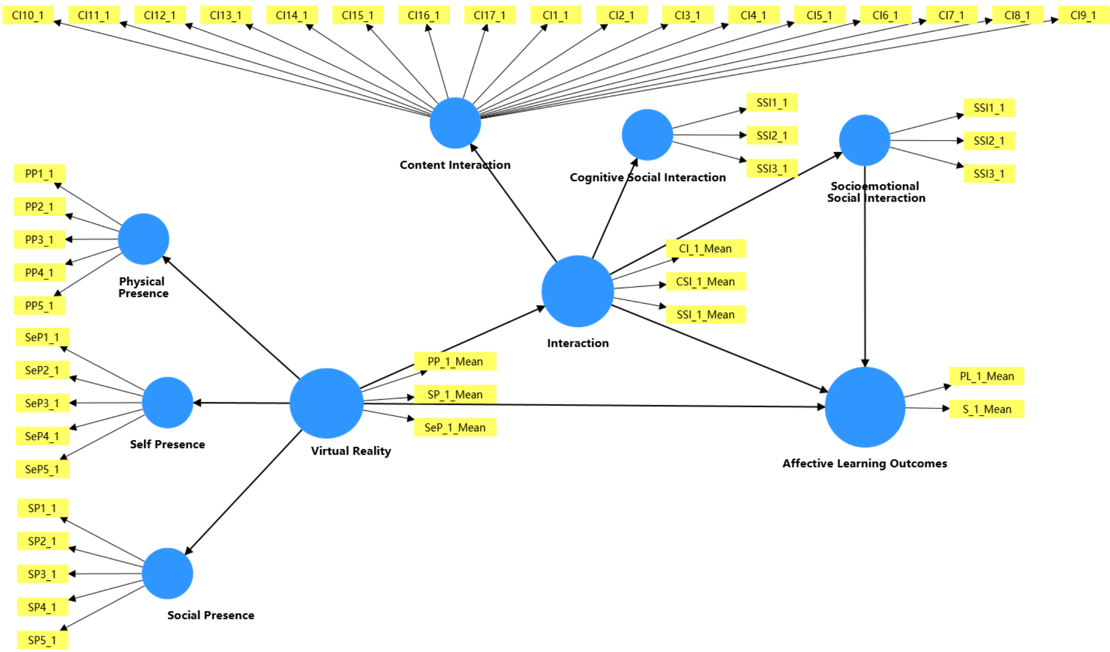


Figure 4.
A priori Model



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Data Analysis

A detailed introduction to Merrill's First Principles and their application in immersive learning environments. This study applied the PLS research method, with grades 4-6 primary school students in Fujian Province as the research subjects. Data was collected through paper questionnaires, manually entered by researchers, and analyzed using the PLS-SEM data analysis method.

IVR-based Science Lessons. Collaborative instructional strategies can also be effectively implemented in VR settings, where students engage in group tasks within shared virtual environments, promoting active learning and more profound understanding through social interaction (Pellas et al., 2021). Integrating techniques like educational games, virtual field trips, observation, role-play, and simulation within VR further enhances the learning experience by making it interactive, engaging, and reflective of real-world scenarios. This approach aligns with Merrill's principles by ensuring that learning is contextual, active, and collaborative, enhancing educational outcomes. Deng and Xu (2021, 2024) explored the application of VR technology in primary school education. Since the selected public school did not have internet access in the classrooms, and although the multimedia room was equipped with internet and computers, renting and applying for its use was required each time, the researcher eventually purchased two portable Wi-Fi devices online. Each portable Wi-Fi device can connect to eight devices. Since each public elementary school class has approximately 50 students, the students were divided into groups of four. The researcher rented 13 VR devices for teaching and research purposes and thus decided to purchase two portable Wi-Fi devices to meet the internet requirements. The following are four lessons designed based on Merrill's principles and Deng and Xu's (2021, 2024) research.

The User Interface and VR Platforms. Briefly describe the interfaces, functions, and interaction features of 'Gazing at the Stars' and 'GKK Metaverse.' **Error! Reference source not found.** shows students collaborating and exploring the theme of the solar system in an immersive environment, demonstrating the organic integration of virtual interaction and task-oriented learning.

