The Impact of Applying Virtual Reality Technology to Spatial Ability Learning in Elementary School Students

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Abstract. This study explored the effects of virtual reality (VR) technology applied to spatial ability learning in elementary school students. As supplement materials to the Geometry Unit in the curriculum, the learning materials were developed based on the mathematics competence indicators for fifth and sixth graders in Taiwan. Designed to enhance spatial concept and logical thinking, the materials tapped into VR technology to transform two-dimensional graphics into three-dimensional spaces, in view of effectively solving the problem of learning abstract 3D spaces. A quasi-experimental method was used to understand the influence of different learning methods on students' learning effectiveness and interest in learning. The experiment found that (1) the use of interactive VR learning materials significantly improved student's spatial ability; (2) using VR learning materials enhanced the learning effectiveness of students with low achievement in mathematics; and (3) the introduction of VR learning materials improved students' motivation for learning spatial concepts. The findings showed that the digital learning materials developed in this study were beneficial to the teaching effectiveness of teachers and the learning needs of students.

Keywords: Spatial ability · Mathematics · Virtual reality · Physical blocks · Digital learning materials

1 Introduction

Spatial ability is an important building block to mathematical ability. Its learning objectives include understanding the properties of geometric shapes, emphasizing the use of visualization, spatial inference, and geometric patterns to solve problems. The Geometry Unit in Taiwan's fifth-grade mathematics curriculum includes recognizing volumes and composite solids, where students are taught how to calculate the volume of stacked solids. When elementary school students learn about volume calculation in mathematics, they must be equipped with a basic understanding of spatial concepts.

Spatial ability is intimately tied to our everyday lives, as it helps us identify the position, size, shape of objects in the real world. Smith [1] proposed that spatial ability consists of three components: mental rotation, spatial visualization and spatial

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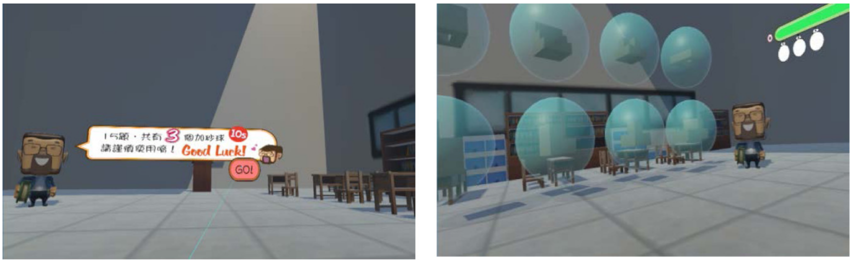
orientation. In the real world, there is a need for spatial ability training. For instance, space design, architectural modeling, graphic design and industrial design all require a good spatial competency foundation before one can understand and produce engineering and design drawings. Spatial orientation must be cultivated from a young age, and its related learning contents, e.g., length, area, surface area, volume, have a great impact on future ability development. Mathematics learning focuses on a logical framework in a stepwise manner. Conventional teaching of spatial ability usually uses three-dimensional perspective graphics as an aid to spatial concept formation. However, some students are unable to use perspective graphics to associate with three-dimensional solids, leading to frustration in the learning process and refusal to learn.

In recent years, the popularization of VR technology has given rise to various studies on VR in education [2]. The three characteristics of VR, i.e., immersion, interactivity and imagination, allow learners to learn as if they are in a real situation during the learning process, while the visual and auditory effects of VR create an immersive and imaginative learning experience. VR is able to attract learner attention, induce their feelings, and enhance the affective and cognitive learning effects [3, 4]. In addition, the tactile simulation and sensory feedback in VR devices allow users to interact with virtual objects [5] and promote active learner engagement [6, 7].

Learning mathematics should be an enjoyable experience, and its learning process should be embedded into a context that develops ways of understanding and thinking. In mathematics education, problem solving, a medium for learning math concepts and skills, is considered an important part of the curriculum and is a topic of ongoing interest by educational researcher [8]. In this study, an interactive VR-based three-dimensional space learning platform was developed in view of enhancing the development of spatial concepts on position, distance, and displacement in elementary school students. With this learning platform, such concepts in three-dimensional space can be enhanced through operating different actions, such as combination, stacking and movement of solids, in a constructed virtual space. An experiment was designed to understand the effectiveness of this platform on spatial ability learning and the impact of VR introduction on the learning motivation of students.

2 Application Implementation

The system was developed using Unity 3D game engine and designed with 3D objects, interactive scenes, learning situations and scoring functions. A complete VR interactive learning environment was created through the use of VR headsets, controllers, and base stations. The learning platform was designed with 2 units: unit 1 is the basic cognitive sense of space and three-dimensional concepts, involving the learning of volume, length, units and distance; and unit 2 focuses on the placement and creation of various three-dimensional objects, where learners are taught to use operations such as flipping, stacking, maneuvering, and assembling to construct three-dimensional structures. Virtual characters were put in place to guide learners through the learning process and score calculations (see Fig. 1).



(a) Virtual character guided learning (b) 3D space learning exercises

Fig. 1. Interactive VR learning scenario.

