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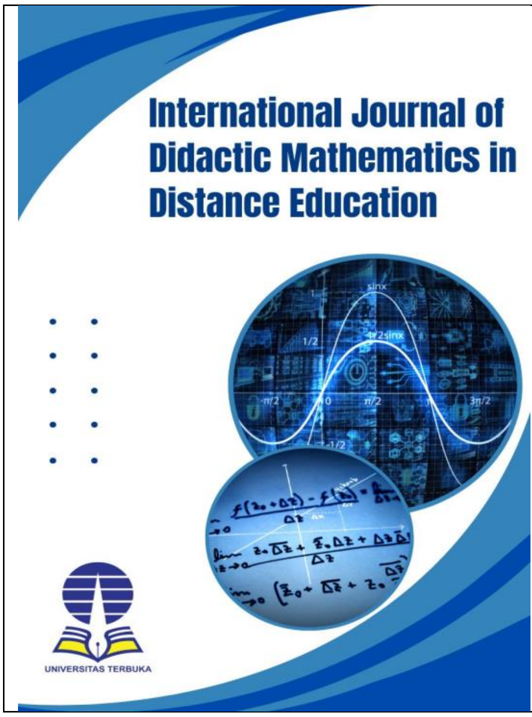

Implementation of virtual reality to enhance spatial abilities: a study on aspects, effects, and differences in participants' initial ability levels

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Implementation of virtual reality to enhance spatial abilities: a study on aspects, effects, and differences in participants' initial ability levels

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Abstract
This research is important because the development of Virtual Reality (VR) technology has shown significant potential in enhancing spatial abilities, which are crucial aspects of education and training across various fields. This study aims to identify and evaluate the extent to which VR can enhance spatial abilities and determine the factors that influence the adoption of VR in educational contexts. The specific target is to identify at least three main factors affecting the effectiveness of VR in improving spatial abilities and to evaluate its impact on differences in students' initial abilities. The research method used is a Systematic Literature Review (SLR), which involves identifying, evaluating, and interpreting all relevant research that answers specific research questions. Data were collected from three major databases: Scopus, ScienceDirect, and Sage Journal, covering 2013 to 2022. This study focuses on considerations for using VR, its impact on differences in initial spatial abilities, and the various aspects of spatial abilities affected by VR intervention. The results from the 26 studies reviewed indicate that the use of VR technology in learning can enhance spatial abilities, with the most studied aspect being mental rotation. Additionally, VR has a greater impact on participants with a low spatial ability background. From an affective aspect, the use of VR significantly influences participants' motivation and interest, attributed to the realistic and interactive effects perceived. The implications of this research provide important contributions for researchers and educational practitioners to develop more effective interventions in enhancing spatial abilities in the future.

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1. Introduction

Mathematics and spatial abilities are closely related, specifically focusing on space and form. On the other hand, spatial ability is the capacity to understand and manipulate visual and spatial information, such as visual memory, spatial construction, mental rotation, pattern filling, and spatial orientation. Regarding this, Gardner (1993) defines spatial ability as the capacity to accurately understand spatial-visual forms, which includes the ability to identify shapes and objects, manipulate forms in the mind and recognize those changes, describe spatial forms mentally and transform them into real shapes, and represent data in graphs. Referring to the aspects studied in geometry, spatial ability plays a crucial role. Spatial ability itself can be defined as the capacity to understand, reason, and remember visual and spatial relationships between objects or spaces (West et al., 2013). In a study conducted by Yang et al. (2014), considering the opinions of Lohman et al. (1987) as well as Carroll (1993), five different spatial abilities were identified: (i) Visuo-spatial memory, (ii) visuo-spatial construction, (iii) mental rotation, (iv) closure, and (v) direction finding.

Previous research has extensively examined the influence of spatial abilities on mathematics and geometry learning outcomes. For example, a meta-analysis conducted by Atit et al. (2021) concluded that spatial skills are significantly related to mathematical skills. It was further explained that spatial skills and mathematical skills have a direct positive relationship. Sudirman and Alghadari (2020) research reveals effective methods for developing spatial abilities in mathematics education, which are essential for enhancing skills such as spatial relations, mental rotation, and spatial visualization. Hawes et al. (2019) also found a strong correlation between spatial skills and mathematical skills. Despite the abundance of real-life objects that can support spatial abilities, without special treatment, the development of spatial abilities remains relatively low. This is consistent with several studies that still find issues with each type of spatial ability. For instance, Onyancha et al. (2009) found that only about 48.3% of students completed spatial tasks. Research by Anggriawan et al. (2017) showed that 40% of students still have low spatial abilities, which aligns with findings by Supriadi et al. (2021) that most first-year (81.25%) and third-year (79.5%) students have very low spatial abilities.

To address these difficulties, several researchers have conducted experiments that have produced recommendations for geometry education. Van Hiele, in his thesis (in Fuys, 1984), proposed phases in the process of learning geometry: Phase 1: Information (Inquiry), Phase 2: Directed Orientation, Phase 3: Explication, Phase 4: Orientation, and Phase 5: Integration. Further, in terms of learning content, the use of visualization media is a widely discussed recommendation, such as the use of GeoGebra (Bhagat & Chang, 2015), real shapes (Vidermanova & Vallo, 2015), and virtual reality (Bamodu & Ye, 2013). Research related to the use of interactive media in learning geometry has also been widely conducted, with the term technology as an alternative in the implementation of learning developing significantly in recent years. Particularly in mathematics education, several studies have found the potential of using VR in geometry topics (Cangas et al., 2021; Rodríguez, 2022). This indicates that readiness to use a tool or learning media significantly affects its impact on the learning process and outcomes. Thus, it is expected that teachers, as facilitators in the learning process, should be able to design teaching materials that are appropriate to the conditions and situations of the environment.

Implementation of VR on Spatial Ability

To spatial ability, numerous studies have been conducted integrating VR into learning to enhance spatial skills. González (2018) attempted to develop VR (Virtual Reality) and AR (Augmented Reality) to test university students' visual perception and spatial expression abilities using SketchUp software for rendering in VR. González concluded that using digital media can stimulate students to learn spatial skills. Another study by Kimura et al. (2019), with the aid of VR, tested two common types of spatial information: geometric type, which includes distance and directional turns. The study showed that younger adults are more capable of adapting to spatial changes in the environment compared to older adults. On the other hand, Lochhead et al. (2022) also evaluated spatial ability in the aspect of mental rotation ability using the Mental Rotation Test (MRT) instrument. In their research, Lochhead et al., through the Oculus Quest medium, demonstrated that MRT performance is better when mental rotation is conducted in 3D VR than in 2D images. Still related to VR research and spatial ability in mental rotation, Guzsvinecz et al. (2022) tested university students using Gear VR with an MRT type of test. The conclusion found by Guzsvinecz et al. is that the completion time for the MRT test using VR for male students is significantly longer than for female students.

