How Does the Metaverse for Kids Enhance the Students' Spatial Ability in Elementary School?

Trimurtini[1,*], Elok F. Sari[1], Moh. F. Irvan[1], Farid Ahmadi[1], Elvi Mailani[2], Muhammad T. Machmud[2], Nurhudayah Manjani[2], Robenhart Tamba[2], and Tassanee Juntya[3]

[1]Department of Elementary School Teacher Education, Faculty of Education and Psychology, Universitas Negeri Semarang, Semarang, Indonesia
[2]Department of Elementary School Teacher Education, Faculty of Education, Universitas Negeri Medan, Medan, Indonesia
[3]Department of Teacher Education, Faculty of Education and Development Sciences, Kasetsart University, Thailand
Email: trimurtinipgsd@mail.unnes.ac.id (T.); elok_pgsd@mail.unnes.ac.id (E.F.S.); farizqo@mail.unnes.ac.id (M.F.I.); farid@mail.unnes.ac.id (F.A.); elvimailani@unimed.ac.id (E.M.); takwinmachmud@unimed.ac.id (M.T.M.); nh.manjani@unimed.ac.id (N.M.); robenharttamba@unimed.ac.id (R.T.); tassanee.o@ku.th (T.J.)
*Corresponding author

Manuscript received November 19, 2025; revised December 12, 2025; accepted January 22, 2026; published June 18, 2026

***Abstract*—Innovative spatial learning has not been presented to stimulate students. Metaverse for Kids (MfK) is an immersive, technology-based learning media innovation developed to help elementary school students hone their spatial skills optimally. The objectives in this study are: (1) to find out the difference in the spatial abilities of elementary school students before and after using MfK; (2) to compare students' spatial abilities by gender; (3) to compare students' spatial abilities based on their types. This study uses a quantitative approach with a pretest-posttest design to measure the effectiveness of implementing the MfK on the spatial ability of fifth-grade students in Semarang City. The participants in this study were 102 fifth-grade students from an elementary school. Data were analyzed using the Wilcoxon Signed Rank Test to compare pretest and posttest scores, the Mann-Whitney U Test for differences based on gender, and the Friedman Test to compare types of spatial abilities. The results of the Wilcoxon analysis revealed a significant increase in spatial abilities following the use of MfK, with a medium effect size ($r = 0.378$). The Mann-Whitney test yielded a p-value of 0.242, which is greater than 0.05, indicating no significant difference in spatial abilities between male and female students. This finding was supported by a small effect size ($r = 0.116$). The Friedman test showed that relational spatial ability was the most developed type, indicated by the highest mean rank value of 3.86. These findings suggest that MfK is effective in enhancing the spatial abilities of elementary school students, particularly in the spatial relational aspect, without exhibiting gender bias. The main finding of this study is that MfK can help elementary school students to better understand the relationships between the geometry objects studied. The conclusions of this study are (1) the practice of using MfK to learn geometry is effective in improving the spatial ability of fifth grade students; (2) in general, there is no difference in spatial ability in the female and male student groups; (3) the type of spatial ability that increases the highest after the use of MfK is spatial relational ability. Suggestions for utilizing the metaverse in elementary school students should focus on incorporating gamification aspects.**

***Keywords*—elementary school students, geometry, metaverse for kids, spatial ability, quality education**

I. Introduction

The advancement of information and communication technology is one of the factors that affect all lines of life, not except in the field of education. Education in the 21st century has challenges and opportunities with the presence of technology that continues to develop. Technological developments in the field of education start from the virtual environment, the floating of digital content into the real world (augmented reality), technology that creates digital simulations (virtual reality), and, more recently, the metaverse. These technologies are categorized as immersive technologies, which are technologies that try to combine the physical and digital worlds [1]. This provides an opportunity for students to learn things that are abstract into concrete so that it is easier to understand the concept of learning. One of the learning that can be accommodated through these technologies is mathematics learning in geometry materials which aims to hone students' spatial thinking.

Spatial thinking learning in Indonesian elementary schools has not been running optimally. This is in line with the findings from [2] which states that the spatial ability of elementary school students remains relatively low due to the abstract nature of mathematics learning, making it difficult for students to learn geometry. The spatial abilities of grade IV students, who are still not optimal, are specifically analyzed on the understanding of regional location, spatial orientation, and distance [3]. Research from [4] It also states that the average spatial ability of elementary school students in Indonesia falls below average in terms of spatial visualization, spatial orientation, and mental rotation. Based on the results of previous research, it is evident that the spatial ability of elementary school students remains suboptimal. This is an interesting study material that warrants further exploration, as well as alternative efforts to address the problem.

Several factors contribute to the low spatial ability of elementary school students in Indonesia. One of them is about the portion of learning that supports spatial skills that have not been sufficiently taught in elementary school [5]. In addition, there are also teachers' limitations in understanding the concept of spatiality, which has an impact on the textual and abstract learning process [6]. Innovative and interesting spatial learning has not been presented to stimulate students to develop good spatial skills. The right learning media is also one of the supporting factors that can create more engaging spatial learning, resulting in a positive impact on the spatial abilities of elementary school students.

The transition from conventional learning to technology-assisted learning has an impact on the use of learning media. Mathematics learning media in the interactive digital era need to be able to stimulate space exploration, manipulate three-dimensional objects, and

doi: 10.18178/ijiet.2026.16.6.2623

develop students' spatial imagination [7]. Based on these needs, one of the technologies that accommodates these activities is metaverse technology. Metaverse technology is a technology in the form of a three-dimensional virtual space built with virtual reality and augmented reality technology [8]. This technology has been applied to support the learning process, but it is still limited to be applied at the elementary school level.

Metaverse for Kids (MfK) is an immersive technology-based learning media innovation developed to facilitate elementary school students to hone their spatial skills optimally. The learning media accommodates several activities that allow students to play while learning in an immersive, collaborative, and space-oriented manner. These activities are supported by virtual reality technology that can train students to significantly improve spatial reasoning. Additionally, the use of augmented reality technology has also shown a positive impact on improvements in spatial orientation and object visualization [9] for preschool and elementary school students. Thus, metaverse technology has a positive influence on supporting the spatial development of students at the elementary education level.

The positive impact of metaverse technology is as a learning medium that supports and trains elementary school students' spatial abilities in mathematics [10]. Although it supports learning in elementary schools, the use of metaverse technology is still not widely implemented. Technological advances in education, particularly those related to the metaverse, have not been effectively aligned with efforts to implement them in the field, as is the case in Semarang City.