Figure 5.
Screenshots Of Students Collaborative Learning in GKK Platform

Structure of the IVR-Based Course. A brief overview of the course based on primary school science curriculum standards, combined with a VR design course structure (4 lessons) and listing of VR resources and activity types.

VR resources used (360° videos, interactive games, etc.).

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Table 1.
Course List

The Solar System's Mysteries: A Course Designed According to Merrill's Principles				
NO.	**lesson**	**VR type**	**Source**	**Applicable grades**
1	Lunar Landing Thematic Inquiry Activities	360-degree video	China Digital Science and Technology Museum www.cdstm.cn and Gazing at the Stars Application	4-6
2	Exploratory activities on the theme of understanding the Earth-Moon system			
3	Practical activities on the theme of I model the solar system			
4	Collaborative Learning	Interactive games	gkk Metaverse Application	

Note. Each class period lasts 40 minutes. Use the equipment for 10-15 minutes per class.

Development of the Instructional Design. This section is the core content of the main text, comprising five subsections that systematically outline the design philosophy of the 'Mysteries of the Solar System' course and how it aligns with Merrill's instructional principles. The course is structured around multiple thematic modules (such as 'Lunar Landing' and 'Earth-Moon System'), with each module designed by the five teaching principles: Problem-Centered Learning, Activation of Prior Knowledge, Demonstration of New Knowledge, Application of New Knowledge, and Integration of New Knowledge. Taking the 'Exploratory Activity Theme: Exploring the Solar System' as an example, this section explains how to implement Merrill's five principles in actual teaching to enhance students' learning outcomes and cognitive construction in virtual scenarios.

This summary uses the lesson 'Exploratory Activities Theme: Traveling to the Solar System' as an example of instructional design, primarily focusing on the five principles of Merrill's Principles: Problem-Centered Learning, Activation of Prior Knowledge, Demonstration of New Knowledge, Application of New Knowledge, and Integration of New Knowledge.

Exploratory Activities Theme: Traveling to the Solar System (English)

Teaching Objectives (VR Teaching Objectives):

1. Learn and understand the composition of the solar system, including the Sun, planets, dwarf planets, and small celestial bodies in their orbits.
2. Enhance the understanding of the solar system through information collection, the use of virtual reality resources, and real-world problem-solving.
3. Develop students' social interaction skills and teamwork through interactive tasks in the virtual world.

Teaching Focus and Difficulties:

- **Teaching Focus:** The composition of the solar system and its orbital paths.
- **Teaching Difficulty:** Building a proportional model of the solar system based on the distance and size of the planets.

Teaching Preparation:

- **Teacher Preparation:** Solar system pictures, multimedia resources, planetary data tables, clay, ruler.

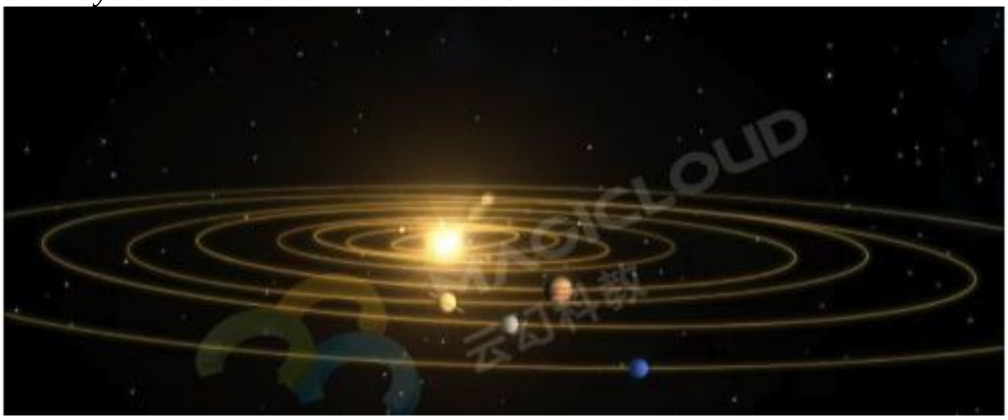
- **Student Preparation:** Collect relevant information about the solar system before class and review existing knowledge about celestial bodies.

1. Problem-Centered Learning

Guiding Questions:

- *Initial discussion:* "What is the solar system? What do you already know about the planets and their distances from the Sun?"
- *Main task:* "Can you design a proportional model of the solar system that helps other students understand the sizes and arrangement of the planets?"