Knowledge Gap and Research Questions

Referring to the processes and results of the previously discussed studies, the implementation of VR technology in spatial abilities has become an increasingly intriguing topic in recent years. Several studies have demonstrated the potential positive effects of VR on spatial abilities (González, 2018; Kimura et al., 2019; Lochhead et al., 2022). Despite the potential benefits of VR in enhancing spatial abilities, further research is needed to understand the extent to which this technology can enhance spatial abilities, considering the various types of spatial skills. Additionally, known issues regarding the barriers and challenges in adopting VR technology to improve spatial abilities need to be further elaborated. Another issue that needs consideration is the difference in initial student abilities, which undoubtedly has a significant impact on their learning process. Given the significant knowledge gap observed, this research focuses on exploring the impact of VR technology on the development of spatial abilities based on initial ability groups and identifying factors to be considered in the adoption and implementation of VR technology across various types of spatial abilities. Based on this description, the research questions to be addressed in this study are as follows:

RQ1. What aspects need to be considered when implementing VR to enhance spatial abilities?
RQ2. How does the use of VR affect the overall enhancement of spatial abilities?
RQ3. How does the use of VR affect the improvement of spatial abilities based on differences in participants' initial spatial ability levels?
RQ4. How does the use of VR impact spatial abilities based on different aspects of spatial skills?

2. Method

In the context of technological development, the concept of virtual reality has garnered increasing attention in recent years. However, the use of this technology for enhancing spatial abilities requires thorough exploration. To achieve this objective, a Systematic Literature Review (SLR) will be employed as the method to identify, evaluate, and interpret all relevant research related to specific research questions, thematic areas, or phenomena of interest. The review and mapping process in this work includes an analysis of relevant research on the use of virtual reality technology in enhancing spatial abilities. The phases followed in this SLR study refer to the steps outlined by Petersen et al. (2015), which include reviewing related research; defining the research questions; establishing inclusion and exclusion criteria; defining the search process; setting quality criteria; data extraction; results and data analysis; and report writing.

2.1. Inclusion and exclusion criteria

The following indicators are used for the inclusion and exclusion criteria. The Inclusion Criteria consist of (i) studies utilizing VR technology to enhance spatial ability; (ii) studies involving participants ranging from pre-primary school, primary school, secondary school, higher education, or the general public; (iii) studies reporting evaluation results of spatial ability following the use of VR; (iv) studies published in English within the timeframe of 2013 to 2022 to ensure recency; (v) studies employing experimental, survey, or observational methods relevant to the research; and (vi) studies explaining aspects to be considered in implementing VR to enhance spatial ability. The Exclusion Criteria consist of (i) studies not utilizing VR technology to enhance spatial ability; (ii) studies containing questions that are too general or broad, thus not providing clear direction to the research; (iii) studies not reporting evaluation results of spatial ability following the use of VR; (iv) studies not published in English and those published before 2013 or after 2022; (v) studies not addressing any of the research questions.

2.2. Search process

The literature search was conducted on three databases: Scopus, ScienceDirect, and Sage Journal. These databases are well-regarded in terms of both quality and quantity. In this review, the search strings for each selected electronic database are as follows.

Table 1
Keywords and Search Limits

Description	Scopus	ScienceDirect	Sage Journal
Keywords	TITLE-ABS-KEY = ("Virtual Reality*" AND "Spatial Ability*")	Find articles with these terms = ("Virtual Reality*" AND "Spatial Ability*")	Search All Content = "Virtual Reality" AND "Spatial Ability"
Limits	(LIMIT-TO (SUBJAREA,"SOCI") OR LIMIT-TO (SUBJAREA,"MATH")) AND (LIMIT-TO (PUBYEAR, 2022 - 2013)) AND (LIMIT-TO (LANGUAGE,"English"))	Applied filters: Social Sciences & Humanities, Education, Communication & Media Studies, Research article, 2013 - 2022	Article type: Research articles; Publication title: Computers & Education, Journal of Surgical Education; Subject areas: Social Sciences; Refine by 2013-2022

2.3. Quality criteria

The research results that meet the inclusion criteria and do not align with any of the exclusion criteria will proceed to be reviewed based on the established quality criteria. Each question has three options, and the answers are coded as yes (1 point), partial (0.5 points), and no (0 points). Research that enters the final process must have a score of 7.0 or higher as the final selection threshold for the paper.

The quality criteria used in this SLR are as follows:

4.3.1. The definition of VR concepts and spatial abilities must be clear in the paper to evaluate the success of the technology implementation.
4.3.2. It is important to establish clear and well-defined research objectives so that the study can be effectively directed.
4.3.3. The research must be well-designed and conducted with appropriate methods to achieve the set objectives.
4.3.4. The research instruments used must be well-explained and suitable for the research design to produce accurate and relevant data.
4.3.5. The sample size and research population must be clearly described to allow for proper analysis of the research results.
4.3.6. The paper must adequately answer the research questions and provide useful information for developing an understanding of VR and spatial abilities.
4.3.7. Conclusions must be clearly explained and based on tested research results to ensure the validity of the research and its relevance to the stated objectives.
4.3.8. The research must acknowledge existing problems and limitations and provide suggestions for further development so that the paper can improve research methods and increase the accuracy of the results obtained.

2.4. Quality criteria

The development stage is the phase that includes the implementation of the SLR, where we refer to the PRISMA standard. PRISMA creates a uniform, peer-reviewed technique that uses checklists of best practices to help ensure the quality and reproducibility of the review process (Conde et al., 2020). Identification, screening, eligibility, and inclusion are the foundational elements of PRISMA as presented in Figure 1. In the initial search process, various types of publications were obtained, such as differences in Article type, Subject areas, and year of publication. Therefore, the selection of articles was adjusted to Keywords and Search Limits (Table 1).

3. Results and Discussion

3.1. Results

The initial search results, based on the selected keywords (Table 1), yielded a total of 490 articles from three major databases: Scopus (228 articles), ScienceDirect (212 articles), and SAGE Journals (50 articles). The first step in the screening process involved eliminating duplicate entries and applying search limits, such as publication dates and document types, as outlined in Table 1. As a result, the number of articles was significantly reduced to 98, with Scopus contributing 73 articles, ScienceDirect 20 articles, and SAGE Journals 5 articles. This initial reduction marked an important phase in refining the pool of studies for further analysis.

The subsequent phase focused on applying the inclusion and exclusion criteria to the remaining 98 articles. These criteria were designed to ensure that only the most relevant studies aligned with the research objectives were retained. Following this process, 54 articles were selected. This stage further refined the collection of articles by filtering out those that did not meet the set requirements, such as studies outside the scope of the research or those lacking the necessary methodological rigor.

Finally, each of the 54 articles underwent a rigorous evaluation based on predetermined quality criteria, with a minimum score of ≥ 7.0 required for inclusion in the systematic literature review (SLR). After this critical assessment, the selection was narrowed down to 26 articles that fully met the quality standards. These articles were deemed robust enough to be analyzed in the SLR. The entire article screening process, from keyword search to quality assessment, is depicted in the PRISMA flow diagram, which outlines the systematic approach taken to ensure a thorough and reliable selection of studies.

