Journal of Computers in Education
https://doi.org/10.1007/s40692-023-00287-7

Augmented reality applications for mathematical creativity: a systematic review

Flavia Aurelia Hidajat[1]

Received: 10 April 2023 / Revised: 15 June 2023 / Accepted: 1 July 2023

Abstract

Augmented reality (AR) applications are often studied in education. However, little literature has systematically reviewed the applications of AR for mathematical creativity. This paper aims to analyze the research trends comprehensively and systematically on 66 articles from 2015 to 2023. Based on the NCTM Principles and Standards guidelines, trends in the application of AR in mathematics education can be analyzed into six themes: equity, mathematics curriculum, mathematics teaching, learning, assessment, and mathematics technology. The results of the study show that (1) AR for mathematical creativity has implications for improving students' cognitive performance; problem-solving process; self-potential; social skills, and self-ability of students; (2) the most dominant features in developing AR applications for mathematical creativity are the Unity3D tool and Vuforia; (3) AR has a positive impact on equity for improving the quality of teaching and learning, supporting the educational curriculum; improve the teaching and learning of mathematics; effective evaluation and technology development in the learning process; (4) AR as a creative learning media; AR helps creative collaboration between students; and able to improve students' creative thinking skills. The results of a systematic review of AR applications for mathematical creativity can help educators and the development of future educational research.

Keywords Augmented reality application · Mathematical creativity · Mathematics education · Systematic review · Literature review

✉ Flavia Aurelia Hidajat
Flaviaaureliahidajat@unj.ac.id

[1] Universitas Negeri Jakarta, Jl. Rawamangun Muka, Rawamangun, Jakarta, Indonesia

Published online: 18 July 2023

Introduction

Augmented reality (AR) applications are the best interactive technology to enhance mathematical creativity. AR applications integrate models, processes, animations, and simulations so students' interactions and intuition appear active (Grodotzki et al., 2023). In addition, AR is a technology that supports student interaction to bring out student creativity (Kang et al., 2023). The application of AR in creativity can positively impact student learning outcomes (Lima et al., 2022; Theodoropoulos & Lepouras, 2021). This is because AR technology combines physical objects with digital visualization through research and development of design prototypes (Radu et al., 2023). Development of AR applications to visualize space designs into reality (Rohil & Ashok, 2022). Therefore, the development of AR applications must be based on an analysis of the needs and experiences of developers and researchers so that the AR applications created can improve learning and educational outcomes.

The target of implementing AR applications for mathematical creativity is very much needed in education. AR applications are a technological advance that uses tablets, cell phones, GPS, built-in cameras, and internet access to support independent creativity in education (Sommerauer & Müller, 2014). Technology from digital AR applications can represent abstract educational concepts to improve students' understanding and creativity (Lionoa et al., 2021). In terms of systems, AR applications combine physical objects related to abstract mathematical concepts, the natural environment, and student creativity (Bujak et al., 2013; Kaufmann & Schmalstieg, 2003; Radu et al., 2023; Salinas et al., 2013; Wan et al., 2022). AR generally affects the acquisition of mathematical knowledge (Sommerauer & Müller, 2014). AR application is an efficient digital technology tool for mathematics learning (Lionoa et al., 2021). AR applications use visualization skills to enhance mathematics learning (Salinas et al., 2013). The application of AR impacts learning outcomes, which are responses, creativity, knowledge, skills, and student performance (Chang et al., 2022). Thus, integrating knowledge, mathematical creativity, mathematics education, and AR technology effectively improves the quality of mathematics learning (Salinas et al., 2013). This shows that AR applications receive special attention in mathematical creativity for future educational development.

The importance of applying AR for mathematical creativity and education in the future, this study will analyze the literature review on the use of AR for mathematical creativity, namely the implications, features, potential, perceptions, user criteria, measurement tools, and evaluation methods of using AR for mathematical creativity. This limited information can hinder the development of AR in future research. Therefore, this study fills this gap to enrich knowledge about the use of AR for mathematical creativity. This study also implicitly analyzes the literature review on the implications of AR as a potential technology for mathematical creativity based on six themes of mathematics content according to the NCTM Principles and Standards guidelines (equity, mathematics curriculum, mathematics teaching, learning, assessment, and mathematics technology). Thus, this study is expected to guide and improve future studies and become a reference for educators, researchers, stakeholders, and policy research in AR applications for mathematical creativity.

Related frameworks

AR consists of three main dimensions, namely physical, cognitive, and contextual problems (Bujak et al., 2013). The physical dimension in AR applications is the physical manipulation that results in natural interactions and representations of educational concepts. The cognitive dimension is the alignment between spatiotemporal information through AR experiences for students' symbolic understanding. Meanwhile, the contextual dimension means that AR applications create collaborative learning between virtual and non-traditional environments based on experiences in everyday life. AR combines 3D and virtual physical objects in mathematics classes (Bujak et al., 2013). More importantly, AR applications act as self-guided guides for learning mathematics and visualizing abstract mathematical concepts for students (Arulanand et al., 2020). This shows that AR applications can effectively address challenges in enhancing students' mathematics learning and creativity (Coimbra et al., 2015; Radu et al., 2023). In addition, AR can increase students' motivation to learn mathematics (Chang et al., 2022; Lionoa et al., 2021), understanding of abstract and complex mathematical principles (Wan et al., 2022), mathematical didactic skills (Salinas et al., 2013; Sommerauer & Müller, 2014); partial skills, and students' mathematical geometric construction (Kaufmann & Schmalstieg, 2003). Therefore, AR applications are effective in digital learning (Arulanand et al., 2020).

AR applications are an effective strategy for all areas of education, so a review of the literature on AR applications has been reviewed in recent years. The bibliometric study by Hincapie et al. (2021) stated that the publication rate of AR applications is increasing yearly because AR applications significantly contribute to education and affect student learning outcomes. In another contribution, Sidani et al. (2021) reviewed 24 of 671 publications about AR publications in the Scopus, Academic Search Ultimate, Current Content, Web of Science, and Science Direct databases. They report that AR applications are new digital technologies that efficiently address challenges from all disciplines. The results of the literature analysis by Lin et al. (2015) and Su et al. (2021) also mention that AR applications are successful and effective for future research, teaching, and development. Chang et al. (2022) also analyzed studies on AR applications from 2012 to 2021. They stated that AR applications could support learning environments in the future. In addition, Theodoropoulos and Lepouras (2021) analyzed 31 studies on AR applications and told them that AR applications could benefit student learning and further research. This shows that AR applications contribute to the world of education, especially mathematics education.

AR applications for mathematics education have been analyzed in previous studies. For example, Salinas et al. (2013) stated that AR technology supports students' mathematics education because abstract mathematical objects can be visualized realistically. AR applications can build a good mathematics learning environment for students (Sommerauer & Müller, 2014). AR application in mathematics learning is a collaboration between a virtual environment, 3D construction, and cognitive mathematics learning content (Bujak et al., 2013). 3D constructions in mathematics learning and education can be built virtually through

AR applications (Kaufmann & Schmalstieg, 2003). This shows that AR applications are quite effective in learning mathematics. A systematic review literature study by Ahmad and Junaini (2020) has analyzed 19 articles on the application of AR for learning mathematics. The results show that the AR application helps with visual problems and understanding abstract mathematics for students. AR application is a technology with the latest innovations to support students' skills and creativity.