Figure 4.
Solar System model used in immersive VR science course



Source: Yunhuan Technology

VR Task:

- Students will use **"Gazing at the Stars"** to observe the distances between planets and learn about their characteristics. They should focus on details such as the planets' distance from the Sun and their relative sizes to the others.
- As students explore, they will be prompted to take notes on the planets' characteristics and start thinking about how this information can be represented in a physical model.
- **Challenge question:** "How would you use what you observed in the VR environment to represent the solar system proportionally in a classroom model?"

Objective: This real-world challenge allows students to focus on problem-solving while providing them with immersive VR experiences to observe planetary distances and sizes in a realistic context.

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2. Activation of Prior Knowledge

Questioning Session:

- *Initial questions:* "Who was the first scientist to propose the heliocentric theory? What do you know about the heliocentric model?"
- *Follow-up question:* "What celestial bodies orbit the Sun besides Earth?"

VR Resources:

- Students will use **"Gazing at the Stars"** to explore how planets move in their orbits and observe the relative distances between planets. They will discuss these findings in small groups, using their prior knowledge to connect what they already know with the new observations from VR.
- As they explore, they can also compare their findings with textbook information.

Objective: This phase ensures that students activate their prior knowledge of the solar system and heliocentric theory, allowing them to build on this foundation while integrating new observations from VR.

3. Demonstration of New Knowledge

VR Demonstration Session:

- The teacher will use **"National Smart Education Platform – VR resources"** to demonstrate the solar system in motion. This includes showing the planets' relative positions, their orbits around the Sun, and their distances from one another.
- **Detailed explanations:** The teacher will explain each planet's characteristics, i.e., size, distance from the Sun, and unique features like rings (e.g., Saturn) or extreme temperatures (e.g., Mercury).

Earth structure：

https://cdn.resources.cdstm.cn/gamefile/VR/39_earth/index.html

Solar system wanderings：

https://cdn.resources.cdstm.cn/gamefile/VR/12_SolarSystemVoyage/index.html

- The teacher will also highlight the difference between dwarf planets and regular planets, such as Pluto's reclassification.

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Exploration in VR:

- *Task:* After the demonstration, students will have time to explore specific planets using **"Gazing at the Stars"** and investigate additional details (e.g., equatorial diameters, orbital periods).
- *Key takeaway:* "What features of the planets did you find surprising or different from what you previously thought?"

Objective: Students gain a deeper understanding of the solar system through both guided teacher demonstration and their own interactive exploration of the planets' features and movements in a virtual environment.

4. Application of New Knowledge

Modeling Session:

- *Hands-on activity:* "Now that we have explored the solar system in VR, let's use clay and other materials to build a proportional model of the solar system."
- **Guided task:** Students will refer to the data they observed in VR (planetary distances and sizes) to model the planets to scale. They will use rulers to measure distances between their clay models and arrange them according to the solar system's layout.

Classroom Discussion:

- "What data do we need to ensure our model is accurate?" (Students will refer to the planetary data tables.)
- "How can we adjust our clay model based on the information we've gathered from VR?" (Adjustments might involve changing the size of certain planets or increasing the distance between them.)

Social Interaction:

- **GKK Metaverse:** Students will enter the **"GKK Metaverse"** to collaborate with peers as avatars, discussing their solar system models in real-time and working together to refine their planetary models.
- **Cognitive Social Interaction:** During these group tasks, students will share knowledge, discuss challenges, and learn from their observations, fostering cognitive development through social engagement.
- **Socioemotional Social Interaction:** As students work in groups, they will also support themselves emotionally, encouraging teamwork and communication.

Objective: Students apply their knowledge from VR and demonstrate it by building a physical model, all while collaborating in the virtual metaverse to enhance both cognitive and social-emotional learning.

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5. Integration of New Knowledge

Summary and Reflection:

- *Group reflection:* "In the process of building the solar system model, what did you learn that was different from what you observed through 'Gazing at the Stars' and the National Smart Education Platform?"
- *Personal reflection:* "After interacting with your peers in the 'GKK Metaverse,' how did teamwork and social interaction help you understand the solar system better?"

Post-Class Task:

- "Use today's lessons to design a problem scenario that will help others understand the solar system's structure. Share your findings and insights in the **'GKK Metaverse'** and present them to your peers in the next class."