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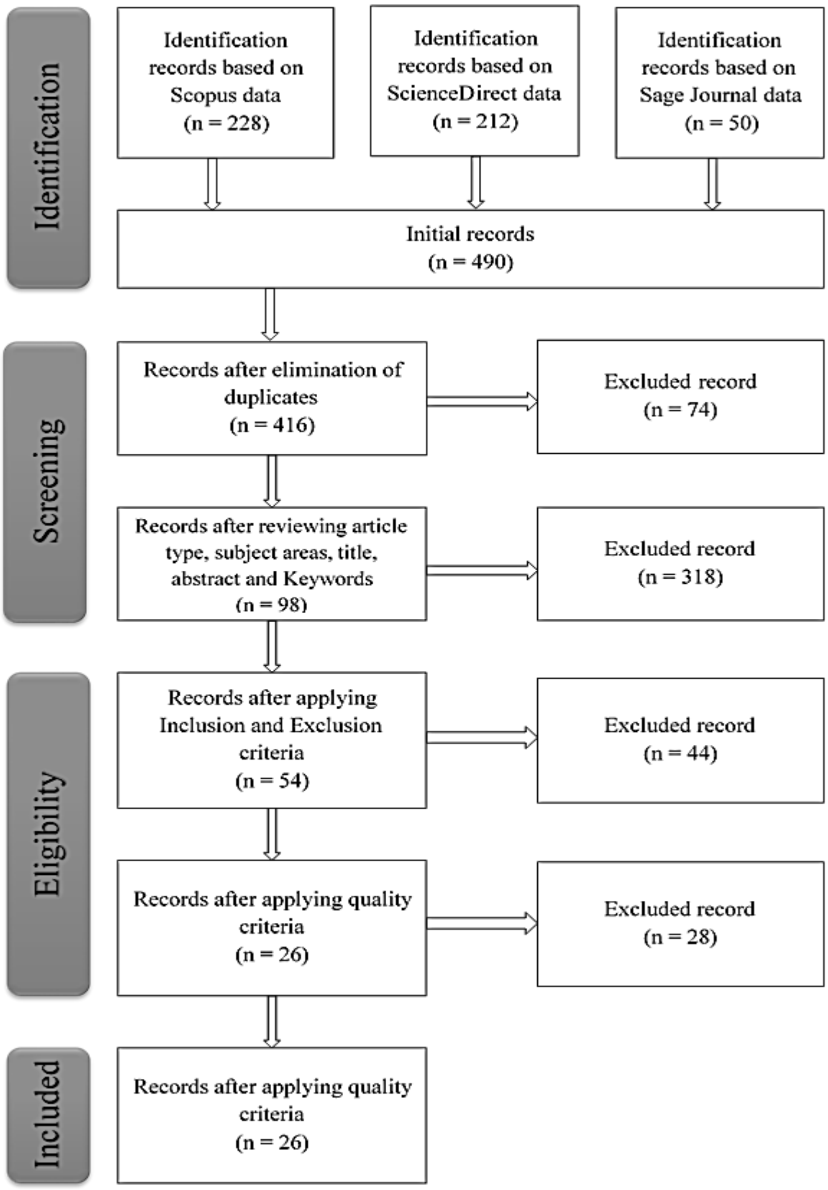
Figure 1
PRISMA flowchart



Referring to the search results, this study analyzed articles published between 2013 and 2022, which were retrieved from three primary databases: Scopus, ScienceDirect, and SAGE Journals. Although the search was focused on these databases, the articles utilized in the study came from various renowned publishers, including Dialnet, Elsevier, IEEE, Inderscience, MDPI, Springer, Taylor & Francis, UCOPres, ULPGC, and Wiley Online Library (Figure 1). This broad scope of sources allowed for a comprehensive view of the research landscape within the field of interest. Of the 490 articles initially retrieved during the search process, 26 were ultimately selected after applying specific criteria, including inclusion and exclusion standards, as well as quality assessment measures. These chosen articles were deemed to best represent the research focus and met the required standards for relevance and quality.

Table 2 below provides detailed data on the studies that were included in the final analysis, offering a closer look at the range and distribution of the research findings.

Table 2
Summary of Selected Studies Included in the Analysis

Author(s)	Publisher	Education Level or Age	Sample Size
Merchant, et al. (2013)	Wiley Online Library	Higher Education	387
Martin-Gutiérrez, et al. (2013)	IEEE	Higher Education	57
Lee & Wong (2014)	Elsevier	Middle School	370
Meng, et al. (2014)	Taylor & Francis	Age 21 to 26 years old	39
Yilmaz, et al. (2015)	Elsevier	Higher Education	61
Qin, et al. (2015)	Springer	Age 20 to 25 years old	20
Gutiérrez, et al. (2015)	Dialnet	Higher Education	202
Chandrasekera, et al. (2015)	SAGE Journals	Higher Education	42
Jang, et al. (2017)	Elsevier	Higher Education	76
Roca-González, et al. (2017)	ULPGC	Higher Education	178
Molina-Carmona, et al. (2018)	Emerald	Higher Education	61
Hong, et al. (2018)	IEEE	Age 7 to 12 years old	237
Hong, et al. (2018)	IEEE	Senior High School	35
Molina-Carmona, et al. (2018)	MDPI	Higher Education	61
Giakis, et al. (2019)	Springer	Elementary School	NA
Rodríguez, et al. (2019)	UCOPres	Age 11 to 14 years old	66
Weng, et al. (2019)	SAGE Journals	Elementary School	80
de Back, et al. (2020)	Springer	Higher Education	40
Chao & Chang (2020)	Springer	Elementary School	NA
Obeid & Demirkan (2020)	Taylor & Francis	Higher Education	42
Wong, et al. (2021)	Inderscience	Higher Education	50
Lu, et al. (2022)	IEEE	Middle School	NA
Zhou, et al. (2022)	IEEE	NA	49
Chakareski, et al. (2022)	IEEE	NA	NA

3.2. Discussion

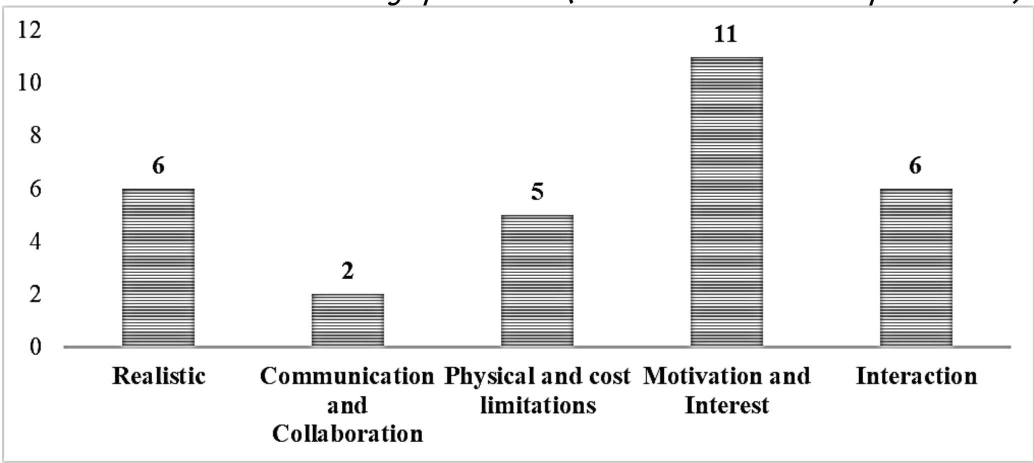
The following discussion explores four main Research Questions (RQs) that delve into the implementation and impact of Virtual Reality (VR) in enhancing spatial abilities. Each RQ addresses different aspects of applying VR technology in the development of spatial skills, aiming to provide a comprehensive understanding of its impact across various dimensions.