As a system, AR applications for student creativity were analyzed in several literature reviews. Giannopulu et al. (2022) stated that AR combines abstract physical objects with the natural environment to support students' mental and imaginative creativity. AR applications link direct user engagement, creativity, and satisfaction (Jessen et al., 2020). AR applications allow students to interact with physical objects and collaborate with colleagues through project-based learning (Radu et al., 2023). Designing AR applications to understand a concept of knowledge is open to the creativity of media designers (Al Fadalat & Al-Azhari, 2022). This shows that AR applications require creativity from the designer to support user creativity. AR applications can support everyone's creativity with various educational sciences, for example, mathematical creativity.

Previous studies have conducted literature review analyses for AR applications in mathematical creativity. Arulanand et al. (2020) and Radu et al. (2023) stated that AR applications effectively offer students many opportunities to be creative. AR applications can overcome the limitations of traditional teaching because AR applications can visualize abstract mathematical concepts into reality. The concept of 3D objects and visuals supports students' mathematical creativity. Research by Salinas et al. (2013) used AR applications to understand mathematical material creatively. AR applications can motivate students' mathematical learning and creativity (Kaufmann & Schmalstieg, 2003). In addition, AR applications create creative learning spaces to improve students' mathematical understanding (Sommerauer & Müller, 2014). Previous studies have not explained that AR applications significantly increase students' mathematical creativity. However, a review of the literature from previous research on AR applications to mathematical creativity is still little studied by researchers.

Based on a review of the literature from recent articles on AR applications for mathematical creativity, the current review aims to complement previous research and enhance research trends on AR applications for mathematical creativity. In addition, this study continues the analysis process from a literature review on the application of AR in mathematics education and mathematical creativity. Specifically, this paper aims to analyze the research trends comprehensively and systematically on AR applications for mathematical creativity from 2015 to 2023. To achieve this goal, the research questions (RQ) in this study are as follows:

RQ1: What are the implications and features of using AR for mathematical creativity?

RQ2: What is the potential of using AR for mathematical creativity based on the six themes from the NCTM Principles and Standards.

RQ3: What are the perceptions of using AR for mathematical creativity, user criteria, measurement tools, and evaluation methods?

Materials and methods

Based on the research questions, this study analyzed the literature review systematically using inclusion and exclusion analysis. This follows Fiskerstrand's (2022) literature review analysis with inclusion and exclusion analysis able to refine and clarify the scope of each research literature review systematically and comprehensively. Inclusion and exclusion analysis aims to systematically select relevant articles to answer research questions by following the specific guidelines of Maybury et al. (2022). Based on the inclusion and exclusion analysis criteria, this study identified implications, features of AR development, and potential parameters according to the NCTM Principles and Standards (2000), in which the articles selected involved six themes from the NCTM guidelines: equity, mathematics curriculum, mathematics teaching, learning, assessment, and mathematical technology. In addition, article analysis was also carried out to identify user criteria, measuring instruments, and evaluation methods of the effectiveness of AR for mathematical creativity.

Data collection

Literature review searches were conducted on various databases, such as Scopus, Web of Science, PubMed, Google Scholar, and ProQuest. The selected literature articles in this study are of high quality with a systematic arrangement. The collection of journal articles in this study engages various countries in presenting the best ideas and research results. Literature data from various databases is the best for analyzing the literature review. This study takes a range of articles from 2015 to 2023 to conduct a comprehensive and systematic literature review analysis of the latest research trends. The initial search for articles in this study was conducted on 91 articles about AR applications for mathematical creativity by searching for "Keyword-Title," namely "Augmented Reality Applications"; "Augmented Reality Applications for Education"; "Augmented Reality Applications for Mathematics Education"; "Augmented Reality Applications for Creativity"; and "Augmented Reality Applications for Mathematical Creativity."

This literature review is based on inclusion and exclusion criteria, namely (1) articles published in international journals from various databases, such as Web of Science, PubMed, Google Scholar, ProQuest, and others; (2) topics of published articles about AR applications for mathematical creativity; (3) article interval from 2015 to 2023. (4) full-text articles; and (5) articles covering the six themes of the NCTM (2000). The articles are downloaded and analyzed systematically to determine if they meet the inclusion and exclusion criteria. The next step is to filter articles according to the inclusion and exclusion criteria. This screening process resulted in the reduction of 91 articles to 66 articles. Furthermore, 66 articles were analyzed more systematically and comprehensively based on research questions.

Data analysis

The data analysis process in this study was based on inclusion and exclusion analysis (Fiskerstrand, 2022). Limitations of the literature review analysis in this study focused on AR applications for creativity. The literature review analysis of journal articles was conducted in 2015–2023. Journal articles that met all the inclusion and exclusion criteria were then analyzed based on (1) the implications and features of using AR for mathematical creativity; (2) the potential of using AR for mathematical creativity based on the six themes of the NCTM Principles and Standards; (3) perceptions of the use of AR for mathematical creativity, participant criteria, and evaluation methods based on journal articles on the application of AR for mathematical creativity from 2015 to 2023.

In analyzing the literature review, this study compared the distribution of articles from various databases regarding features, implications, and potential of using AR for mathematical creativity. This study continues the analysis to the next step, namely comparing articles about perceptions, user criteria, measurement tools, and evaluation methods of the effectiveness of AR for mathematical creativity. The number and citations of articles from each year were determined in detail and analyzed to answer this research question systematically. Data analysis consisted of collecting data from 66 articles from 2015 to 2023 related to using AR for mathematical creativity, filtering and describing more straightforward research questions (without repetition), and counting the number of citations from the selected articles in this study. All data information is inputted into Microsoft Excel based on research questions. Data analysis in this study uses descriptive statistics. In addition to presenting graphs, tables, and diagrams, they are also used for detailed analysis in identifying information about AR applications for mathematical creativity.

Results

This study compares previous studies on identifying AR applications for mathematical creativity from 2015 to 2023. The literature consists of 66 articles that were previously synthesized and analyzed. Literature review activities focused on finding implications, features, and potential parameters according to the six themes of the NCTM Principles and Standards (2000), user criteria, measurement tools, and evaluation methods of using AR for mathematical creativity. Therefore, this study will answer and explain the three research questions in depth (Table 1).

What are the implications and features of using Augmented reality for mathematical creativity?