The selection of Semarang as a major city and the varying conditions of schools and students are notable. This condition was chosen because big cities in Indonesia have varied conditions, both in terms of geographical conditions and school and student conditions. The selection of four schools for research is based on locations scattered throughout Semarang City, in the center of the city, and on its outskirts. The results of the study can be generalized because the sample selection process can represent the conditions of student variation in Semarang City.

Metaverse technology has begun to be developed to support learning, but has not been specifically implemented in elementary schools in Semarang City as an effort to improve spatial abilities. This could be a subject for further research. In addition, the limited research on the impact of immersive technology interventions, such as the metaverse, on elementary students' spatial abilities presents an interesting area of study to understand its effects based on gender and the various types of spatial abilities that exist.

Based on the background explanation presented earlier, this study has three objectives. (1) To determine the differences in elementary school students' spatial abilities before and after using MfK; (2) To compare students' spatial abilities based on gender; (3) To compare students' spatial abilities based on their different types.

II. Literature Review

A. Spatial Ability

Spatial ability can be defined as the ability to generate, maintain, retrieve, and manipulate well-structured visual images [11]. This ability serves as a foundation in STEM learning, enabling the solution of problems such as those in geometry, mental modeling, and navigation. Efforts to train spatial ability can be made by facilitating children in concrete manipulative activities. This can be facilitated through playing with blocks, tangrams, puzzles, origami, and 3D construction games, in line with the opinion [12] that spatial ability is related to experience in manipulating and rotating 3D objects. These activities can also be supported through the use of technology and digital media, such as spatially based games.

Spatial ability can be categorized into five types [13]. These five types of spatial abilities are: 1) spatial visualization: the ability to show changes in parts of a 2D or 3D shape; 2) spatial relations: the ability to understand the relationships between parts of an object; 3) spatial rotation: the ability to rotate 2D or 3D objects; 4) spatial perception: the ability to perceive objects in vertical or horizontal positions, and 5) spatial orientation: the ability to recognize objects from various angles.

Several factors influence a person's spatial ability. These factors include age, familiarity with the environment, landmark attributes, surrounding complexity, and gender [14]. Studies have shown that gender differences can influence performance on specific spatial tasks, particularly mental rotation [15]. There is another opinion that states that spatial ability is not determined by gender; in this case, men have higher abilities, but it is based on experiences that individuals have had related to activities that influence spatial ability [16]. Although several studies have examined the influence of gender on students' spatial abilities, there has been no research that attempts to compare the five types of spatial skills in elementary school students based on their gender.

B. Metaverse for Kids (MfK)

The combination of immersive Augmented Reality (AR) and Virtual Reality (VR) into a single technology is known as the metaverse [17]. This technology has great potential for supporting the learning process in schools. More effective communication, innovative and interactive learning, and thus higher-quality learning are the benefits of utilizing metaverse technology in learning [18]. Furthermore, the AR and VR technologies contained in metaverse media make it easier for students to understand abstract concepts more concretely, making this media highly potential to support mathematics learning in elementary schools [19]. Through metaverse media, students can also directly engage in manipulative activities to explore their knowledge independently.

One of the innovations in mathematics learning media at the elementary school level is MfK. MfK is utilized by teachers and students in geometry learning, one of which aims to hone geometric skills. MfK learning media provides features such as learning materials for plane shapes (2D) and spatial shapes (3D), allowing students to study the material in greater depth independently.

Here are the features of MfK, along with their explanations. The primary feature of MfK is the MfK center, which serves as an information hub and acts as a connecting point between other spaces. The next MfK features are (1) the features of concrete objects on spatial geometry objects (Fig. 1), (2) the features of the shape and characteristics of the spatial building, and (3) the composition and decomposition features of the spatial building (Fig. 2). The duration of using MfK for students is 4 meetings, each lasting 35 minutes.

Fig. 1. MfK features of the shape and characteristics of the spatial building.

Fig. 2. MfK features of the composition and decomposition of the spatial building.

These exploration activities make learning more interesting for students. The contextual and socio-culturally based teaching materials provided make it easier for students to understand geometry concepts [20]. The use of learning technology developed based on context-based materials enhances students' understanding of the material being learned. A good understanding of learning in geometry learning further improves students' spatial abilities with the support of AR and VR technology found in learning media [21]. Research on the use of the metaverse as a learning medium has shown a positive impact on students' spatial abilities, particularly in higher education [22, 23]. However, studies on utilizing metaverse learning media to support students' spatial abilities in elementary schools are still limited.

III. Materials and Methods

A. Research Design

This study uses a quantitative approach with a pretest–posttest design. This design is used to measure the effectiveness of implementing Metaverse for Kids on the spatial abilities of fifth-grade elementary school students in Semarang City. Metaverse for Kids is a learning media application developed by the research team in 2024 and has undergone an initial effectiveness test. In this study, the application, which contains flat and spatial geometric shapes, was used by each student selected as a research sample.

B. Research Participants

The participants in this research consisted of 102 fifth-grade elementary school students from four elementary schools in Semarang City. The selection of schools for research was based on locations scattered throughout Semarang City, encompassing both the central area and the city's outskirts. Ethical approval and participant consent were obtained, involving elementary school students assisted by class teachers and principals, who helped communicate the research objectives to students' parents regarding the implementation of MfK for elementary school students.

The selection of schools and students was done through simple random sampling. Each student was allowed to use the MfK application. Through this application, students can learn while engaging with various features that visually and interactively support the understanding of geometric concepts.

C. MfK Implementation

The duration of using MfK for students is 4 meetings, each lasting 35 min. Each student utilizes MfK with guidance from the researcher. The details of the activity protocol of the 4 meetings are as follows. The first meeting fosters good relationships with students and introduces the tools used in MfK, as well as its key features. The second meeting of students using MfK focuses on the central feature of MfK, namely, introducing various plane and solid shapes and their characteristics through the gallery in MfK. In the third and fourth meetings, students enter the virtual space section to recognize various combinations of geometric shapes provided and carry out tasks of moving, dismantling, and rebuilding geometric shapes in the virtual space.

D. Data Collection Techniques

Research data was obtained through spatial ability tests administered twice, namely before (pretest) and after (posttest) the students used MfK. The spatial ability instrument used was adapted from the Spatial Ability module developed by an international educational organization, and tailored to the five types of spatial abilities as stated by Maier *et al*. [11, 13], namely:

1) Spatial visualization is the ability to visualize changes or movements of parts of a shape, whether two-dimensional or three-dimensional.
2) Spatial relational, which is the ability to understand the arrangement and relationships between parts of an object.
3) Spatial rotation, which is the ability to rotate two- or three-dimensional objects accurately;
4) Spatial perception, which is the ability to perceive objects in vertical or horizontal positions;
5) Spatial orientation, which is the ability to recognize the shape of an object when viewed from different angles.