3.2.1 What are the considerations that need to be taken into account in implementing VR to enhance spatial abilities? (RQ1)

Virtual Reality (VR) is a technology that enables users to experience immersive scenarios that are physically impossible (Bailey & Bailenson, 2017). The use of VR allows users to feel as though they are inside a virtual world created by this technology. Due to VR's capability to create profound experiences, it is widely employed as a tool in the learning process. Several reasons underlie referenced research on the use of VR, particularly for enhancing spatial abilities: (i) it can create realistic experiences; (ii) it provides more realistic and immersive interactive experiences; (iii) it can enhance motivation and learning interest; (iv) it can help overcome physical limitations and costs; and (v) it can aid in improving collaboration and communication among users. A detailed exposition is presented in Figure 2.

Figure 2

Considerations in the Use of VR: Enhancing Spatial Skills (Source: Review of 26 Sampled Articles)



Firstly, VR can create realistic experiences. By using VR, users can undergo experiences closely resembling real-world environments. VR enables users to "enter" 3D environments that provide more realistic learning experiences and allow for easier visualization of spatial concepts. However, findings from reviewed studies on realistic experiences vary. Yilmaz et al. (2015) demonstrate that three-dimensional virtual worlds can capture users' attention by providing rich interactions in environments akin to the real world. Chandrasekera et al. (2015) designed environments as realistically as possible, adding sound effects to achieve interactions that simulate real-world experiences. In another study, Giakis et al. (2019) found that participants with low spatial abilities benefited more from the intuitive manipulation and interactivity advantages provided by VR-based learning compared to those with high spatial abilities. Jang et al. (2017) had participants wear 3-D stereoscopic glasses to enable a more realistic visual representation of anatomical structures. Furthermore, to enhance realism, Chakareski et al. (2022) explored VR's use by integrating 360-degree video streaming, focusing on user navigation modeling, rate-distortion analysis, and end-to-end optimization for viewport-driven streaming. Lu et al. (2022) also examined VR's application in programming environments to enhance students' spatial skills. However, research results indicate that VR's impact on students' spatial skills may vary depending on their initial experience with computational and spatial visualization skills. Despite VR's capacity to create realistic experiences, Roca-González et al. (2017) argue that the real world still provides more information and intense sensations compared to VR. This perspective aligns with Chandrasekera et al. (2015), who found limitations in virtual environments' analogy to the real world and observed that participants in VR environments tended to be passive in their activities.

Secondly, VR provides a deep interactive experience, allowing users to freely explore 3D environments. Research indicates that users can interact with objects within these environments, facilitating intuitive spatial learning. Studies have explored VR's potential as an effective and engaging learning tool, particularly for spatial skills. Yilmaz et al. (2015) examined how interaction in 3D virtual environments enhances exploration and engagement, finding a strong correlation between interaction depth and engagement duration, and a moderate one with spatial ability. Meanwhile, de Back et al. (2020) highlighted the benefits of collaborative learning in VR environments using CAVE (Cave Automatic Virtual Environment). Virtual reality games developed in this study offered interactive and engaging learning experiences for student groups, utilizing CAVE's immersive four-wall setup. Another study by Zhou et al. (2022) explored enhancing spatial and mental rotation abilities through VR environments, leveraging their immersive visualizations for spatial training tasks. Additionally, Meng et al. (2014) focused on developing VR panorama manifestation (PM) systems for navigation, employing six monitors to create a circular display with interactive seating equipped with rotation sensors and control knobs. Lastly, research by Chao & Chang (2020) and Molina-Carmona et al. (2018) discussed the use of VR in interactive learning to significantly improve students' spatial abilities.

Thirdly, VR can enhance motivation and learning interest. In educational implementations, VR is often cited for increasing motivation and interest due to its enjoyable learning experiences. Users report VR as an engaging learning method, which helps boost motivation and interest in spatial concepts. Giakis et al. (2019) demonstrated VR's use in enhancing student motivation and interest in mathematics through the educational game "The Wizard of Upside-Down." Rodríguez et al. (2019) further emphasized VR's potential in mathematics education to enhance learning interest and experience, providing immersive and interactive learning environments. Beyond spatial and mathematical skills, VR can visually and spatially teach complex academic subjects like neuroanatomy. Hong et al. (2019) indicated VR's effectiveness in improving spatial skills and positively correlating with student interest and experience. In a more specific context, Yilmaz et al. (2015) explored VR usage based on gender, experience, and spatial ability groups, finding that embodied interaction and gamification can enhance motivation. de Back et al. (2020) underscored the collaborative learning benefits of using VR technology, particularly in immersive environments like CAVE. Lu et al. (2022) studied VR's use in programming environments to enhance students' spatial skills, noting varying impacts depending on students' initial spatial and computational visualization abilities.

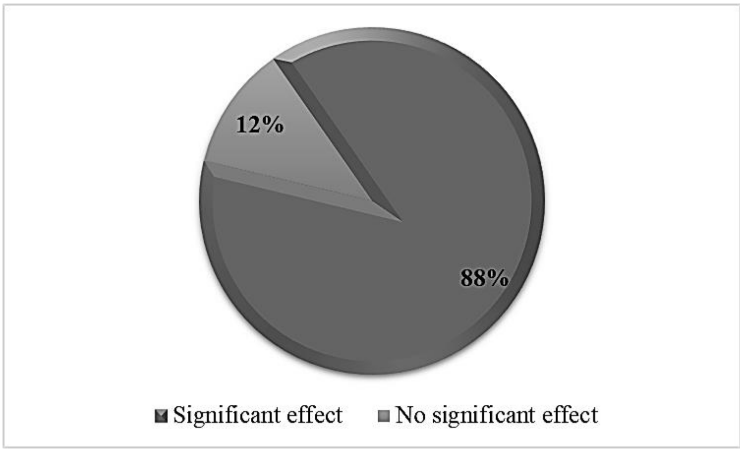
Fourthly, VR can help overcome physical limitations and costs. In abstract learning contexts such as mathematics and physics, VR is identified as an ideal medium for digitally visualizing complex objects realistically. This not only aids in visualization and object interaction but also eliminates distance and location barriers through online accessibility. de Back et al. (2020) highlighted VR's use in neuroanatomy education, showing benefits in enhancing learning outcomes and overcoming the high costs of physical models. Similarly, in engineering fields, Martin-Gutiérrez et al. (2013) demonstrated how VR and 3D models can enhance engineering education more affordably compared to physical objects. Wong et al. (2021) tested spatial skills' impact on core STEM topics using augmented reality and VR, combining scaffolding and repetition to enhance learning efficiency and confidence economically. Meng et al. (2014) showed VR panorama manifestation (PM) systems outperforming desktop systems in cost and completion time for spatial visualization tasks.

Fifthly, VR can enhance collaboration and communication among users by providing a three-dimensional virtual environment where interactions feel natural and intuitive. Yilmaz et al. (2015) found that VR improves collaboration and communication within these environments, enhancing interaction with objects and surroundings similar to real-world interactions. Chakareski et al. (2022) explored new challenges in utilizing VR and 360° video technology for advanced video communication systems to maximize Quality of Experience (QoE) for users.