The articles were analyzed and grouped based on the types of implications of using AR for mathematical creativity that is rooted in the development of other abilities or skills of students. Based on the implications, 15 articles discuss using

Table 1 The implication, user criteria, evaluation method, and measuring instrument of using augmented reality for mathematical creativity

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
1	Saidin et al. (2015)	Augmented reality (AR) technology has positive potential and advantages in education. AR in mathematics aims to teach geometry through the use of 3D geometric concepts in mathematics learning so that AR develops creativity, knowledge, and innovation in education	Students in various levels of education	The results of the literature review	Meta-analysis
2	Sejzi (2015)	College students can use augmented reality and virtual reality to understand mechanical engineering, mathematics, and geometry; students can interpret reality according to experience and produce novelty, understanding, and knowledge	Students in various levels of education	The results of the literature review	Analysis of study literature
3	Sannikov et al. (2015)	Augmented reality (AR) motivates students to study natural sciences, physics, and mathematics, develop technical creativity, and carry out research activities and projects to be important	Students in second education	The results of the literature review	Analysis of study literature

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
4	Coimbra et al. (2015)	AR applications create integration and interaction between real and virtual environments, enabling enormous versatility and creativity in applications. Thus, Augmented Reality improves Higher Education students in learning mathematics	Students from the Portuguese Polytechnic Higher education	Product Effectiveness	Questionnaire and interview, and observation; test
5	Lin et al. (2015)	This study shows the effectiveness of solid geometry learning using an augmented reality-assisted learning system because the design of a learning system with AR can combine real, creative, and media environments into a hybrid environment	76 Eighth-grade students from Tainan City, Taiwan	Students' math scores and spatial perception	Test; observations and interviews
6	Ahn and Choi (2015)	This research develops educational programs to enhance student learning effects and suggests more systematic and practical problem-solving procedures for inquiry learning	Students in various levels of education	Survey results	Survey

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
7	Radu et al. (2015)	The use of Cyberchase Shape Quest as an augmented reality math application to teach geometry and involve elementary school children's spatial cognition skills. Applications can lead student teams to be creative to reinforce perceptual cues	Designed for children 6–8 years old, elementary-school children	Product feasibility test results, video data to identify student responses	Test product effectiveness with formative evaluation and video recording
8	Kiat et al. (2016)	The integration of technology from Augmented Reality (AR), Virtual Learning Environment (VLE), and Mobile Learning (ML) in the teaching and learning process can provide a new, creative, innovative learning environment and improve the quality of teaching and learning	Students in various levels of education	The results of the literature review	Meta-Analyze
9	Oh et al. (2016)	Media puzzle Augmented Reality system for improving students' creative thinking skills and problem-solving abilities	Infant	The results of the literature review	Theoretical study

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
10	Buchori et al. (2016)	Private school teachers are more interested in developing a Character Building Learning Model using Mobile Augmented Reality media to learn mathematics because it can increase students' creativity and critical thinking	The subjects were sixth-year students from 10 public schools and five private primary schools	Product feasibility	Questionnaire
11	Tekederea and Göker (2016)	A Meta-Analysis regarding the implications of the effectiveness of Augmented Reality applications in education. In teaching mathematics and geometry, AR can achieve high academic success and student motivation; increase imagination and creativity	Students in various levels of education	The results of the literature review	Meta-analysis
12	Albayrak et al. (2016)	Augmented reality-based Robot Media can increase the interest, motivation, and creativity of elementary education students in Turkey. Media Robot has a positive effect on improving student learning practices in learning science and mathematical principles	Primary school-age children	The results of the literature review	Theoretical study

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
13	Giasiranis and Sofos (2016)	The module "Representation of information on a computer" using two different technologies, "Augmented Reality and the Web," contributes positively to student performance improvement, motivation, and creativity	42 Students in the second year of junior high school	Quiz and questionnaire data	Quiz; Questionnaire
14	Yilmaz and Goktas (2016)	Augmented reality technology contributes positively to improving elementary school students' narrative skills and creativity in storytelling activities	100 Fifth grade elementary school students	Post-test scores to measure students' creativity and narrative skills	Post-test
15	Saltan and Arslan (2017)	Penggunaan Augmented Reality berdampak positif terhadap peningkatan students' academic achievement, motivation, minat, knowledge acquisition, knowledge retention, satisfaction, dan kreativitas siswa pada pembelajaran berbasis inkuiri dalam pendidikan formal	K-12 students; Higher Education	The results of the literature review	Literature review using inclusion and exclusion criteria, and the PRISMA model

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
16	Salinas and Pulido (2017)	The ability of augmented reality technology can overcome anxiety about mathematics; increase learning motivation; students' spatial abilities, understanding the concept of cones in mathematical knowledge	Student in mathematics education	The results of the literature review	Literature review
17	Cascales-Martínez et al. (2017)	Promote math learning with Augmented Reality Enhanced Tabletop System consisting of a set of interactive 3D educational materials that can visualize real objects and creative scenarios for solving math problems in virtual shopping simulation games	Twenty-two students, whose ages are between 6 and 12, enrolled in primary education in a public school in Alicante (Spain)	Pre-test results, post-test results	Pre-achievement test; post achievement test and the motivation questionnaire
18	Sanabria and Arámburo-Lizárraga (2017)	Augmented reality can develop collaborative creativity; as well as supporting creativity-based learning such as in the integrated study of Science, Technology, Engineering, Arts and Mathematics (STEAM)	Student in various levels of education	The results of the literature review	Theoretical study

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
19	(Zhu et al. (2017)	Augmented Reality technology in an interactive educational game is designed to learn various abstract concepts, such as color mixing, mathematics, and recognition of 2D–3D geometric shapes in preschool children aged 4–7 years. The product developed is more focused on developing children's creativity	This study involved five volunteer parents who had children aged 4–6 years and had experience using tablets or smartphones	Product use experience	Tests, surveys and interviews
20	Buchori et al. (2017)	The interaction between Direct Instruction Learning Strategy and Mobile Augmented Reality can improve students' cognitive learning outcomes, motivation, and spatial skills, so that the learning process becomes active and creative	245 Students in the course of Geometry. Subject from mathematics education of the University of PGRI Semarang	Cognitive learning outcomes of students and effectiveness of learning strategies with Mobile Augmented Reality	Interview, test, and documentation
21	Martin-Gutierrez (2017)	The use of Augmented reality and Virtual reality technology in the application of specific learning strategies has an impact on reducing anxiety levels during mathematics lessons, increasing motivation and students' creativity and innovation	Students in engineering education	Pandangan menyeluruh tentang penelitian relevan yang berkaitan dengan Penggunaan augmented reality technology dalam pendidikan teknik	Literature review

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
22	Le and Ki (2017)	Augmented reality applications and hand gestures can increase the creative power and logical analysis of students and students. In addition, hand gestures provide students with an intuitive and natural way to interact with 3D shapes in learning 3D geometry	Twenty-seven High school students and university students	Results of product trials	Product trial, questionnaires
23	Chen et al. (2017)	The review analysis also examines the implications of Augmented Reality (AR) in learning geometry providing new opportunities for teaching, learning, research, or creative inquiry	–	The results of the literature review	Literature review
24	Hsu et al. (2017)	STEM learning with Augmented reality impacts positive perceptions, interest, motivation, and student learning performance. The students' experience thinking through these AR lessons inspires them to be innovative and creative	A total participant of 32 grade 10 students from a private senior high school in Taipei City	Perceptions and experiences of students from using the product	Questionnaire