3 Research Methods

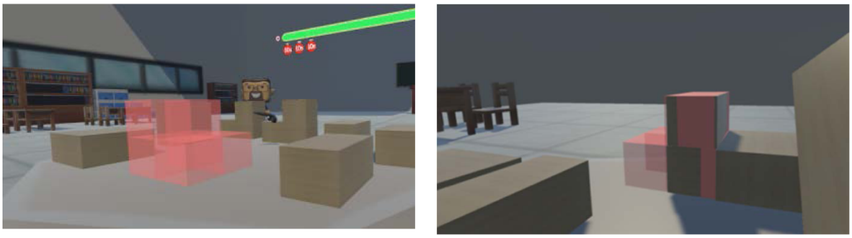
3.1 Research Design

This study was conducted using a quasi-experimental pre-post-test design. Two classes of fifth-grade students were the research subjects, where one class was the experimental group who were taught spatial orientation using the VR learning system, and the other class was the control group who were taught with the use of solid blocks. Before and after the experimental teaching, tests were conducted, and questionnaires were administered to the subjects to understand their spatial ability learning experience. Figures 2 and 3, respectively, show the use of learning aids in the control group and the experimental group.

Fig. 2. Control group students using physical blocks to assist in their learning.

3.2 Research Subjects

The subjects of this study were 50 fifth-grade students in an elementary school in Taiwan. The experimental group consisted 24 students, including 14 boys and 10 girls. The control group consisted 26 students, including 13 boys and 13 girls. At a total of 27 boys and 23 girls, the two classes were taught by the same teacher who had had 8



(a) 3D structure construction (b) Virtual object maneuvering

Fig. 3. Experimental group students using VR learning transform to assist in their learning.

years of mathematics teaching experience, and the learning content of the two classes was the same.

3.3 Research Tools

Spatial ability test (pre-post-test): Test questions on three-dimensional building block rotation, a common test for exploring spatial ability, were prepared to investigate students' spatial ability before and after the learning experiment.

Learning motivation scale: The learning motivation scale of this experiment was adapted from Hwang et al. [9]. The questionnaire consisted of two dimensions, intrinsic motivation and extrinsic motivation, with a total of 9 questions measured using the Likert 5-point scale to analyze the learning motivation difference between the two groups of students before and after the experiment.

The spatial ability pre-test and the learning motivation questionnaire were administered to both groups of students before the experiment started. At the beginning, students in the experimental group were given an introduction and demonstration on the operation of the VR system to ensure that they knew how to operate it. After that, the two groups of students were subjected to different learning methods. After the completion of the experimental course, the two groups were given post-tests and questionnaires. Figure 4 shows the experimental process. The experimental analysis and discussion are as follows.

4 Findings and Discussion

4.1 The Composition of the Experimental Group and the Control Group

The subjects of the experiment were 50 school students, including 24 students in the experimental group (14 boys and 10 girls) and 26 students in the control group (13 boys and 13 girls). The mathematics scores of both groups in the previous semester were analyzed. Independent sample t test showed that the mean score in the experimental group was 87.2, and that of the control group was 86.6 ($F(1, 48) = 0.051$, $t = 0.25$, $p > 0.05$), denoting no significant difference.

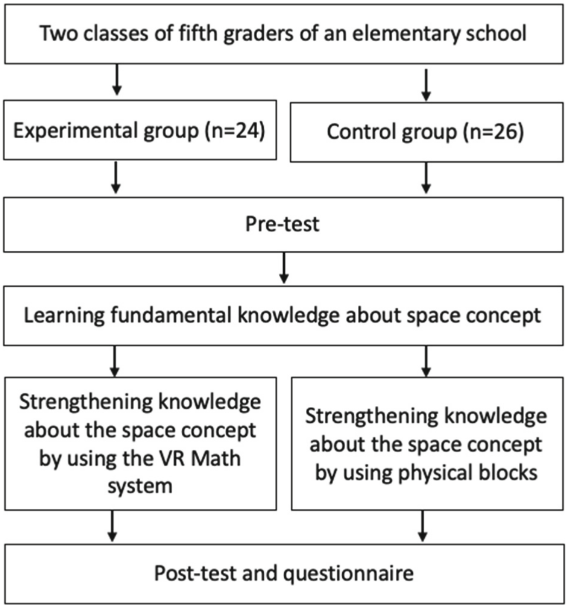


Fig. 4. Diagram of the experimental design.

4.2 Pre-post-Test Data Analysis of Experimental Group and Control Group

As shown in Table 1, the pre-test mean of the control group was 84.10 and post-test mean was 83.90, registering a slight 0.20 decrease. Meanwhile, the pre-test mean of the experimental group was 79.80 and the post-test mean was 86.80. After the introduction of VR learning materials, the mean score in the experimental group significantly increased 7 points. Table 1 shows that the pre-test and post-test in the control group using the conventional textbook did not reach a significant difference ($t = 0.05$, $p > 0.05$). On the other hand, the pre-test and post-test results of the experimental group using VR learning materials in the learning process were significantly different ($t = 5.22$, $p < 0.001$).

Table 1. *t*-test analysis of the learning motivation scale.