Objective: Through reflection and shared problem-solving, students integrate their new knowledge into their real-world understanding, solidifying what they've learned about the solar system and enhancing their communication skills through social interaction in the virtual world.

Implementation of the IVR Course. Describe the operational details of teaching equipment, network configuration, group teaching, course cycle arrangements, teacher roles, etc.

FINDINGS

This study collected 433 questionnaires from a primary school in Fujian Province, China (grades 4–6). After rigorous data screening and cleaning, incomplete questionnaires, i.e., obvious response patterns, missing values exceeding 10%, were excluded. Ultimately, 376 valid questionnaires were retained for subsequent PLS-SEM analysis (Hair et al., 2017; Makransky & Lilleholt, 2018). To address common method bias (CMB), the complete multicollinearity assessment method in SmartPLS was employed. The results showed that the VIF values for all variables were below 3.3, indicating no significant bias (Kock, 2015). Additionally, following the questionnaire processing practices of Aldalalah et al. (2019) in augmented reality education research, the data processing procedures were ensured to align with cutting-edge empirical research standards. The aforementioned preprocessing steps ensured data integrity and the validity of the structural model analysis.

A measurement model analysis was conducted on the a priori model in Figure 4, and the composite reliability (CR) of all constructs was greater than 0.7, indicating good internal consistency (Hair et al., 2021). Most average variance extracted (AVE) values reached 0.5, with a few (e.g., Physical Presence = 0.498) slightly lower but still acceptable given the CR thresholds (Fornell & Larcker, 1981). Structural model analysis was conducted using the Bootstrapping method to test the significance of path coefficients (Hair et al., 2021). As shown in Table 2, all paths were significant ($p < .05$), including one negative path. Given its statistical significance and theoretical interpretability, this study did not adjust the model and retained the original theoretical structure.

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Table 2.
Results of Hypotheses Testing Based on Path Coefficients, t-values, and p-values

	Path Coefficients	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
Interaction -> Affective Learning Outcomes	0.833	0.832	0.118	7.032	0
Interaction -> Cognitive Social Interaction	0.879	0.879	0.012	76.175	0
Interaction -> Content Interaction	0.856	0.856	0.019	45.475	0
Interaction -> Socioemotional _Social Interaction	0.88	0.88	0.012	76.434	0
Socioemotional _Social Interaction -> Affective Learning Outcomes	-0.304	-0.304	0.106	2.856	0.004
Virtual Reality -> Affective Learning Outcomes	0.202	0.203	0.067	3.002	0.003
Virtual Reality -> Interaction	0.705	0.704	0.036	19.723	0
Virtual Reality -> Physical _Presence	0.858	0.859	0.019	44.284	0
Virtual Reality -> Self Presence	0.878	0.879	0.012	71.549	0
Virtual Reality -> Social Presence	0.772	0.772	0.034	23.021	0

Although most paths showed a significant positive relationship, the path coefficient for the 'social-emotional interaction → affective learning outcomes' path was negative (β = -0.304). This result is inconsistent with expectations but may indicate that in specific immersive environments, excessive social-emotional burdens or ineffective interactions may weaken learning motivation and engagement (Makransky & Lilleholt, 2018). Similar studies have also found that overly strong social-emotional factors can sometimes distract attention and reduce learning outcomes in task-oriented learning (Lim & Richardson, 2021).