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
25	Papanastasiou et al. (2018)	The development of Augmented reality and Virtual reality can improve digital era literacy, creative thinking, collaboration, problem-solving skills, and communication between students	K-12, higher and tertiary education students	The results of the literature review	Literature review with inclusion and exclusion criteria
26	Chandrasekera and Yoon (2018)	Augmented and virtual reality affect students' learning styles during creative design	Thirty volunteers participated in the study	Product effectiveness	Post-test: technology acceptance model; and pre-test: the VARK learning styles inventory
27	Pritami and Muhimmah (2018)	Developing digital game applications with Augmented Reality can create a fun environment, increase creativity and motivate students to learn mathematics	Participants were students in the primary schools in Yogyakarta; Ngemplak 2 public elementary school	Product effectiveness	Black Box Testing; Observation and interview
28	Raghaw et al. (2018)	The development of Augmented reality using the Unity Tool significantly contributes deeply to student engagement and instructive performance results because the class becomes interactive, lively, and interesting for students	Student in history education	The results of the literature review	Literature review

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
29	Kiryakova et al. (2018)	Augmented Reality (AR) has the potential to be effective for learning complex mathematics (geometry) by visualizing 3D models so that students' spatial thinking develops. Learners will have the competence, essential skills, and knowledge to solve real problems appropriately and creatively	Students in various levels of education	The results of the literature review	Literature review
30	Chao and Chang (2018)	Augmented Reality mathematics (AR Math) in digital learning can raise the ability to think independently, interest, creativity, and critical analysis of high school students	6th-Grade students of an elementary school with a total of 63 students	Students' motivation, understanding of learning, and acceptance of technology	Achievement tests; questionnaires and teachers' and children' interviews
31	Isti'aroh et al. (2018)	The Victory of Culture Games (VOC-Game), a media for learning mathematics based on augmented reality, provides space for students to optimize their potential and develop their reasoning and creativity	Students in various levels of education	The results of the literature review	Literature review

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
32	Agustina et al. (2019)	Augmented reality with STEM-based learning (STEM-AR) has the potential to support scientific literacy in vocational education	Students in vocational education	The results of the literature review	Literature review
33	Sarkar et al. (2019)	Developing an open, collaborative learning environment using Augmented Reality Interaction Media (AIMs) as a scaffold to increase creativity, divergent thinking, fluency, flexibility, and originality. A collaborative open-ended approach using AIM can improve collaborative creative problem solving based on the Mathematics syllabus	7th-Grade students at a suburban Indian school	Student performance and product feasibility test	Video recordings; Observation Logs; students' answers sheet; interview transcript; divergent thinking test
34	Tzima et al. (2019)	The teacher's point of view in developing augmented reality (AR) applications is that AR can improve the learning process, motivation, creativity, and learning effectiveness	20 Teachers, 13 women, and seven men, working in secondary education; junior high schools and senior high schools	Teaching experience on augmented reality applications in education	Questionnaire and Interview Guide

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
35	Ruhaiyem and Kei (2019)	Teaching complex mathematical operations using AR can improve abstract thinking; cultivate reasoning power, spatial skills; critical thinking; creativity; communication; and problem-solving abilities	Teacher and student in math education	The results of the literature review	Literature review
36	Al-Azawi et al. (2019)	The virtual environment from the effective use of Augmented Reality (AR) and Virtual Reality (VR) can encourage student creativity and innovation in learning in STEM classes	Student in various levels of education	The results of the literature review	Literature review
37	Aldalalah et al. (2019)	Using applications from augmented reality and simulation mode can positively affect students' achievement in mathematics and visual thinking. In addition, augmented reality also stimulates thought and creativity in learning geometry	All 7th-grade students et al. Manar School in Abu Dhabi. The sample consists of 86 students in mathematics	Achievement of mathematics and visual thinking students	Mathematics test and Visual thinking test
38	Silva et al. (2019)	The use of augmented reality has a positive impact on motivation, cognitive performance, collaboration, and creativity in mathematics and science learning content	106 School teachers	Participants experience using augmented reality	Online structured survey

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
39	Herrera et al. (2019)	The development of 3D tools with augmented reality, virtual environments, and 3D printing positively impacts students' spatial mathematical skills so that visualization skills and mathematical creativity can develop through augmented reality	Analysis of variance with a sample of $N=993$ students and participants who took the spatial test were $N=442$ students	Spatial test results; participants' perceptions and experiences of using 3D tools	Surveys; test of spatial math skills
40	Langer et al. (2020)	The "AR3 Vector" application is a development of an augmented reality application that can help students to see the world around them in a new way, realistically and creatively connected to students	Students in higher education	Literature on "Vector AR3" Applications in STEM Education	Literature review
41	Pamungkas (2020)	Augmented reality media combined with a pedagogical approach can attract students' motivation and curiosity so that students are more active, creative, and highly enthusiastic about learning especially mathematics	Students in various levels of education	The results of the literature review	Literature review

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
42	Guntur et al. (2020)	Augmented reality technology is one of the solutions to improve problem-solving and spatial skills; augmented reality technology can combine the real and virtual worlds. Students become motivated to be creative and innovative when facing problems	Students in various levels of education	The results of the literature review	Literature review
43	Saundarajan et al. (2020)	The need for learning Algebra with Augmented Reality through photo math has a significant impact on improving Algebra learning in lower secondary education. A new and creative way to learn and teach mathematics using augmented reality technology	33 Lower secondary students in Malaysia	Pre-test data and post-test data; Questionnaire data	Pre-test, post-test, and questionnaire
44	Hanid et al. (2020)	Various learning strategies (such as interactive learning, game-based learning, collaborative learning, and experiential learning) with augmented reality have great potential in the design of creative teaching strategies	Students in various levels of education	The results of the literature review	A systematic literature search in databases: Scopus, Web of Science, Science Direct, Taylor Francis, and Springer

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
45	Aditama and Setiawan (2020)	Augmented Reality technology with Indigenous Bali can create opportunities for cultural preservation in creative media during the Industrial Revolution 4.0	–	Recommend positive regarding augmented reality prototype	Test the product with feedback on an augmented reality prototype
46	Suryanti et al. (2020)	Augmented reality can trigger students' critical thinking and creativity in learning mathematics for integer material	Ninety-five students from five schools on Bawean Island. The students are all in seventh grade	Students' critical thinking	Pretest and posttest to test critical thinking; and questionnaire
47	Wittayakhom and Piriyasurawong (2020)	Learning the STEAM model (science, technology, engineering, and mathematics) in the Massive Open Online Course using Augmented Reality technology can increase student Creativity and Innovation	–	Product feasibility	Validation test by seven experts
48	Ahmad and Junaini (2020)	A Systematic Literature Review shows that augmented reality technology can help increase students' understanding of STEM (Science, Technology, Engineering, and Mathematics) education and collaborative creativity between students during mathematics learning	Students in various levels of education	The results of the literature review	A systematic review and Meta-analyses (PRISMA)