	N	Pre-test		Post-test		*t*
		M	*S.D.*	*M*	*S.D.*	
Control group	26	84.10	9.94	83.90	14.08	−0.05
Experimental group	24	79.80	12.12	86.80	11.77	5.22^{***}

$^{***}p < 0.001$

4.3 The Learning Effectiveness of Students with Different Mathematical Abilities in the Experimental Group

Table 2 shows the data of the low-achieving subset, who were slower in math learning, and the high-achieving subset in the experimental group of students after using VR learning materials. According to data analysis, there were 14 students in the low-achieving subset (pre-test scores between 60–79). Their mean pre-test score was 69.14 (*S.D.* = 7.98) and the mean post-test score was 79.64 (*S.D.* = 13.07). The mean difference between the pre- and post-tests was 10.50 (= 79.64–69.14). Meanwhile, there were 10 students in high-achieving subset (pre-test scores between 80–100). Their mean pre-test score was 89.12 (*S.D.* = 5.51) and the mean post-test was 93.90 (*S.D.* = 5.41). The mean difference between their pre-test and post-test scores was 4.78 (= 93.90–89.12). Both the low- and high-achieving subsets reached a significant level in the score difference ($t = -4.89$; $t = -3.02$). In terms of the degree of difference, the enhancement of the learning effectiveness using VR materials in the low-achieving subset was higher than that of their high-achieving counterparts.

Table 2. Analysis on the learning effectiveness of students with different mathematical abilities in the experimental group.

	N	Pre-test		Post-test		*t*
		M	*S.D.*	*M*	*S.D.*	
Low achiever group	14	69.14	7.98	79.64	13.07	−4.89***
High achiever group	10	89.12	5.51	93.90	5.41	−3.02***

***$p < 0.001$

4.4 The Learning Effectiveness of Students with Different Mathematical Abilities in the Control Group

In the control group (Table 3), there were 10 students in the low-achieving subset (pre-test scores between 60–79). Their mean pre-test score was 72 (*S.D.* = 8.42) and the mean post-test score was 70.55 (*S.D.* = 13.80). The mean difference between their pre-test and post-test score was −1.45 (= 70.55–72). On the other hand, there were 17 students in the high-achieving subset (pre-test scores between 80–100). Their mean pre-test score was 89.23 (*S.D.* = 4.62) and the mean post-test score was 89.71 (*S.D.* = 9.78). The mean difference between their pre-test and post-test score was 0.48 (= 89.71–89.23). Neither the low- and high-achieving subsets reached a significant level in the score difference ($t = -0.31$; $t = 0.25$).

4.5 Comparison of Learning Motivation

A pre- and post-test analysis of learning motivation was conducted to understand the influence of different learning materials on students' spatial learning ability before and after the experiment. From the data analysis (Table 4), the mean pre-test and post-test scores in the experimental group's learning motivation were 3.89 and 4.41, respectively, which were statistically significant by the paired-sample t test ($t = 3.51$,

Table 3. Analysis on the learning effectiveness of students with different mathematical abilities in the control group.

	N	Pre-test		Post-test		*t*
		M	*S.D.*	*M*	*S.D.*	
Low achiever group	10	72.00	8.42	70.55	13.80	−0.31
High achiever group	16	89.23	4.64	89.71	9.78	0.25

$p < 0.01$). In the learning motivation of the control group, the mean pre-test and post-test scores were 3.97 and 3.77, respectively. The paired-sample t test ($t = -0.16$, $p < 0.876$) did not reach statistical significance (as shown in Table 4). Student learning motivation in the experimental group increased from 3.89 to 4.41 after using the VR learning platform, showing the integration of VR learning materials in learning can effectively enhance students' learning motivation. Meanwhile, the learning motivation of students in the control group dropped from 3.97 to 3.77, suggesting that the lack of variation and innovation in the conventional textbook-based learning model can lead to low learning motivation which in turn affects learning effectiveness.

Table 4. t-test analysis of the learning motivation scale.

	N	Pre-test		Post-test		*t*
		M	*S.D.*	*M*	*S.D.*	
Experimental group	24	3.89	0.79	4.41	0.58	3.51**
Control group	26	3.97	0.85	3.77	0.93	−0.16

$^{**}p < 0.01$

5 Conclusion

The VR learning materials developed in this study aimed to create an interactive experience to enhance students' spatial ability. Students were given the chance to use rotation, stacking, maneuvering, and combination to explore the complete geometries of three-dimensional objects, thereby strengthening their ability to understand three-dimensional space. The experiment findings showed that the use of VR-assisted learning materials can arouse the interest and curiosity of learners with low mathematics ability, bringing into full play the advantages of integrating technology into learning. Kang, Hong, & Lee [10] suggested virtual simulation is an educational strategy that can effectively help students stay engaged in learning and achieve positive learning outcomes. The virtual environment created by VR allows students to have direct contact with the immersive, simulated world it presents, and the complete interactive experience motivates students to learn. Characterized by its elements of challenge and feedback, digital learning can reduce learning boredom or anxiety when the learning process is an immersive experience. Increased learning motivation enables learners to identify solutions through trial and error or imitation of examples [11].

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