The pretest and posttest were conducted in a controlled classroom setting with the same amount of time allocated for all participants. The spatial ability test was administered twice: before and after students used Metaverse for Kids (MfK). The spatial ability test instrument was adapted from the Spatial Ability module developed by an international educational organization and tailored to five types of spatial ability: spatial visualization, spatial orientation, spatial rotation, spatial perception, and spatial relational skills. Before being used in the main study, the instrument was piloted on 100 elementary school students with characteristics similar to those of the study subjects. Item validity was tested using Pearson Product-Moment correlation, with an r-table value of 0.1966 ($\alpha = 0.05$). The analysis showed that all items had a calculated r-value > r-table, thus all items were deemed valid and suitable for use.

The instrument's reliability was assessed using Cronbach's Alpha coefficient, yielding an α value of 0.518, which is categorized as moderately reliable. However, this reliability value is still acceptable for exploratory research and the development of learning media, particularly in the context of measuring the cognitive abilities of elementary school students.

The spatial ability test consisted of 20 questions, each with four multiple-choice options and a single correct answer. The correct answer score is 1, and the incorrect answer score is 0.

E. Data Analysis Techniques

Data analysis was conducted in several stages, using quantitative methods. First, a prerequisite test for analysis was conducted, namely the normality test, to ensure that the distribution of spatial ability variable data met the assumptions of parametric analysis. However, since the results of the prerequisite test indicated that the data were not normally distributed, a non-parametric statistical test was conducted to compare the pretest and posttest scores of overall spatial abilities in order to determine the effectiveness of using MfK.

After that, further analysis (post-hoc analysis) and descriptive statistics were conducted to identify the types of spatial ability that showed the most significant improvement after using MfK. This analysis aimed to identify the five types of spatial ability that developed the most through the application of MfK.

To analyze the differences in students' spatial abilities before and after using MfK, the Wilcoxon Signed-Rank Test was employed. In addition to testing the significance of the differences, this study also reports effect sizes using the r coefficient to illustrate the strength of the practical impact of MfK implementation. Furthermore, to compare students' spatial abilities by gender, the Mann-Whitney U Test was used, as the data were independent and did not meet parametric assumptions. Effect sizes were also calculated to interpret the strength of differences between groups. To identify the type of spatial ability that developed most after using MfK, the Friedman Test was used, a non-parametric test for repeated data in more than two conditions. The results of the Friedman test were analyzed using descriptive statistics, specifically mean ranks, to determine the developmental level of the five types of spatial abilities. All data analyses were conducted at a significance level of α = 0.05.

IV. Results and Discussion

A. Differences in Spatial Ability before and after Using Metaverse for Kids

Normality tests using the Kolmogorov-Smirnov and Shapiro-Wilk tests showed that the data were not normally distributed ($p < 0.05$); therefore, the analysis continued using the Wilcoxon Signed Rank Test. The following is the interpretation of Table 1—the Asymp. A Sig value of 0.000 < 0.05 indicates a significant difference between students' spatial abilities before and after the implementation of Metaverse for Kids. The positive mean rank is greater than the negative, indicating an increase in overall spatial abilities. Thus, the use of the MfK has a positive and significant effect on improving the spatial abilities of fifth-grade elementary school students.

Table 1. Wilcoxon spatial ability test results before and after using MfK

Description	*N*	Mean Rank	Sum of Ranks	Test Statistics
Negative Ranks	17	31.53	536.00	
Positive Ranks	49	34.18	1675.00	
Ties	36			
Z				−3.819
Asymp. Sig (2-tailed)				0.000
Total	102			

Data analysis using the nonparametric Wilcoxon test yielded an effect size of $r = 0.3781$ in the category of the influence of MfK use on students' spatial ability, indicating a moderate effect.

Descriptively, Table 2 below presents the distribution of spatial ability data before and after the use of MfK in fifth-grade elementary school students.

Table 2. Description of spatial ability data before and after using MfK

Description	Pretest	Posttest
N	102	102
Mean	6.51	6.97
Median	7.00	7.00
Standard deviation	1.91	1.84
Minimum	0	0
Maximum	9	10

The distribution of spatial abilities before and after using MfK is shown in Fig. 3. The distribution of spatial abilities in the pretest and posttest is relatively clustered at the middle value. Initial spatial abilities in the pretest are more evenly distributed in the lower part of the range, from 0 to 3, compared to the posttest. Posttest data show a wider spread and more clustering in the high range of values, namely 7.5 and above, compared to the pretest value. This indicates an increase in posttest scores compared to pretest scores, although initial and final spatial abilities tend to cluster at high scores. In addition, the results of descriptive data analysis showed that the spatial ability scores below the first quartile for the pretest and posttest results were as follows: data numbers 38, 49, 56, 133, 134, 158, and 173.

The results of this study confirm that the application of immersive technology based on Metaverse for Kids can significantly improve the spatial abilities of elementary school students. This finding is in line with the results of other studies that show that the metaverse environment allows students to experience increased visual-spatial abilities through virtual space exploration and three-dimensional interactions [24–26]. Meta-analyses and systematic reviews confirm that virtual technologies, including VR and metaverse platforms, have moderate to significant positive effects on the development of spatial abilities, with the most pronounced improvements in mental rotation and spatial visualization tasks [27–29]. Further experimental research has demonstrated that VR-based training yields significant improvements in spatial skills, with immersive VR outperforming desktop or 2D environments in terms of usability, engagement, and learning outcomes [30–32]. Meanwhile, research in the field of neuroimaging and cognitive load reveals that VR environments can reduce cognitive load and increase neural efficiency during spatial tasks, making them particularly beneficial for learners with lower initial spatial abilities [33–35].

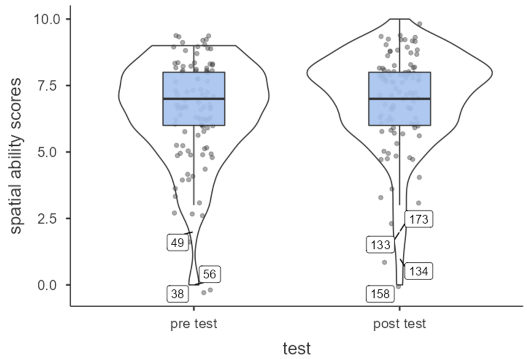

Fig. 3. Distribution of spatial ability pretest (a) and posttest (b).

Many studies and research on metaverses suggest that utilizing them offers several benefits. Learning in a VR or metaverse environment can increase mental imagery and spatial manipulation activities, namely, students are actively involved in exploring three-dimensional virtual worlds [36–38], observing objects from various points of view [39–42], improving spatial and conceptual abilities [39, 41, 42], increasing student active involvement and student learning motivation [40, 41, 43, 44], and developing higher-order thinking skills such as analysis, evaluation, creativity and problem solving [39, 42].