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
49	Arulanand et al. (2020)	Learning experiences using augmented reality frameworks on mobile phones offer opportunities for students to be creative and an element of motivation and collaboration in engineering education. The application of AR is adapted to the syllabus of an engineering education curriculum	Students in engineering education	A Framework for Using Augmented Reality for engineering education	Exploration for the effectiveness of implementing Augmented reality
50	Rashevska et al. (2020)	Augmented reality tools effectively reduce fear and anxiety toward geometry class, encourage students' interest in mathematics, increase students' creative potential, and solve two-dimensional geometric problems	Students of grades 7–9	The results of the analysis of product effectiveness	Analysis from two augmented reality tools: ArloonGeometry and Geometry AR
51	Syafril et al. (2021)	Development of a virtual geometry prototype model that can display objects and learning materials realistically, feature videos, images, and animations, so that the prototype can increase students' interest in learning mathematics, the willingness and creativity of students during learning mathematics	One hundred and twenty students in three junior high schools in Padang; Indonesia	Product effectiveness	Tests and analysis. Mock-up (evaluation)

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
52	Sholikhah and Cahyono (2021)	The development of augmented reality worksheets with a problem-based learning design helps students visualize 3D objects. This aims to improve students' mathematical literacy skills and the ability to think and act creatively, productively, independently, collaboratively, and communicatively	Students from Islamic State Junior High School 3 Kebumen	Student literacy skills; product feasibility	Product feasibility test; math literacy test (pre-test and post-test)
53	Yousef (2021)	Students are satisfied with using Smart-flashcard as a mobile augmented reality application, which significantly impacts their learning outcomes	The population was first-grade pupils aged between 6 and 7 years old. The sample consisted of 62 primary school pupils enrolled in public schools in Cairo, Egypt	The pupils' achievement, motivation and creativity	Basic Geometry Concepts Test (BGCT); Torrance Tests of Creative Thinking (TTCT); Instructional Materials Motivation Survey (IMMS). Post-test: BGCT; TTCT; IMMS
54	Salako et al. (2021)	Augmented reality technology effectively increases elementary school student's achievement and creative thinking, motivation, and learning involvement in learning geometry	Students in art education	Product effectiveness; and students' knowledge before and after the use of AR applications	Pre-test and post-test

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
55	Hamzah et al. (2021)	The development of augmented reality applications can increase understanding, generate motivation, creativity, and interest, and visualize students' thoughts in learning computer network devices	31 Students of the Information System Study Program, Sultan Syarif Kasim State Islamic University, Indonesia	Product Effectiveness	Evaluation using the SUS score (System Usability Scale)
56	Palanci and Turan (2021)	A Systematic Review shows that augmented reality (AR) technology can improve students' spatial abilities and motivation in mathematics education. AR can increase students' productivity, creativity, and collaboration in mathematics	Students in mathematics education	The results of the literature review	Literature review
57	Theodoropoulos and Lepouras (2021)	The positive impact of augmented reality in programming education is active student involvement, fun interventions; motivated collaboration; creativity; immediate feedback, communication, and social skills of students	Students in programming education	The results of the literature review	Literature review

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
58	Lin and Wang (2022)	The application of augmented reality can increase participants' perceptions and creative thinking. Participants can form ideas, appreciate new ideas, and evaluate critical ideas	39 Taiwanese freshmen	Perceptions of creative thinking and learning motivation	The Instructional Materials Motivation Survey (IMMS), an augmented reality survey; test
59	Chen et al. (2022)	Using the Cosmos Planet Go application based on augmented reality can improve student learning performance, learning effectiveness, and motivation. Implementing creative situated augmented reality learning can support student involvement in creative expression	The Experimental group had 40 students. The control group has 40 students in 5th grade and 6th grade	Learning effectiveness, learning motivation, flow experience, and creative perception	Post-test; IMMS (Instructional Materials Motivational Scale) and flow experience test scale; interview
60	Cui (2022)	Augmented reality (AR) mobile apps can improve piano skills. The study results may interest piano teachers seeking innovative opportunities to modernize pedagogical practice	Forty-seven university students in Harbin, Heilongjiang Province, China	Technical skills of a pianist	Pedagogical practice; students' subjective attitudes and personal learning progress

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
61	Iqbal et al. (2022)	The use of Augmented Reality in STEM education (Science, Technology, Engineering, and Mathematics) to deliver practical and creative teaching parts	Augmented reality for students in the early grades and higher grades	To explore AR learning applications	A systematic review
62	Raccanello et al. (2022)	The use of GeoGebra augmented reality is effective for learning and teaching mathematics because students are involved in a virtual environment that is integrated into their real world, and the content of the material is explored in a creative way that students learning mathematics learn	Freshman students in mathematics education	Learning experience	Exploring mathematics teaching and learning process using GeoGebra with Augmented reality
63	Rizki et al. (2023)	The integration of Android-based adventure games and augmented reality is effective in increasing students' interest in learning; interactive, creative, and efficient learning	Augmented reality application is applied to 3 teachers and 11 students	The validity, Effective, Interactive, Efficient, and Creativity of the product	A questionnaire using the Likert scale

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
64	Gao et al. (2023)	Augmented reality (AR) applications' interactive design with mathematical simulations supports virtual experiments and produces data that resembles real experiments. Applications can foster students' creativity and imagination because they have positive experiences using mobile AR applications	Student in chemical engineering	Pre-test and post-test scores	Pre-test and post-test; questionnaire
65	Yulianti et al. (2023)	An augmented reality-integrated science book focusing on environmental pollution and global warming in STEAM education can lead students to think critically by looking at real-life problems from different perspectives, having dialogue and discussion, sharing ideas, and creating creative solutions	The AR-integrated science book was delivered to 2 science teachers and their 15 junior high school students in Malang, Indonesia	Perceptions of teachers and students	Questionnaire Sets

Table 1 (continued)

No	Citation	Implications	User criteria	Evaluation Method	Measuring instrument
66	Ou Yang et al. (2023)	Augmented reality-based virtual educational robotics effectively encourages students' computational thinking skills (CT), learning enjoyment, academic achievement, increased creative thinking, critical thinking, and problem-solving skills	The experimental group is 41 students who use AR Bot, and the control group is 34 students who use Scratch	Test score	Test

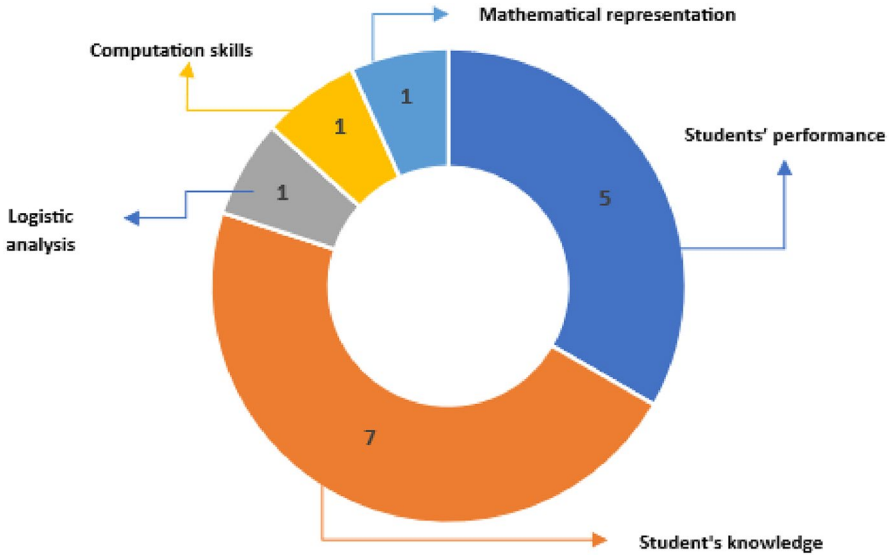

Fig. 1 Distribution of articles on augmented reality with implications for cognitive performance

AR in mathematical creativity and its implications for improving students' cognitive performance. Based on the implications for cognitive performance, 5 of the 15 articles discuss that AR in mathematical creativity has implications for increasing student learning performance; 7 out of 15 articles explain increasing student knowledge; 1 article describes the implications of AR for logistics analysis; another article focuses on the implications of AR for computation skills; and 1 other article focuses on the implications of using AR for mathematical representation (Fig. 1).