3.2.2 How does the use of VR influence the overall enhancement of spatial abilities? (RQ2)

The utilization of Virtual Reality (VR) technology has experienced rapid development in recent years and has been applied across various fields, including education. One of the primary advantages of VR is its ability to enhance spatial abilities. Several studies indicate that the use of virtual reality technology in learning can improve spatial abilities. A review of 26 studies overall shows both significant and nonsignificant positive impacts on spatial abilities. Among these studies, three did not demonstrate significant effects (Figure 3).

Figure 3
Data on the Impact of VR Usage on Spatial Abilities (Source: Review of 26 Sampled Articles)



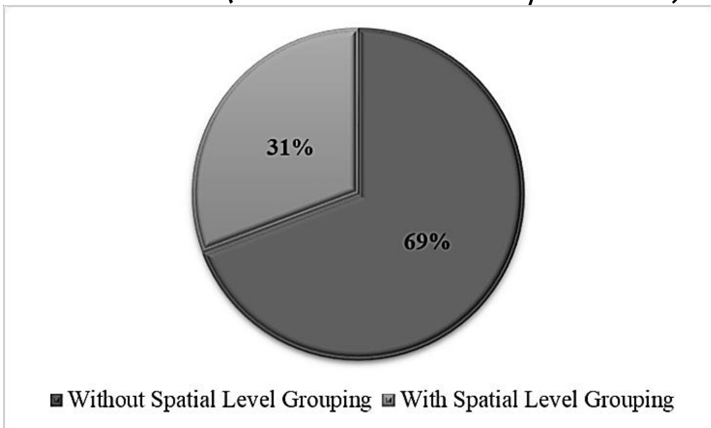
Research findings from several studies suggest that the use of VR technology positively influences the spatial abilities of students and VR users. Yilmaz et al. (2015) demonstrate that spatial abilities and experience influence user interaction in three-dimensional virtual environments. Meanwhile, Molina-Carmona et al. (2018) found that VR technology can enhance students' spatial perception. Other studies also show that VR technology can improve mental rotation abilities (Chandrasekera et al., 2015; Hong et al., 2019; Molina-Carmona et al., 2018; Roca-González et al., 2017; Zhou et al., 2022). Similar results were found in Giakis et al. (2019) study, which successfully enhanced spatial abilities and mental rotation skills in elementary school children through virtual reality learning games. Additionally, VR technology significantly aids students with low spatial abilities in understanding the 3-D nature of molecules, as evidenced by Merchant et al. (2013). Furthermore, integrating virtual reality and augmented reality into textbooks or learning materials can improve students' learning outcomes, particularly those with low spatial abilities, as shown in studies by Weng et al. (2019) and Wong et al. (2021). Regarding navigation, Meng et al. (2014) demonstrate that VR enhances effectiveness and efficiency in various navigation tasks. Chao & Chang (2020) research indicates that interactive VR learning materials can significantly improve students' spatial abilities and the effectiveness of learning mathematics among low-achieving students. Studies also indicate significant differences when participants estimate distances with or without time pressure, and that virtual environments can influence distance perception (Qin et al., 2015). Moreover, immersive virtual design environments can facilitate creativity and improve flow states associated with student interest in learning, as demonstrated by Obeid & Demirkan (2020). Some studies also show that the use of VR technology and 3D applications can enhance students' spatial abilities in technical and engineering graphics subjects (Gutiérrez et al., 2015; Martin-Gutiérrez et al., 2013). The use of soundscapes can also enhance navigation abilities in virtual environments, as shown by Chandrasekera et al. (2015). Nonetheless, this study still finds varied research outcomes and suggests the need for further research to comprehensively understand their overall impact (Hong et al., 2019).

Although the selected studies in this review generally indicate an influence of VR application on spatial abilities, at least 3 out of a total of 26 studies show that the use of VR does not significantly impact spatial abilities. Lu et al. (2022) demonstrate that while there was an improvement in spatial visualization performance in the first group of students after intervention using the MYR cloud-based programming environment, statistical significance was not achieved. The second group of students, who had higher initial experience in computational and spatial visualization skills, also did not further improve their spatial visualization skills. Merchant et al. (2013) show that there were no statistically significant differences between the control group and the group using Second Life (SL) in understanding the 3-D nature of molecules. However, students classified as having poor spatial abilities showed much greater improvement in understanding the 3-D nature of molecules if they engaged in relevant activities in the 3-D virtual world compared to students who only worked with 2-D images. Meanwhile, Gutiérrez et al. (2015) concluded that the use of 3D virtual technology in training spatial skills did not significantly influence the improvement of students' spatial abilities compared to traditional methods. Nonetheless, overall, students who participated in subjects using VR technology generally showed improvements in their spatial abilities.

3.2.3 How does the use of VR influence the enhancement of spatial abilities based on differences in initial spatial ability levels among participants? (RQ3)

The discussion regarding the influence of virtual reality (VR) technology on enhancing spatial abilities considers the effectiveness of VR technology in improving spatial abilities, which can also depend on individuals' initial spatial skills. Some studies indicate that individuals with higher initial spatial abilities may not derive significant benefits from VR technology in enhancing their spatial abilities. Therefore, this research is categorized into two groups. The first category consists of studies demonstrating the effectiveness of VR use among groups with lower initial spatial abilities. Several studies have found that VR technology significantly enhances spatial abilities among groups with lower initial spatial skills. For example, de Back et al. (2020) found that immersive learning in CAVE was effective in improving performance for learners with low spatial abilities. This study suggests that VR can help overcome difficulties faced by this group in understanding and visualizing spatial information. Another study showing similar results is by Jang et al. (2017), indicating that direct manipulation of anatomical structures in a VR environment can enhance spatial abilities in groups with lower initial spatial skills. Similar outcomes were also found in the studies of Lu et al. (2022) and Merchant et al. (2013), demonstrating the potential of VR technology in enhancing spatial abilities among medical students and undergraduate learners, particularly in visually and spatially complex aspects.

Figure 4
VR-spatial abilities based on initial skills (Source: Review of 26 Sampled Articles)