Metavers for kids (MfK) directly presents an immersive three-dimensional learning environment in the form of geometric shapes that actually exist in life, for example, geometric shapes of blocks presented in the form of wooden blocks that can be seen, rotated, enlarged, and moved by students who interact virtually with the object in MfK. In the context of spatial abilities, this process can stimulate visual-spatial cognitive processes, including mental rotation, spatial perception, and understanding of position relations. Dual Coding Theory (DCT) [45] explains that processing visual and verbal information simultaneously can improve conceptual understanding. These individual differences in imagination abilities and habits have important consequences for education. Students who struggle with imagination may have difficulty understanding other spatial concepts concretely and may be less successful in visualizing the steps in geometric proofs. Dual Coding Theory (DCT) provides an analytical framework for understanding nonverbal tests and their relationship to imaginative abilities. Nonverbal tasks involve specific traits in the imaginary system, namely the capacity to integrate and rearrange information. In this study, it is associated with the capacity of imagery in the form of spatial transformation. MfK not only provides geometric object shapes but also includes brief explanatory texts about the geometric objects in MfK. So, MfK allows both visual and verbal information channels to work in synergy.

For fifth-grade elementary school students, MfK can provide an engaging learning environment that encourages students to be actively involved, as it helps them focus and retain the visual information they obtain. Based on Moreno's Cognitive-Affective Theory of Learning, updated by Park [46] The use of multimedia can improve cognitive perspectives if the process also considers motivational and affective aspects. The cognitive process that occurs when students learn to use MfK can begin with students obtaining appropriate information through visual channels and directing it as needed. The information is organized into coherent mental representations to gain meaningful knowledge and understanding. In addition, affective processes play a role in increasing learning motivation and cognitive effort, acting as a driver of cognitive processes. So MfK not only functions as a digital learning medium but also as a cognitive learning environment that can hone spatial abilities through interactive, contextual, and multisensory learning experiences.

B. Comparison of Spatial Ability by Gender

Because the data were homogeneous ($P > 0.05$) but not normally distributed ($P < 0.05$), the Mann-Whitney test was used to compare spatial abilities between male and female students.

Table 3. Mann–Whitney test results based on gender

Gender	*N*	Mean Rank	Sum of Ranks	Spatial Ability
Male	51	54.85	2797.50	
Female	51	48.15	2455.50	
Asymp. Sig (2-tailed)				0.242

The following is the interpretation of Table 3. The Sig value (0.242)> 0.05 indicates that there is no significant difference between the spatial abilities of male and female students after using Metaverse for Kids. However, the average spatial ability of male students was slightly higher than that of female students, although the difference was not statistically significant. A more detailed comparison of the pretest and posttest results for spatial ability is provided in the following image, with a focus on the gender of grade 5 students.

Fig. 4(a) shows that the distribution of spatial ability before using MfK from the male and female student groups appears relatively similar. However, there are slight differences in the distribution and the median value. The spatial ability of female students has a higher median value than that of male students, as indicated by the boxplot. However, the variation in data, as indicated by the range of female students' scores, appears broader than that of the male students, as shown by the wider violin plot. This means that the initial spatial ability of female students is more diverse, ranging from low scores to high scores. The distribution of scores for both groups shows that most students have initial spatial ability scores in the range of 5 to 8, indicating a medium level of spatial ability, before the learning intervention with MfK.

Fig. 4(b) shows an increase in students' spatial abilities after using MfK, with a relatively even distribution of scores; however, there are differences in the distribution patterns between the male and female student groups. In the female group, the distribution of posttest scores tends to be homogeneous, with the majority of scores concentrated in the range of 6 to 9. The median value is around 7; this indicates that most female students achieved posttest scores above average. Meanwhile, in the male student group, the distribution of scores appears more varied than in the female student group. The median score for the male group is also around 7, but the distribution of scores is wider, with some students getting low scores of around 2 to 3. This shows that although the average score of the male group's spatial abilities after using MfK is quite good, the variation in individual scores is quite significant in the male student group. The data distribution pattern, presented in the form of a violin plot, tends to be normal, indicating that more than half of the students have developed increased spatial abilities after practicing MfK.

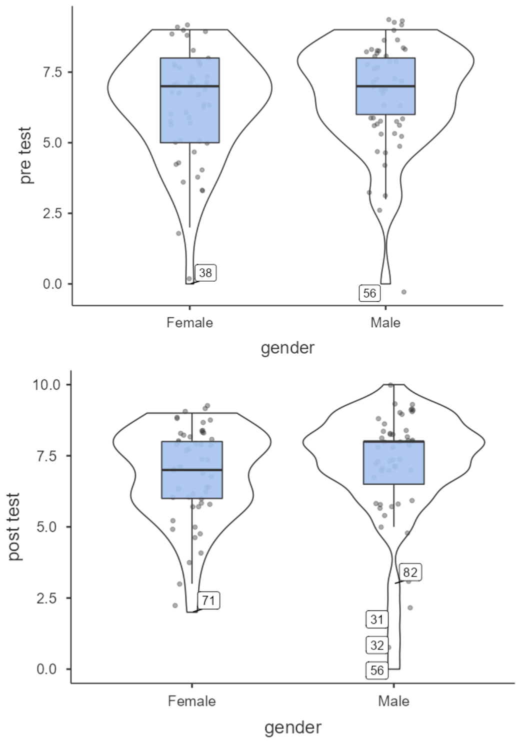

Fig. 4. Distribution of Spatial ability among male and female students; (a). distribution of spatial ability pretest of male and female students; (b). distribution of spatial ability posttest (b) of male and female students.

In both Figs. 4(a) and 4(b), the female and male student groups have opposite data distributions. At the beginning (pre-test), the distribution of female students has a wider distribution than the final data (post-test). However, in contrast, the distribution of male students tends to be centralized, symmetrical, and stable initially, but eventually tends to spread out. The results of the descriptive analysis revealed outlier data on the spatial ability of both pretest and posttest for both male and female students. The outlying data are in data numbers 38, 56, 71, 31, 32, 56, and 82. All of the outlier data are below the first quartile.

Furthermore, the study's results also showed that the application of MfK in fifth-grade elementary school students did not reveal significant differences between male and female students. These results are consistent with the finding that digital spatial experience-based training can reduce the gender gap in children's spatial abilities. Digital games and 3D modeling have been shown to improve spatial abilities for all children. Several studies have reported that this form of intervention can reduce gender differences, especially in mental rotation and in children who initially have low spatial abilities [47, 48]. This means that MfK has the potential to become an inclusive and gender-equal learning medium.