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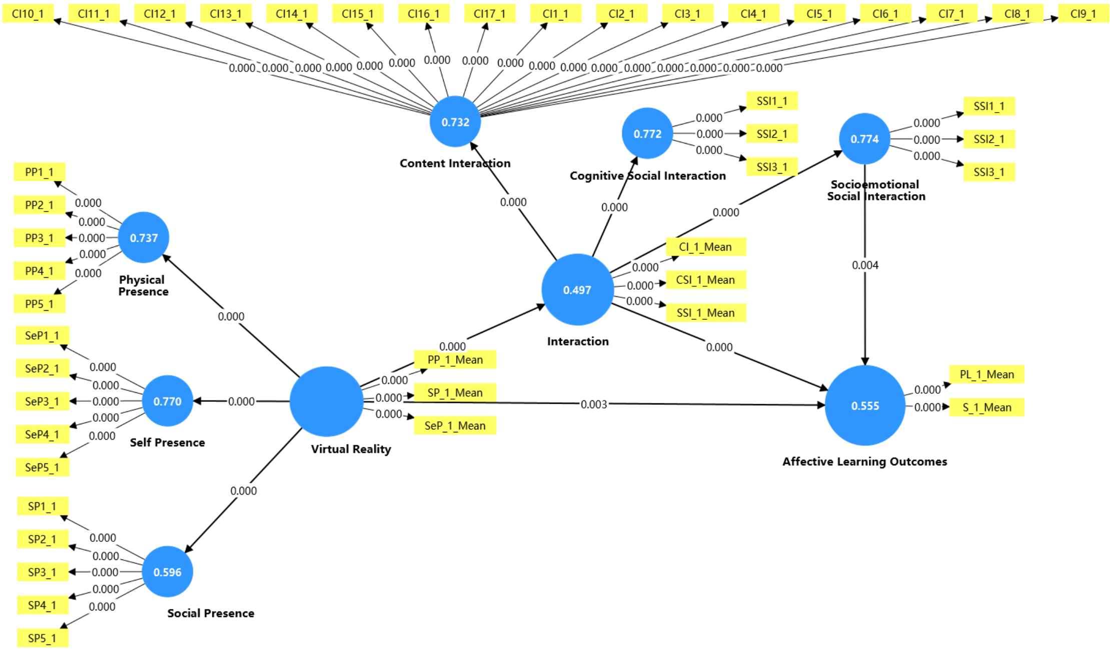
Figure 5.
The Final Model



DISCUSSION

Although most paths exhibit positive significant relationships, the path coefficient for the 'social-emotional interaction → affective learning outcomes' path is negative (β = -0.304). This result is inconsistent with expectations but may indicate that in specific immersive environments, excessive social-emotional burdens or ineffective interactions may weaken learning motivation and engagement (Makransky & Lilleholt, 2018). Similar studies have also found that in task-oriented learning, overly strong social-emotional factors can sometimes distract attention and reduce learning effectiveness (Lim & Richardson, 2021). Although most paths received empirical support, the 'social-emotional interaction → affective learning outcomes' path did not reach statistical significance, suggesting that the impact of social-emotional factors on learning outcomes remains unclear in this study and warrants further exploration in future research. This study found that social-emotional interaction's impact on affective learning outcomes was negative and significant, which is inconsistent with some traditional research conclusions. Possible reasons include: 1) In IVR immersive learning contexts, students focus more on task completion and content exploration, and redundant social activities may interfere with their emotional engagement; 2) Younger learners have weaker emotional regulation abilities, and immersive collaboration and social interaction may not always be positive. This finding suggests that future VR collaborative learning tasks should manage social-emotional factors more carefully to avoid cognitive overload.

Additionally, Lim and Richardson (2021) noted that in virtual teaching environments, social presence does not always impact learning outcomes in specific contexts positively, prompting educators to handle social design cautiously to prevent cognitive overload and emotional interference. In summary, the research findings generally support the effectiveness of VR courses in enhancing students' learning interest, scientific understanding, and group collaboration (Makransky et al., 2019; Radianti et al., 2020) while also validating the applicability of Merrill's instructional principles in immersive environments (Merrill, 2002). However, this study also highlights potential challenges associated with social-emotional interactions, including the social burden experienced by students in immersive learning, limited emotional regulation abilities among younger learners, and the potential for social activities to interfere with cognitive tasks (Lim & Richardson, 2021; Makransky & Lilleholt, 2018). This finding aligns with some research indicating that social interactions in IVR, if not effectively designed, may affect learners with low spatial abilities adversely (Lee & Wong, 2014). Therefore, future designs of VR collaborative

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learning tasks should more carefully manage social-emotional factors to maximize learning outcomes (Makransky & Petersen, 2021).

CONCLUSION

This study confirms that combining virtual reality with Merrill's instructional principles and conducting instructional design under the guidance of TICOL theory can significantly enhance primary school students' collaborative interaction and immersive participation experience in science courses. Students achieve knowledge construction and application transfer through problem-oriented tasks in group collaboration. Future research can further explore how immersive interaction can optimize feedback mechanisms, virtual character collaboration, and dynamic division of labor among learners in science courses to deepen the effectiveness of virtual collaborative learning.

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