Based on the student's knowledge aspect, three of the seven articles focused on using AR in mathematical creativity, which has implications for knowledge development. One of seven articles shows that the use of AR has implications for acquiring knowledge; another article shows the use of AR, which has implications for the smoothness of the process of assimilation of knowledge; and another article focused on AR, which has implications for finding creative solutions. This is shown visually in Fig. 2.

Studies from 2015 to 2023 have investigated the implications of AR in mathematical creativity, which have implications for problem-solving processes. Based on the problem-solving process, seven articles discuss the use of AR in mathematical creativity, which has implications for improving students' comprehension. Eleven articles inform the use of AR in mathematical creativity, which has implications for improving problem-solving abilities. Nine articles explain AR in mathematical creativity, which has implications for increasing students' interest. Two articles show that AR has implications for improving students' reasoning. The development of AR can increase students' reasoning (Ruhaiyem & Kei, 2019). AR can produce a visually environmental to make student learning

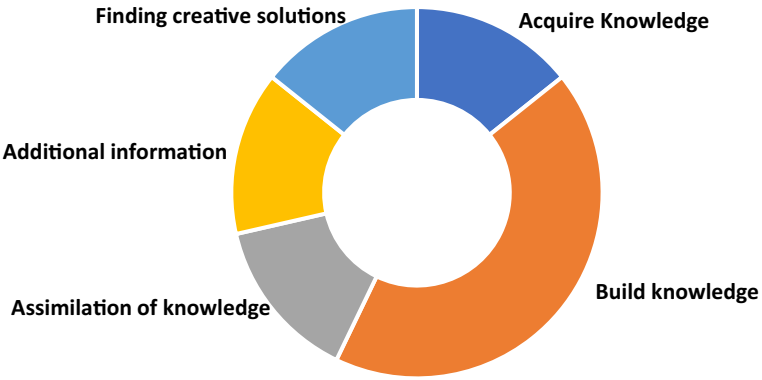

Fig. 2 Distribution of articles on Augmented Reality with implications for Student's Knowledge

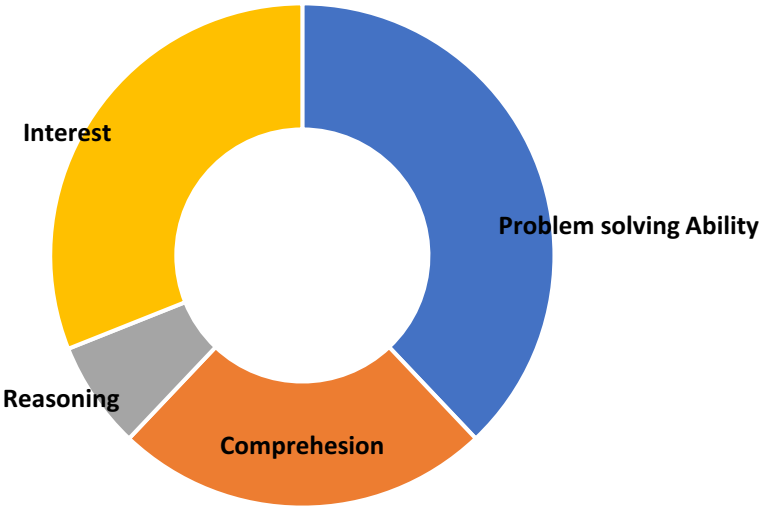

Fig. 3 Distribution of articles related to the Implications of Augmented Reality in the problem-solving process

experiences creative and meaningful (Chandrasekera & Yoon, 2018). The distribution of articles related to the implications of AR in the problem-solving process is shown in Fig. 3.

Based on the analysis of the literature review from 2015 to 2023, the use of AR for mathematical creativity also has implications for increasing students' self-potential. Based on self-potential, 22 articles examine the use of AR in mathematical creativity, which has direct implications for increasing student learning motivation. There is one article that discusses the implication of creative AR on increasing students' curiosity, another article that discusses the implications of AR on increasing student satisfaction, and another article about the implications of AR on increasing the enjoyment of learning. On the other hand, four articles examine the use of AR in

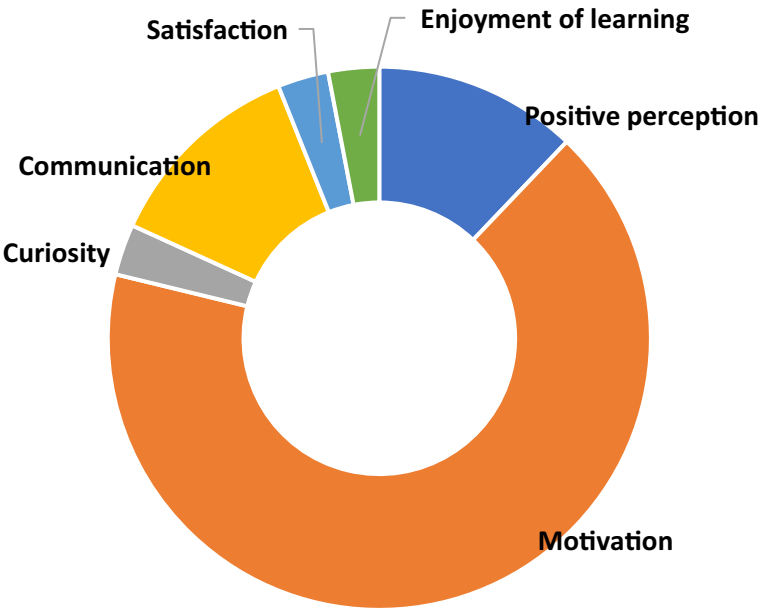

Fig. 4 Distribution of articles on the implications of Augmented Reality for Self-Potential

mathematical creativity, which has implications for students' mathematical communication, and four other articles examine the implications of AR on students' positive responses or perspectives. The distribution of articles discussing AR in mathematical creativity, which has direct implications for self-potential development, is shown in Fig. 4.

The results of the literature review analysis show that AR has implications for creativity and the development of social skills from students (Papanastasiou et al., 2018; Theodoropoulos & Lepouras, 2021). Based on developing self-skills, two articles state AR's implications for developing students' visual thinking skills. Seven articles examine AR's implications for spatial thinking. Three articles show AR's implications for improving students' literacy skills. On the other hand, only one article shows AR can improve students' narrative skills, namely (Yilmaz & Goktas, 2016) (Fig. 5).