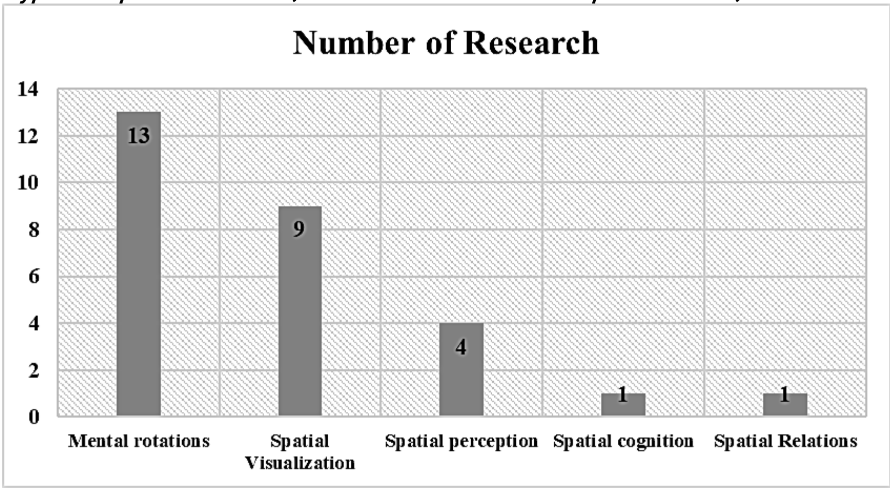
In contrast, the second category focuses on the impact of using virtual reality desktop and mixed reality (AR and VR) technologies in enhancing spatial abilities among students across various levels of initial spatial skills. Lee & Wong (2014) showed that the use of virtual reality desktop significantly improved performance for learners with low spatial abilities. Weng et al. (2019) and Wong et al. (2021) demonstrated that the use of mixed reality in textbooks and technical training can enhance learning outcomes and skills, particularly among students with low spatial abilities. Meanwhile, Chao & Chang (2020) indicated that the use of VR learning materials among elementary school students in Taiwan significantly improved their spatial abilities, learning effectiveness in mathematics for low-achieving students, and learning motivation in spatial concept education. Therefore, the use of AR and VR technologies holds promising potential in enhancing students' spatial abilities across various levels of initial spatial skills.

3.2.4 What is the impact of using VR on spatial abilities based on various aspects of spatial ability? (RQ4)

Spatial ability encompasses a range of cognitive skills crucial for understanding and manipulating shapes and objects in visual-spatial contexts. One fundamental aspect is mental rotation, which involves mentally rotating objects and detecting changes within them (Shepard & Metzler, 1971). Spatial cognition extends this by engaging in processes like spatial orientation, visualization, cognitive mapping, navigation, and reasoning to interact effectively with spatial environments (Johnson & Moore, 2020). Additionally, spatial perception plays a vital role in interpreting visual information related to spatial dimensions, such as shapes, sizes, distances, depths, colors, and movements (Johnson & Moore, 2020). Spatial relations further build upon these abilities, facilitating the understanding of spatial relationships like distance, direction, orientation, and congruence between objects or their parts (Pellegrino et al., 1984). These relations are integral to cognitive functions such as spatial perception, orientation, visualization, and reasoning. Moreover, spatial visualization allows individuals to mentally generate and manipulate images of objects or situations that are not physically present (Pellegrino et al., 1984).

Figure 5

Data based on types of spatial abilities (Source: Review of 26 Sampled Articles)



As previously discussed, spatial ability encompasses various skills such as mental rotations, spatial visualization, spatial perception, spatial cognition, and spatial relations. Mental rotation ability plays a significant role in this regard. The implementation of VR has had a considerable impact, particularly on mental rotation ability across different educational stages, from elementary school (e.g., Giakis et al., 2019), through secondary school (as studied by Hong et al., 2018), and even into higher education (explored by Martin-Gutiérrez et al., 2013). Additionally, VR's influence has been investigated across various learning subjects such as Mathematics (Chao & Chang, 2020; Rodríguez et al., 2019), Technical Graphics (Gutiérrez et al., 2015), Anatomy Structures (Jang et al., 2017), Programming (Lu et al., 2022), Chemistry (Meng et al., 2014), and Natural Sciences (Weng et al., 2019).

Regarding other supportive factors, VR's application to diverse aspects of spatial ability has been extensively studied. For instance, Jang et al. (2017) found that the depth of VR interaction is influenced not by gender but by experience and mental rotation ability. Moreover, apart from enhancing mental rotations, VR technology has been identified to improve spatial perception, as observed in Giakis et al. (2019). Lu et al. (2022) conducted interventions using My Reality (MYR), and although statistical significance was not achieved, there were indications of improved spatial visualization and mental rotation performance based on the spatial ability measurement instruments used.

Further research indicates that three-dimensional virtual worlds like Second Life® (SL) can enhance spatial abilities and academic performance among undergraduate students, particularly those with poor spatial skills (Merchant et al., 2013). The virtual environment FORSpatial has also been shown to enhance spatial visualization and mental rotation abilities (Zhou et al., 2022). The virtual reality panorama manifestation (PM) system has been developed to aid navigation in spatial cognition tasks (Meng et al., 2014). Meng et al. (2014) further discovered that participants using the PM system achieved significantly higher success rates and required less completion time compared to those using the desktop system (DT). Immersive virtual design environments have proven effective in facilitating participants' design creativity compared to non-immersive environments (Obeid & Demirkan, 2020). Moreover, immersive virtual reality learning systems have been shown to enhance spatial visualization and mental rotation abilities in learners (Hong et al., 2018). Hong et al. (2018) additionally found a positive relationship between students' learning interest and flow experience.

4. Conclusion

This systematic study provides a detailed overview of the factors influencing the adoption of VR technology to enhance spatial abilities. It identifies various related aspects, including considerations regarding differences in students' initial abilities that may affect the effectiveness of VR interventions in improving spatial skills. In this research, we analyzed 26 selected publications through keyword screening, inclusion-exclusion criteria, and quality assessment criteria. Based on our analysis, our conclusions are categorized according to the predefined research questions. In the context of this study, the impact of VR usage on spatial abilities extends beyond specific learning subjects and has been explored across various fields such as Mathematics, Engineering Graphics, Anatomy Structure, Programming, Chemistry, and Natural Sciences. The advantages of VR in enhancing spatial abilities primarily lie in its ability to create realistic and interactive visual experiences, which can be integrated into educational games to enhance motivation and learning interest.

Furthermore, VR helps overcome physical and cost constraints, particularly in learning abstract and technical topics. Regarding the influence of VR interventions on spatial abilities, it is evident that overall, VR interventions have a significantly positive impact. The greatest potential is observed in individuals with initially low spatial abilities, where their spatial skill improvements are more significant compared to participants with moderate or high initial spatial abilities. Overall, various aspects of spatial abilities such as mental rotation, spatial perception, spatial visualization, and spatial relations have been shown to significantly benefit from VR interventions. However, mental rotation was the primary focus of this study. Nevertheless, this study has several limitations, including heterogeneity in hardware and VR software usage, differences in educational levels and ages, as well as a lack of detailed research focusing on gender differences among participants. Before making suggestions, it is best to convey these limitations first. Therefore, recommendations for further research include conducting studies that specifically address these subject condition differences. Addressing these limitations will help refine the understanding of VR's impact on spatial abilities and guide the development of more effective and inclusive interventions.

Limitations

This study has several limitations that should be noted. First, there is heterogeneity in the use of hardware and VR software across the various studies analyzed, which may affect the consistency of the results. The wide range of devices and VR applications makes comparisons between studies more complex. Second, differences in educational levels and ages of participants in the analyzed studies also pose a limitation, as the effects of VR may vary depending on participants' cognitive levels and prior experience. Third, this research lacks a detailed focus on gender differences in the impact of VR interventions on spatial abilities. The absence of data related to gender effects limits the understanding of result variations based on gender. These limitations highlight the need for further research that specifically addresses differences in subject conditions, such as the type of hardware used, educational level, and gender factors, to provide a more comprehensive and accurate understanding of VR's influence on spatial abilities. Addressing these limitations will help in developing more effective and inclusive VR interventions, benefiting a wider range of learners.