C. Comparison of Spatial Ability Based on Type of Spatial Ability

Spatial ability consists of the main abilities, namely (1) spatial visualization, (2) spatial rotation, (3) spatial orientation, (4) spatial relational, and (5) spatial perception. Because the data is not normally distributed, the Friedman Test is used to determine the differences between the five types of spatial ability. Table 4 presents the results of the Friedman test, which indicate significant differences among the five types of spatial ability.

Table 4. Friedman test results for spatial ability types

Description	Value	Explanation
N	102	—
Chi-Square	173.604	—
Df	4	—
Asymp. Sig	0,000	< 0.05 (significant)

Table 5 below describes the posttest data for the five types of spatial abilities studied. Table 5 presents descriptive results of the spatial abilities of fifth-grade students after using MfK, which encompasses five aspects of spatial ability: spatial visualization, spatial relational, spatial rotation, spatial perception, and spatial orientation. The analysis was conducted on two groups based on gender: male and female students, each comprising 51 fifth-grade students.

In general, the average scores indicate that both male and female students experienced improvements in spatial abilities after participating in Metaverse-based learning. However, there were variations in the average differences between genders in each spatial aspect. This is explained below.

Table 5. Description of spatial ability type data after using MfK reviewed by gender

Description	gender	Spatial visualization	Spatial relational	Spatial rotation	Spatial perception	Spatial orientation
N	Female	51	51	51	51	51
	Male	51	51	51	51	51
Missing	Female	0	0	0	0	0
	Male	0	0	0	0	0
Mean	Female	0.765	1.86	1.39	1.22	1.63
	Male	0.706	1.78	1.53	1.39	1.67
Mean	Female	1	2	1	1	2
	Male	1	2	2	2	2
Standard deviation	Female	0.473	0.348	0.666	0.642	0.631
	Male	0.576	0.541	0.644	0.695	0.589

1) Spatial visualization

The average spatial visualization ability of the female student group (M = 0.765; SD = 0.473) was slightly higher than that of the male group (M = 0.706; SD = 0.576). This indicates that female students have a slightly better visual-spatial ability in recognizing the shape and position of objects visually after practicing with MfK.

2) Spatial relational

In spatial relational ability, the female student group also showed a higher average (M = 1.86; SD = 0.348) compared to the male group (M = 1.78; SD = 0.541). This means that the female student group was better able to understand the relationship between objects in space after practicing using MfK.

3) Spatial rotation

The male student group has the ability to rotate and visualize various objects in three-dimensional space. This is supported by data in the form of an average score of spatial rotation ability for the male student group (M=1.53; SD=0.644), which is higher than the female student group (M=1.39; SD=0.666). Conversely, in terms of spatial rotational ability, students

4) Spatial perception

It is indicated that the male student group has a different perspective on object perception. The female student group has a lower average score (M = 1.22; SD = 0.642) than the male student group (M = 1.39; SD = 0.695) in spatial perception ability.

5) Spatial orientation

In terms of spatial orientation ability, the female and male student groups were relatively similar, as indicated by the minor average differences. The overall data analysis demonstrates that MfK effectively improves the spatial abilities of fifth-grade male and female elementary school students. However, the types of spatial abilities possessed by the male and female students varied. Some types of spatial abilities are higher in male students (rotational and perceptual spatial abilities), while others are higher in female students (visual and relational spatial abilities).

The distribution of data across the five types of spatial abilities varies greatly, as shown in Fig. 5. Spatial relational ability tends to cluster at high scores above 2, whereas spatial visualization ability tends to cluster at low scores below 1. Meanwhile, the distribution of spatial rotational and spatial perceptual abilities is relatively similar.

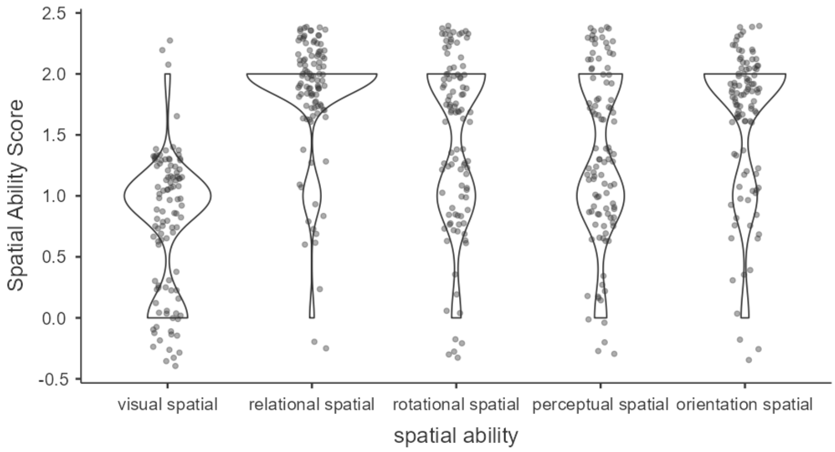

Fig. 5. The distribution of posttest scores is reviewed based on the type of spatial ability.

Next, a post hoc test was conducted to determine whether significant differences existed among the five types of spatial abilities studied, and it was found that such differences did exist. The ranking, from highest to lowest, is as follows: spatial relational, spatial orientation, spatial rotation, spatial perception, and spatial visualization.

An interesting point to discuss further is spatial relation ability, a type of spatial ability that achieved the highest score after students used MfK to learn geometry. Students practiced MfK through a simulation game that combined various geometric shapes by dismantling and reassembling them. Through this practice of using MfK, students became more familiar with various geometric objects in the form of solid or flat shapes and saw the relationships between these geometric shapes.

Additionally, the development of MfK was tailored to the learning needs of grade 5 students during the needs analysis stage. In 2024, students and teachers in grade 5 from the city of Semarang, who were selected as respondents, completed a needs analysis questionnaire. The results of the needs analysis showed that their needs related to students' ability to analyze the relationship between geometric structures, so MfK was developed. This feature was introduced to students at the first meeting, and they were directed to identify the similarities and differences between the geometry objects studied. From this task, students' experiences were formed to see the proximity between the geometry objects studied.

The results of the study [49] show that they align with the characteristics of MfK, indicating that a relationship between objects and building representations can be established through interactive 3D simulations in geometry learning, thereby reducing misconceptions and increasing the accuracy of spatial representations. In this regard, MfK can encourage students to solve space-based problems and understand the concepts of position and the relationships between various elements in cyberspace.

However, MfK, which is a combination of AR and VR, has not incorporated gamification elements into its practical use, so students are still playing freely and have not been directed to important parts that can be repeated according to their individual needs. According [50] Gamification is a key element in implementing the metaverse as a learning tool. Gamification can take the form of game mechanics, such as the use of game levels and game dynamics, with rewards or challenges provided to metaverse users.