Based on the aspect of improving self-ability, the results of the analysis show that five articles examine students' critical thinking improvement by AR; one article examines AR has implications for increasing intuitive thinking, one article shows AR has implications for fluency in the production of new ideas, and one other article discussing the advantages of AR in increasing divergent thinking. The distribution of articles about the implications of AR for increasing self-ability is shown in Fig. 6.

The results of the literature review analysis show the features in the development of AR for mathematical creativity. One article mentions that the features of head-mounted displays and personal interaction panels are useful in developing AR applications. Another article mentions that 3D Visualization and AR are good

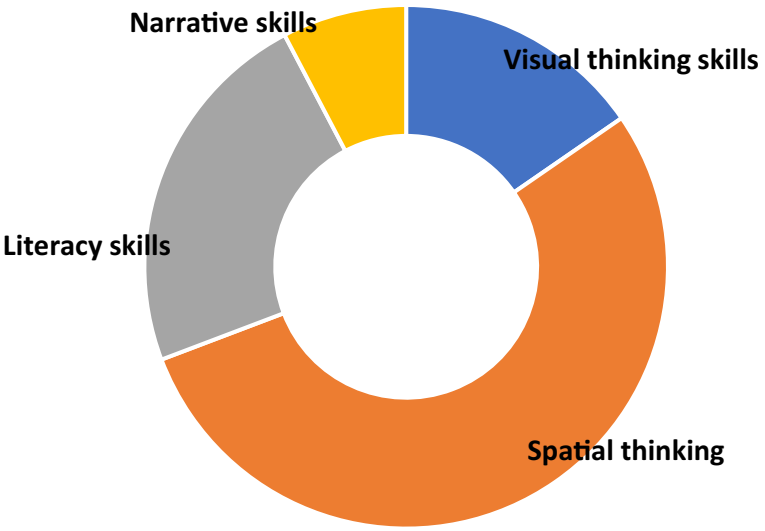

Fig. 5 Implications of Augmented Reality for the improvement of social skills

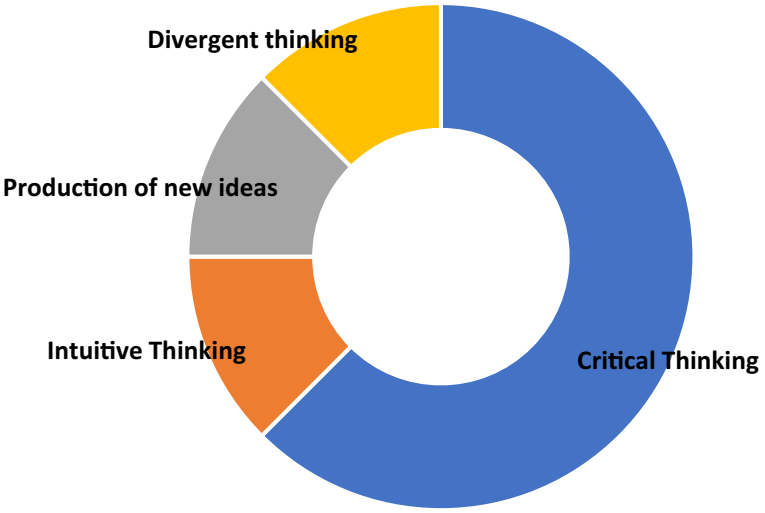

Fig. 6 Distribution of articles about the implications of Augmented Reality for self-ability

for learning. Other important features from the development of AR are Unity3D (Raghaw et al., 2018) and Vuforia (Palanci & Turan, 2021); HP Reveals; Blippar; ENTiTi Creator; HD Augmented Reality; Metaio SDK (Ahmad & Junaini, 2020). The literature review results show that the most dominant features used in developing AR for mathematical creativity are the Unity3D tool and Vuforia (Fig. 7).

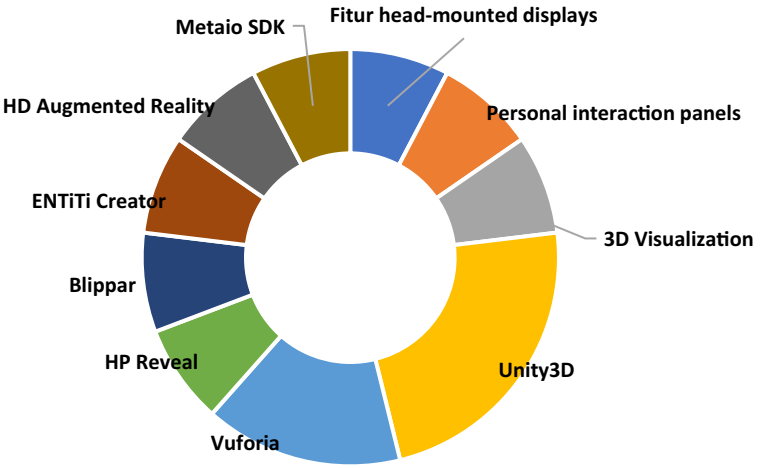

Fig. 7 Distribution of features from using Augmented Reality

What is the potential of using Augmented reality for mathematical creativity based on the six themes from NCTM Principles and Standards?

The results of the literature review analysis show the potential of AR for mathematical creativity, which are grouped based on six themes from the NCTM Principles and Standards (2000): equity, mathematics curriculum, mathematics teaching, learning, assessment, and mathematics technology. There may be overlapping groupings of article publications based on the six themes of NCTM (2000), as shown in Table 2.

Based on Table 2, the results of the analysis of the literature review show that 29 articles discuss the equity of AR. Equity in this study focuses on the advantages of AR for improving learning practices and student performance. Six articles discuss using AR in mathematical creativity based on improving the educational curriculum. AR application development supports the educational curriculum (Papanastasiou et al., 2018). Fourteen articles discuss the effectiveness of AR-based teaching in increasing students' creativity and self-skills. Thirty-two articles discuss learning activities based on AR and processes to construct student understanding. Seven articles discuss the evaluation of the application of AR in the teaching and learning of mathematics. Fourteen articles discuss the development of AR technology into developing new AR applications that are interesting and support increased student performance. Based on NCTM (2000), technology is very important in improving the teaching and learning of mathematics. This study analyzes the development of AR technology or combining AR with other applications to become creative new AR applications. Publications

Table 2 Publication of articles on the potential of Augmented Reality based on the NCTM (2000)