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Author Contribution
Author 1: Conceptualization, Methodology, and Writing - Original Draft.
Author 2: Formal analysis, Validation, and Supervision.
Author 3: Resources, Data Curation, Writing - Review & Editing.

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Conflict of Interest
The authors declare no conflict of interest.

5. References

Anggriawan, B., Effendy, E., & Budiasih, E. (2017). Kemampuan Spasial dan Kaitanya dengan pemahaman mahasiswa terhadap materi simetri. *Jurnal Pendidikan: Teori, Penelitian, Dan Pengembangan*, *2*(12), 1612–1619. https://doi.org/10.17977/JPTPP.V2I12.10299

Atit, K., Power, J. R., Pigott, T., Lee, J., Geer, E. A., Uttal, D. H., Ganley, C. M., & Sorby, S. A. (2021). Examining the relations between spatial skills and mathematical performance: A meta-analysis. *Psychonomic Bulletin & Review 2021 29:3*, *29*(3), 699–720. https://doi.org/10.3758/S13423-021-02012-W

Bailey, J. O., & Bailenson, J. N. (2017). Immersive virtual reality and the developing child. In *Cognitive development in digital contexts* (pp. 181-200). Academic Press.

Bamodu, O., & Ye, X. M. (2013). Virtual reality and virtual reality system components. *Advanced Materials Research*, *765*, 1169–1172. https://doi.org/10.2991/icsem.2013.192

Bhagat, K. K., & Chang, C.-Y. (2015). Incorporating GeoGebra into Geometry Learning lesson from India. *Eurasia Journal of Mathematics, Science and Technology Education*, *11*(1), 77–86. https://doi.org/10.12973/eurasia.2015.1307a

Cangas, D., Codina, A., Chavil, D. I., Fernández, J. M., García, M. M., Kamerling, J., López, E., Morga, G., Rodríguez, J. L., & Romero, I. M. (2021). Using notice VR for STEAM education in virtual reality. *Conference Proceedings. The Future of Education 2021*. https://conference.pixel-online.net/files/foe/ed0011/FP/7401-MATH5175-FP-FOE11.pdf

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies* (Issue 1). Cambridge University Press.

Chakareski, J., Corbillon, X., Simon, G., & Swaminathan, V. (2022). User navigation modeling, rate-distortion analysis, and end-to-end optimization for viewport-driven 360<inline-formula><tex-math notation="LaTeX">$^\circ $</tex-math></inline-formula> Video Streaming. *IEEE Transactions on Multimedia*, *25*, 5941–5956. https://doi.org/10.1109/TMM.2022.3201397

Chandrasekera, T., Yoon, S.-Y., & D'Souza, N. (2015). Virtual environments with soundscapes: a study on immersion and effects of spatial abilities. *Environment and Planning B: Planning and Design*, *42*(6), 1003–1019. https://doi.org/10.1068/b130087p

Chao, W.-H., & Chang, R.-C. (2020). The impact of applying virtual reality technology to spatial ability learning in elementary school students. *International Conference on Innovative Technologies and Learning*, 137–144. https://doi.org/0.1007/978-3-030-63885-6_16

Conde, M. Á., Sedano, F. J. R., Fernández-Llamas, C., Gonçalves, J., Lima, J., & García-Peñalvo, F. J. (2020). RoboSTEAM project systematic mapping: Challenge-based learning and robotics. *2020 IEEE Global Engineering Education Conference (EDUCON)*, 214–221. https://doi.org/10.1109/EDUCON45650.2020.9125103 deBack, T. T., Tinga, A. M., Nguyen, P., & Louwerse, M. M. (2020). Benefits of immersive collaborative learning in CAVE-based virtual reality. *International Journal of Educational Technology in Higher Education*, *17*(1), 1-18. https://doi.org/10.1186/s41239-020-00228-9

Fuys, D. (1984). English translation of selected writings of Dina van Hiele-Geldof and Pierre M. van Hiele. https://files.eric.ed.gov/fulltext/ED287697.pdf

Gardner, H. (1993). *Multiple intelligences: The theory in practice*. Basic Books/Hachette Book Group.

Giakis, T., Koufaki, I., Metaxa, M., Sideridou, A., Thymniou, A., Arfaras, G., Antoniou, P., & Bamidis, P. (2019). Enhancing spatial ability through a virtual reality game for primary school children: "The wizard of upside down": An experimental approach. *Communications in Computer and Information Science*, *993*, 519–528. https://doi.org/10.1007/978-3-030-20954-4_39/FIGURES/10

González, N. A. A. (2018). Development of spatial skills with virtual reality and augmented reality. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *12*, 133–144. https://doi.org/10.1007/s12008-017-0388-x

Gutiérrez, J. M., Domínguez, M. G., & González, C. R. (2015). Using 3D virtual technologies to train spatial skills in engineering. *International Journal of Engineering Education*, *31*(1), 323–334.

Guzsvinecz, T., Orban-Mihalyko, E., Sik-Lanyi, C., & Perge, E. (2022). An Overview of Received Results on MRT, MCT, and PSVT Spatial Ability Tests in Virtual Environments. *1st IEEE International Conference on Internet of Digital Reality, IoD 2022*, 83–88. https://doi.org/10.1109/IoD55468.2022.9987064

Hawes, Z., Moss, J., Caswell, B., Seo, J., & Ansari, D. (2019). Relations between numerical, spatial, and executive function skills and mathematics achievement: A latent-variable approach. *Cognitive Psychology*, *109*, 68–90. https://doi.org/10.1016/j.cogpsych.2018.12.002

Hong, J.-C., Hwang, M.-Y., Tai, K.-H., Tsai, C.-R., & Australia, C. S. U. D. S. et al. ; I. E. S. I. N. S. W. S. U. of W. (2019). Training Spatial Ability through Virtual Reality. In M. J. W. Lee, S. Nikolic, G. K. W. Wong, J. Shen, M. Ros, L. C. U. Lei, & N. Venkatarayalu (Eds.), *2018 IEEE International Conference on Teaching, Assessment, and Learning for Engineering, TALE 2018* (pp. 1204–1205). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/TALE.2018.8615333

Jang, S., Vitale, J. M., Jyung, R. W., & Black, J. B. (2017). Direct manipulation is better than passive viewing for learning anatomy in a three-dimensional virtual reality environment. *Computers and Education*, *106*, 150–165. https://doi.org/10.1016/j.compedu.2016.12.009

Johnson, S. P., & Moore, D. S. (2020). Spatial thinking in infancy: Origins and development of mental rotation between 3 and 10 months of age. *Cognitive Research: Principles and Implications*, *5*(1), 10. https://doi.org/10.1186/s41235-020-00212-x

Kimura, K., Reichert, J. F., Kelly, D. M., & Moussavi, Z. (2019). Older adults show less flexible spatial cue use when navigating in a virtual reality environment compared with younger adults. *Neuroscience Insights*, *14*, 2633105519896803. https://doi.org/10.1177/2633105519896803

Lee, E. A.-L., & Wong, K. W. (2014). Learning with desktop virtual reality: Low spatial ability learners are more positively affected. *Computers and Education*, *79*, 49–58. https://doi.org/10.1016/j.compedu.2014.07.010