This study has several limitations that should be considered when interpreting the findings. The first important limitation concerns differences in students' levels of technological familiarity. Differences in prior experience with digital devices and 3D media can increase cognitive load during VR navigation and thereby impair spatial learning, mainly by making interface operation itself a demanding extra task [51–53]. Although the Metaverse for Kids learning environment was designed to be child-friendly, not all students had the same prior experience in using digital devices or interactive 3D learning media. As a result, some students may have experienced difficulties in navigating the virtual environment, which could have increased their cognitive load and reduced their focus on the spatial learning tasks. Consequently, students who were more familiar with digital technologies may have benefited more from the metaverse-based learning environment [54, 55], while those with lower technological familiarity may not have fully utilized the features provided. Future research is recommended to more rigorously control students' technological familiarity, for example, by providing longer training sessions, using pre-tests of digital literacy, or ensuring a more homogeneous level of technological experience among participants before implementing metaverse-based instruction.

The second limitation is the location. Research on the implementation of metaverse learning in urban and rural elementary schools threatens generalizability. This is because school location is closely linked to inequalities in resources, socioeconomic context, and learning environments. Urban-rural/suburban disparities in infrastructure, teacher quality, and poverty profiles are well-documented and may translate into different learning opportunities and outcomes, regardless of the metaverse intervention itself [52, 56–58]. However, the use of technology or applications in geometry learning in elementary schools that already exist in Semarang City varies greatly from simple ones, namely learning video media, AR, and VR applications, so that researchers find it difficult to determine a uniform technology in the control classroom for students. This certainly has an influence on students' initial experience with using technology in learning geometry from different angles, especially for students in suburban schools and those in the middle of Semarang.

Continuous follow-up in this study requires substantial funding, as the use of MfK necessitates expensive tools costing up to 4-5 million rupiah. So that schools have difficulty providing support tools for the independent implementation of MfK. However, it is possible if it is supported by the increased costs of school operations.

Overall, this study demonstrates that MfK is efficacious in improving elementary school students' spatial abilities, particularly in relational aspects. Furthermore, the results highlight the importance of integrating immersive technology into the elementary school curriculum in Indonesia, particularly in Semarang City, as it can support the development of 21st-century skills, including spatial thinking, creativity, and technological literacy.

V. Conclusion

The research results indicate that the practice of using MfK for learning geometry is efficacious in improving the spatial abilities of 5th-grade elementary school students. This is demonstrated by an increase in students' abilities before and after practicing MfK. In general, there is no significant difference in spatial abilities between male and female student groups; however, descriptively, female students tend to excel in spatial visualization and relational abilities, while male students show an advantage in spatial rotation and spatial perception abilities. Among the five types of spatial abilities, the one that increased the most after using MfK is relational spatial ability.

The recommendation from this study is that the use of the metaverse for elementary school students should consider gamification aspects, so that users can be more directed, and it can provide a positive impact according to the needs and development of elementary school students.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This research is divided into the following tasks: Trimurtini and Farid Ahmadi conducted the research, while Elok F. Sari and Elvi Mailani analyzed the data; Moh. F. Irvan wrote the paper, Muhammad T. Machmud and Nurhudayah Manjani collected the research data; Robenhart Tamba served as the proofreader; Tassanee Juntya as the validator; all authors approved the final version.

Acknowledgment

We would like to express our gratitude to LPPM UNNES for their generous provision of a grant for this research project, which is identified as Number B/397/UN37/HK.02/2025.

References

[1] J. Kang, X. Xu, and L. Yan, "Leveraging affordances of Immersive Technology-Supported Collaborative Learning (ITCL): A systematic review," *Educ. Inf. Technol.*, vol. 30, no. 1, pp. 607–647, Jan. 2025. doi: 10.1007/s10639-024-13079-y

[2] A. F. Mubarok and M. Islamiyah, "What is the spatial ability profile of elementary school students in solving geometry problems ?" *El-Aulad J. Pendidik. Dasar*, vol. 01, no. 01, pp. 10–18, 2024. doi: https://doi.org/10.47731/ppjkpj24

[3] S. Maemunah, S. F. Giwangsa, and M. Somantri, "The effectiveness of using Google earth to improve the spatial skills of phase B elementary school students," *PALAPA*, vol. 13, no. 2, pp. 189–201, Nov. 2025. doi: 10.36088/palapa.v13i2.5873

[4] U. Hasanah, S. Putrawangsa, E. Purwanta, F. Agus Setiawati, and Y. W. Purnomo, "Primary student spatial reasoning abilities: Progression and challenges," *J. Pendidik. Mat.*, vol. 18, no. 3, pp. 329–348, Aug. 2024. doi: 10.22342/jpm.v18i3.pp329-348

[5] H. Burte, A. L. Gardony, A. Hutton, and H. A. Taylor, "Think3d !: Improving mathematics learning through embodied spatial training," *Cogn. Res. Princ. Implic.*, vol. 2, no. 13, pp. 1–18, 2017. doi: 10.1186/s41235-017-0052-9

[6] C. Ananda and L. Loustiawaty, "Studi kualitatif tentang penggunaan media gambar interaktif dalam meningkatkan pemahaman geometri dasar pada siswa kelas 4 SDN 2 Begawat," *Papanda J. Math. Sci. Res.*, vol. 4, no. 2, pp. 273–283, Sep. 2025. doi: 10.56916/pjmsr.v4i2.2316

[7] L. Margarita, M. Herrera, S. J. Ordóñez, S. Ruiz-loza, F. Reinhold, and S. Ruiz-loza, "Enhancing mathematical education with spatial

visualization tools," *Front. Educ.*, no. February, pp. 1–13, 2024. doi: 10.3389/feduc.2024.1229126

[8] K. Owusu-antwi and F. Edem, "Understanding the Metaverse : A review of virtual worlds and augmented reality environments," *Curr. J. Appl. Sci. Technol.*, vol. 42, no. 23, pp. 42–48, 2023. doi: 10.9734/CJAST/2023/v42i234172

[9] Ş. Baltaci and S. Çetin, "The effect of augmented reality on achievement and spatial visualization skills in technical drawing course," *J. Learn. Teach. Digit. Age*, vol. 7, no. 2, pp. 250–259, Jul. 2022. doi: 10.53850/joltida.1047477

[10] P. Haryo and A. Makmur, "The use of Metaverse in providing interactive learning experiences in schools," *Perspekt. Ilmu Pendidik.*, vol. 38, no. 1, pp. 10–24, Apr. 2024. doi: 10.21009/PIP.381.2

[11] P. H. Maier, "Spatial geometry and spatial ability-how to make solid geometry solid," in *Proc. Anual Conference of Didactics of Mathematics*, 1996, pp. 69–81.

[12] F. Anvari, H. M. T. Tran, and M. Kavakli, "Using cognitive load measurement and spatial ability test to identify talented students in three-dimensional computer graphics programming," *Int. J. Inf. Educ. Technol.*, vol. 3, no. 1, pp. 94–99, 2013. doi: 10.7763/IJIET.2013.V3.241

[13] I. G. N. Pujawan and I. P. P. Suryawan, "Effectiveness of STEM approach on mathematical communication ability," in *Proc. the 5th Asian Education Symposium 2020 (AES 2020)*, 2021, vol. 566, no. 20, pp. 368–372. doi: 10.2991/assehr.k.210715.078

[14] L. Piccardi, R. Nori, J. M. Cimadevilla, and M. Kozhevnikov, "The contribution of internal and external factors to human spatial navigation," *Brain Sci.*, vol. 14, no. 6, p. 585, Jun. 2024. doi: 10.3390/brainsci14060585

[15] M. C. Linn and A. C. Petersen, "Emergence and characterization of sex differences in spatial ability: A meta-analysis," *Child Dev.*, vol. 56, no. 6, p. 1479, Dec. 1985. doi: 10.2307/1130467

[16] N. Newcombe, M. M. Bandura, and D. G. Taylor, "Sex differences in spatial ability and spatial activities," *Sex Roles*, vol. 9, no. 3, pp. 377–386, Mar. 1983. doi: 10.1007/BF00289672

[17] Y. K. Dwivedi *et al.*, "International journal of information management Metaverse beyond the hype : Multidisciplinary perspectives on emerging challenges , opportunities, and agenda for research , practice and policy," *Int. J. Inf. Manage.*, vol. 66, no. July, 102542, 2022. doi: 10.1016/j.ijinfomgt.2022.102542

[18] R. S. Pujasari, A. S. Fatimah, M. Sri, and F. Sulastri, "Potential benefits of metaverse concept implementation in English for tourism course: A case study in Indonesian higher education contexts," *Int. J. Lang. Educ.*, vol. 8, no. 3, pp. 520–532, Oct. 2024. doi: 10.26858/ijole.v8i3.66494

[19] K. Topraklıkoğlu and G. Öztürk, "Metaverse application development for teaching geometry in virtual reality environment," *J. Educ. Technol. Online Learn.*, vol. 8, no. 1, pp. 112–135, Jan. 2025. doi: 10.31681/jetol.1596173

[20] K. Al-said, E. Margarian, and V. Spichak, "Personal competence formation in education : The effectiveness of the development and use of gamified learning based on the metaverse," *Int. J. Inf. Educ. Technol.*, vol. 15, no. 1, pp. 70–79, 2025. doi: 10.18178/ijiet.2025.15.1.2219

[21] J. M. Krüger, K. Palzer, and D. Bodemer, "Learning with augmented reality : Impact of dimensionality and spatial abilities," *Comput. Educ. Open*, vol. 3, no. December 2021, 100065, 2022. doi: 10.1016/j.caeo.2021.100065

[22] A. Nguyen *et al.*, "Conceptualizing and enhancing metaverse literacy for education," *Educ. Inf. Technol.*, vol. 30, no. 12, pp. 17133–17153, Aug. 2025. doi: 10.1007/s10639-025-13486-9

[23] R. Susilana, L. Dewi, and G. Rullyana, "Exploring student perceptions of virtual learning experiences: A study of the use of the spatial.io 3D metaverse platform," *J. Educ. Technol.*, vol. 8, no. 4, pp. 673–683, Nov. 2024. doi: 10.23887/jet.v8i4.85190

[24] A. Hamdan, A. Kurnia, and I. Tan, "Geo-Virtual Reality (GVR): The creative materials to construct spatial thinking skills using virtual learning based metaverse technology," *Think. Ski. Creat.*, vol. 54, no. November 2023, 101664, 2024. doi: 10.1016/j.tsc.2024.101664

[25] M. A. Camilleri, "Metaverse applications in education: A systematic review and a cost-benefit analysis," *Interact. Technol. Smart Educ.*, vol. 21, no. 2, pp. 245–269, Apr. 2024. doi: 10.1108/ITSE-01-2023-0017

[26] T. Kim, J. Planey, and R. Lindgren, "Theory-driven design in metaverse virtual reality learning environments: Two exemplary cases," *IEEE Transactions on Learning Technologies*, 2023. doi: 10.1109/TLT.2023.3307211

[27] X. Di and X. Zheng, "A meta-analysis of the impact of virtual technologies on students' spatial ability," *Educ. Technol. Res. Dev.*, vol. 70, no. 1, pp. 73–98, 2022. doi: 10.1007/s11423-022-10082-3

[28] S. Pahmi, A. Vrapi, and E. Supriyadi, "Implementation of virtual reality to enhance spatial abilities: A study on aspects, effects, and differences in participants' initial ability levels," *Int. J. Didact. Math. Distance Educ.*, vol. 1, no. 2, pp. 54–69, Aug. 2024. doi: 10.33830/ijdmde.v1i2.9108

[29] K. Betts *et al.*, "An examination of the effects of virtual reality training on spatial visualization and transfer of learning," *Brain Sci.*, vol. 13, no. 6, 890, May 2023. doi: 10.3390/brainsci13060890

[30] Y. Zhou, T. Xu, H. Yang, and S. Li, "Improving spatial visualization and mental rotation using forspatial through shapes and letters in virtual environment," *IEEE Trans. Learn. Technol.*, vol. 15, no. 3, pp. 326–337, 2022.doi: 10.1109/TLT.2022.3170928

[31] J. Lee, H. C. Lum, J. R. Lee, S. Evans, Y. Liu, and T. Kampf, "Impact of immersion in Virtual Reality (VR) and desktop environments on spatial ability," no. September, pp. 2–7, 2024. doi: 10.1177/10711813241265656

[32] R. Molina-Carmona, "Virtual reality learning activities for multimedia students to enhance spatial ability," *Sustainability*, pp. 1–13, 2018. doi: 10.3390/su10041074

[33] R. Sun, Y. Jim, and W. Qian, "The effect of a virtual reality learning environment on learners' spatial ability," *Virtual Real.*, 0123456789, 2018. doi: 10.1007/s10055-018-0355-2

[34] R. S. Soares, K. L. Ramirez-Chavez, A. Tufanoglu, C. Barreto, J. R. Sato, and H. Ayaz, "Cognitive effort during visuospatial problem solving in physical real world, on computer screen, and in virtual reality," *Sensors*, vol. 24, no. 3, p. 977, Feb. 2024. doi: 10.3390/s24030977