Lochhead, I., Hedley, N., Çöltekin, A., & Fisher, B. (2022). The immersive mental rotations test: Evaluating spatial ability in virtual reality. *Frontiers in Virtual Reality*, *3*, 820237. https://doi.org/10.3389/frvir.2022.820237

Lohman, D. F., Pellegrino, J. W., Alderton, D. L., & Regian, J. W. (1987). Dimensions and components of individual differences in spatial abilities. In *Intelligence and cognition: Contemporary frames of reference* (pp. 253–312). Springer. https://doi.org/10.1007/978-94-010-9437-5_6

Lu, J., Seavey, L., Zuk, S., Dimino, J., & Martin, F. (2022). Evaluating Student Spatial Skills Learning in a Virtual Reality Programming Environment. *2022 IEEE Frontiers in Education Conference, FIE 2022*, *2022-October*. https://doi.org/10.1109/FIE56618.2022.9962403

Martin-Gutiérrez, J., Garcia-Dominguez, M., González, C. R., Corredeguas, M. C. M., & Society, I. of E. and E. E. (IEEE) C. S. A. S. for E. E. (ASEE)-; E. R. M. (ERM) D. I. of E. and E. E. (IEEE) E. (2013). Using different methodologies and technologies to training spatial skill in engineering Graphic subjects. *43rd IEEE Annual Frontiers in Education Conference, FIE 2013*, 362–368. https://doi.org/10.1109/FIE.2013.6684848

Meng, F., Zhang, W., & Yang, R. (2014). The development of a panorama manifestation virtual reality system for navigation and a usability comparison with a desktop system. *Behaviour and Information Technology, 33*(2), 133–143. https://doi.org/10.1080/0144929X.2013.857432
Merchant, Z., Goetz, E. T., Keeney-Kennicutt, W., Cifuentes, L., Kwok, O., & Davis, T. J. (2013). Exploring 3-D virtual reality technology for spatial ability and chemistry achievement. *Journal of Computer Assisted Learning, 29*(6), 579–590. https://doi.org/10.1111/jcal.12018
Molina-Carmona, R., Pertegal-Felices, M. L., Jimeno-Morenilla, A., & Mora-Mora, H. (2018). Assessing the Impact of Virtual Reality on Engineering Students' Spatial Ability. In *The Future of Innovation and Technology in Education: Policies and Practices for Teaching and Learning Excellence* (pp. 171–185). Emerald Group Publishing Ltd. https://doi.org/10.1108/978-1-78756-555-520181013
Obeid, S., & Demirkan, H. (2020). The influence of virtual reality on design process creativity in basic design studios. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2020.1858116
Onyancha, R. M., Derov, M., & Kinsey, B. L. (2009). Improvements in spatial ability as a result of targeted training and computer-aided design software use: Analyses of object geometries and rotation types. *Journal of Engineering Education, 98*(2), 157–167. https://doi.org/10.1002/j.2168-9830.2009.tb01014.x
Pellegrino, J. W., Alderton, D. L., & Shute, V. J. (1984). Understanding spatial ability. *Educational Psychologist, 19*(4), 239–253. https://myweb.fsu.edu/vshute/pdf/shute%201984_a.pdf
Petersen, K., Vakkalanka, S., & Kuzniarz, L. (2015). Guidelines for conducting systematic mapping studies in software engineering: An update. *Information and Software Technology, 64*, 1–18. https://doi.org/10.1016/j.infsof.2015.03.007
Qin, H., Liu, B., & Wang, D. (2015). The impact of time pressure on spatial ability in virtual reality. *Virtual, Augmented and Mixed Reality: 7th International Conference, VAMR 2015, Held as Part of HCI International 2015, Los Angeles, CA, USA, August 2-7, 2015, Proceedings 7*, 60–66. https://doi.org/10.1007/978-3-319-21067-4_7
Roca-González, C., Martin-Gutierrez, J., García-Dominguez, M., & Carrodeguas, M. C. N. (2017). Virtual technologies to develop visual-spatial ability in engineering students. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(2), 441–468. https://doi.org/10.12973/eurasia.2017.00625a
Rodríguez, J. L. (2022). Exploring dynamic geometry through immersive virtual reality and distance teaching. In *Mathematics Education in the Age of Artificial Intelligence: How Artificial Intelligence can Serve Mathematical Human Learning* (pp. 343–363). Springer. https://doi.org/10.1007/978-3-030-86909-0_15
Rodríguez, J. L., Morga, G., & Cangas-Moldes, D. (2019). Geometry teaching experience in virtual reality with NeoTrie VR. *Psychology, Society & Education, 11*(3), 355–366. https://doi.org/10.21071/PSYE.V11I3.13951
Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(3972), 701–703. https://facultypsy.hope.edu/psychlabs/exp/rotate/readings/ShepardMetzler_1971.pdf
Sudirman, S., & Alghadari, F. (2020). Bagaimana mengembangkan kemampuan spasial dalam pembelajaran matematika di sekolah?: Suatu tinjauan literatur. *Journal of Instructional Mathematics, 1*(2), 60–72. https://doi.org/10.37640/jim.v1i2.370
Supriadi, S., Wildan, W., Hakim, A., Savalas, L. R. T., & Haris, M. (2021). Model mental dan kemampuan spasial mahasiswa tahun pertama dan ketiga pendidikan kimia di Universitas Mataram. *Jurnal Pijar Mipa, 16*(3), 282–287. https://doi.org/10.29303/jpm.v16i3.1366
Vidermanova, K., & Vallo, D. (2015). Practical geometry tasks as a method for teaching active learning in geometry. *Procedia-Social and Behavioral Sciences, 191*, 1796–1800. https://doi.org/10.1016/j.sbspro.2015.04.421
Weng, C., Rathinasabapathi, A., Weng, A., & Zagita, C. (2019). Mixed reality in science education as a learning support: A revitalized science book. *Journal of Educational Computing Research, 57*(3), 777–807. https://doi.org/10.1177/0735633118757017
West, R. L., Morris, C. W., & Nichol, G. T. (2013). Spatial cognition on nonspatial tasks: Finding spatial knowledge when you're not looking for it. In *The development of spatial cognition* (pp. 13–39). Psychology Press.

Wong, J., Yu, K., & Giacaman, N. (2021). Scaffolding spatial ability with augmented reality and virtual reality. *International Journal of Mobile Learning and Organisation*, *15*(1), 50–70. https://doi.org/10.1504/IJMLO.2021.111597

Yang, Y., Conners, F. A., & Merrill, E. C. (2014). Visuo-spatial ability in individuals with Down syndrome: Is it really a strength? *Research in Developmental Disabilities*, *35*(7), 1473–1500. https://doi.org/10.1016/j.ridd.2014.04.002

Yilmaz, R. M., Baydas, O., Karakus, T., & Goktas, Y. (2015). An examination of interactions in a three-dimensional virtual world. *Computers and Education*, *88*, 256–267. https://doi.org/10.1016/j.compedu.2015.06.002

Zhou, Y., Xu, T., Yang, H., & Li, S. (2022). Improving spatial visualization and mental rotation using for spatial through shapes and letters in virtual environment. *IEEE Transactions on Learning Technologies*, *15*(3), 326–337. https://doi.org/10.1109/TLT.2022.3170928