[35] W. Li, C. Wang, W. Wang, Q. Feng, and B. Liu, "Learning in the spherical video-based virtual reality context : Effects of immersion level and spatial ability on learning performance and experience," *Interact. Learn. Environ.*, vol. 33, no. 2, pp. 1216–1237, 2025. doi: 10.1080/10494820.2024.2367019

[36] P. Onu, A. Pradhan, and C. Mbohwa, "Potential to use metaverse for future teaching and learning," *Educ. Inf. Technol.*, vol. 29, no. 7, pp. 8893–8924, May 2024. doi: 10.1007/s10639-023-12167-9

[37] T. Bobko, M. Corsette, M. Wang, and E. Springer, "Exploring the possibilities of edu-metaverse: A new 3-D ecosystem model for innovative learning," *IEEE Trans. Learn. Technol.*, vol. 17, pp. 1278–1289, 2024. doi: 10.1109/TLT.2024.3364908

[38] E. Youssef, M. A. Malak, and M. Bayoumy, "Metaverse in education: A survey-based investigation of collaborative learning and immersive experiences," *Emerg. Sci. J.*, vol. 8, pp. 379–395, Feb. 2025. doi: 10.28991/ESJ-2024-SIED1-022

[39] B. Kye, N. Han, E. Kim, Y. Park, and S. Jo, "Educational applications of metaverse: Possibilities and limitations," *J. Educ. Eval. Health Prof.*, vol. 18, no. 32, p. 32, Dec. 2021. doi: 10.3352/jeehp.2021.18.32

[40] S. Kaddoura and F. Al Husseiny, "The rising trend of metaverse in education: Challenges, opportunities, and ethical considerations," *PeerJ Comput. Sci.*, vol. 9, pp. 1–33, 2023. doi: 10.7717/peerj-cs.1252

[41] A. Marini *et al.*, "Mobile augmented reality learning media with metaverse to improve student learning outcomes in science class," *Int. J. Interact. Mob. Technol.*, vol. 16, no. 07, pp. 99–115, Apr. 2022. doi: 10.3991/ijim.v16i07.25727

[42] X. Zhang, Y. Chen, L. Hu, and Y. Wang, "The metaverse in education: Definition, framework, features, potential applications, challenges, and future research topics," *Front. Psychol.*, no. October, pp. 1–18, 2022. doi: 10.3389/fpsyg.2022.1016300

[43] Y. Diao and Y. Su, "Exploring the impact of the metaverse on promoting students' access to quality education: A meta-analysis," *IEEE Trans. Learn. Technol.*, vol. 18, pp. 321–334, 2025. doi: 10.1109/TLT.2025.3550714

[44] X. Geng and Y.-S. Su, "Enhancing K-12 students' STEM learning through the integration of the metaverse into online and blended environments: A meta-analysis," *Int. J. Sci. Math. Educ.*, vol. 22, no. S1, pp. 111–143, Dec. 2024. doi: 10.1007/s10763-024-10484-0

[45] J. M. Clark and A. Paivio, "Dual coding theory and education," *Educ. Psychol. Rev.*, vol. 3, no. 3, pp. 149–210, 1991. doi: 10.1007/BF01320076

[46] B. Park, J. L. Plass, and R. Brünken, "Cognitive and affective processes in multimedia learning," *Learn. Instr.*, vol. 29, pp. 125–127, 2014. doi: 10.1016/j.learninstruc.2013.05.005

[47] K. B. Vukman, "The effect of 3D-modeling training on students' spatial reasoning relative to gender and grade," *Journal of Educational Computing Research*, 2016. doi: 10.1177/0735633115620430

[48] J. Chi and S. Y. Chen, "Computers & education effects of gender differences and spatial abilities within a digital pentominoes game," *Comput. Educ.*, vol. 55, no. 3, pp. 1220–1233, 2010. doi: 10.1016/j.compedu.2010.05.019

[49] B. Gustav, V. Stenberdt, R. E. Mayer, and G. Makransky, "Computers & education collaborative generative learning activities in immersive virtual reality increase learning," *Computers & Education*, vol. 207, no. April, 2023. doi: 10.1016/j.compedu.2023.104931

[50] J. Karapakdee and P. Wannapiroon, "Immersive digital storytelling learning experience with a metaverse gamification game platform to enhance game developer competency," *Environment*, vol. 13, no. 6, 2023. doi: 10.18178/ijiet.2023.13.6.1884
[51] R. Nori, M. M. Zucchelli, M. Palmiero, and L. Piccardi, "Environmental cognitive load and spatial anxiety: What matters in navigation?" *J. Environ. Psychol.*, vol. 88, no. May, 102032, Jun. 2023. doi: 10.1016/j.jenvp.2023.102032
[52] F. Ahmadi, S. E. Mulyono, B. A. A.-R. Al-Ghamdi, and D. Harjunowibowo, "Comparative study of the development of android-based flipped classroom model between Jeddah and Indonesia," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 10, no. 2, pp. 542–547, Apr. 2020. doi: 10.18517/ijaseit.10.2.11447
[53] M. A. Kuhail, A. ElSayary, S. Farooq, and A. Alghamdi, "Exploring immersive learning experiences: A survey," *Informatics*, vol. 9, no. 4, p. 75, Sep. 2022. doi: 10.3390/informatics9040075.
[54] M. Li and Z. Yu, "A systematic review on the metaverse-based blended English learning," *Front. Psychol.*, vol. 13, pp. 1–15, Jan. 2023. doi: 10.3389/fpsyg.2022.1087508
[55] A. S. Al-Adwan, N. Li, A. Al-Adwan, G. A. Abbasi, N. A. Albelbisi, and A. Habibi, "Extending the Technology Acceptance Model (TAM) to predict university students' intentions to use metaverse-based learning platforms," *Educ. Inf. Technol.*, vol. 28, no. 11, pp. 15381–15413, Nov. 2023. doi: 10.1007/s10639-023-11816-3
[56] J. R. Logan and J. Burdick-Will, "School segregation and disparities in urban, suburban, and rural areas," *Ann. Am. Acad. Pol. Soc. Sci.*, vol. 674, no. 1, pp. 199–216, Nov. 2017. doi: 10.1177/0002716217733936
[57] K. Bischoff and P. Rich, "Neighborhood effects on schools and students," *The Sage Handbook of Sociology of Education*, pp. 481–500, 2024. doi: 10.4135/9781529783506.n31
[58] W. Fu and A. T. B. M. Hashim, "The impact of urban and rural education gap on student achievement differences," *J. Contemp. Educ. Res.*, vol. 8, no. 9, pp. 145–150, Sep. 2024. doi: 10.26689/jcer.v8i9.8388