Theme	Citations
Equity	Albayrak et al. (2016), Buchori et al. (2016), (2017), Chandrasekera and Yoon (2018, Chao and Chang (2018), Chen et al. (2022), Chen et al. (2017), Coimbra et al. (2015), Cui (2022), Gao et al. (2023), Guntur et al. (2020), Hamzah et al. (2021), Herrera et al. (2019), Kiat et al. (2016), Langer et al. (2020), Lin et al. (2015), Ou Yang et al. (2023), Pamungkas (2020), Pritami and Muhimmah (2018), Raghaw et al. (2018), Rashevska et al. (2020), Ruhaiyem and Kei (2019), Salinas and Pulido (2017), Sanabria and Arámburo-Lizárraga (2017), Sejzi (2015), Silva et al. (2019), Tekederea and Göker (2016), Wittayakhom and Piriyasurawong (2020), and Yousef (2021)
Curriculum	Chen et al. (2022), Gao et al. (2023), Giasiranis and Sofos (2016), Papanastasiou et al. (2018), Tzima et al. (2019), and Yousef (2021)
Teaching	Arulanand et al. (2020), Chao and Chang (2018), Chen et al. (2022), Chen et al. (2017), Cui (2022), Giasiranis and Sofos (2016), Hamzah et al. (2021), Hanid et al. (2020), Iqbal et al. (2022), Langer et al. (2020), Raccanello et al. (2022), Rashevska et al. (2020), Tekederea and Göker (2016), and Zhu et al. (2017)
Learning	Agustina et al. (2019), Ahmad and Junaini (2020), Ahn and Choi (2015), Al-Azawi et al. (2019), Albayrak et al. (2016), Buchori et al. (2016), Cascales-Martínez et al. (2017), Chao and Chang (2018), Chen et al. (2022), Chen et al. (2017), Chui et al. (2016), Hanid et al. (2020), Herrera et al. (2019), Hsu et al. (2017), Iqbal et al. (2022), Isti'aroh et al. (2018), Kiryakova et al. (2018), Langer et al. (2020), Lin et al. (2015), Palanci and Turan (2021), Pritami and Muhimmah (2018), Raccanello et al. (2022), Saltan and Arslan (2017), Sanabria and Arámburo-Lizárraga (2017), Sannikov et al. (2015), Sholikhah and Cahyono (2021), Silva et al. (2019), Tekederea and Göker (2016), Tzima et al. (2019), Wittayakhom and Piriyasurawong, (2020), Yulianti et al. (2023), and Zhu et al. (2017)
Evaluation	Chen et al. (2022), Gao et al. (2023), Giasiranis and Sofos (2016), Hamzah et al. (2021), Hanid et al. (2020), Lin and Wang (2022), and Sarkar et al. (2019)
Technology	Albayrak1 et al. (2016), Cascales-Martínez et al. (2017), Chao and Chang (2018), Isti'aroh et al. (2018), Langer et al. (2020), Le and Ki (2017), Oh et al. (2016), Ou Yang et al. (2023), Pritami and Muhimmah (2018), Radu et al. (2015), Rizki et al. (2023), Saundarajan et al. (2020), Syafril et al. (2021), and Zhu et al. (2017)

related to the attributes of AR Application technology development are shown in Table 3.

What are the perceptions of using Augmented Reality (AR) for mathematical creativity, user criteria, measurement tools, and evaluation methods?

Perceptions of using Augmented Reality (AR) for mathematical creativity

The perception from the literature review regarding the use of AR is that AR can develop students' creativity and innovative mathematics with real or real visualization (Al-Azawi et al., 2019; Albayrak et al., 2016; Aldalalah et al., 2019; Arulanand et al., 2020; Buchori et al., 2016; Cascales-Martínez et al., 2017; Chao & Chang,

Table 3 Attributes related to the development of augmented reality technology

Attributes	Citations
Cyberchase Shape Quest: Patch the Path, Feed the Critters, dan Hide and Seek	Radu et al. (2015)
Integration of Augmented Reality (AR), Virtual Learning Environment (VLE), and Mobile Learning (ML)	Kiat et al. (2016)
Picture puzzle augmented reality system	Oh et al. (2016)
Robotics based on Augmented reality	Albayrak et al. (2016)
Integration of Augmented Reality and the Web	Giasiranis and Sofos (2016)
Tabletop System with Augmented reality	Cascales-Martínez et al. (2017)
Augmented reality application with hand gestures	Le and Ki (2017)
Integration of Virtual reality and Augmented reality	Al-Azawi et al. (2019), Chandrasekera and Yoon (2018), Papanastasiou et al. (2018), and Sejzi (2015)
Digital games using Augmented reality	Pritami and Muhimmah (2018) and Zhu et al. (2017)
AR Math app	Chao and Chang (2018)
The Victory of Culture Games (VOC-Games)	Isti'aroh et al. (2018)
AR3 Vector Application	Langer et al. (2020)
Application of Photomath	Saundarajan et al. (2020)
Virtual geometry (VirGO) based on augmented reality	Syafril et al. (2021)
Integration of Adventure Game and Augmented Reality	Rizki et al. (2023)
Augmented reality-based science book	Yulianti et al. (2023)
Virtual educational robotics with Augmented reality	Ou Yang et al. (2023)

2018; Chen et al., 2022; Coimbra et al., 2015; Gao et al., 2023; Giasiranis & Sofos, 2016; Guntur et al., 2020; Hamzah et al., 2021; Herrera et al., 2019; Hsu et al., 2017; Iqbal et al., 2022; Isti'aroh et al., 2018; Kiryakova et al., 2018; Lin & Wang, 2022; Ou Yang et al., 2023; Palanci & Turan, 2021; Pamungkas, 2020; Pritami & Muhimmah, 2018; Radu et al., 2015; Rizki et al., 2023; Ruhaiyem & Kei, 2019; Saidin et al., 2015; Salako et al., 2021; Saltan & Arslan, 2017; Sanabria & Arámburo-Lizárraga, 2017; Sannikov et al., 2015; Sholikhah & Cahyono, 2021; Silva et al., 2019; Suryanti et al., 2020; Syafril et al., 2021; Tekederea & Göker, 2016; Theodoropoulos & Lepouras, 2021; Tzima et al., 2019; Wittayakhom & Piriyasurawong, 2020; Yilmaz & Goktas, 2016; Yousef, 2021; Zhu et al., 2017) (Fig. 8).

Based on perceptions related to student creativity through AR, six articles explain perceptions regarding the effective use of AR as a creative learning media. Three articles show perceptions regarding using AR to help creative collaboration between students. Two articles stated that AR could improve students' creative thinking skills, two articles stated that AR is a good topic for creative research, and one article stated that integrating AR and teaching strategies is the best creative teaching strategy.

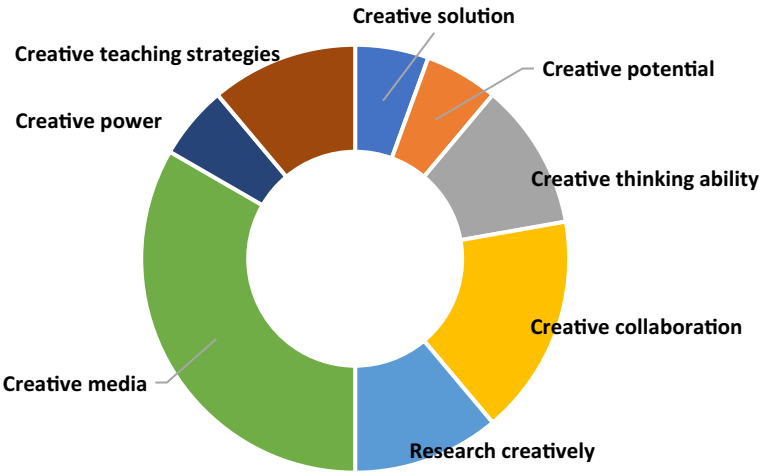

Fig. 8 Distribution of articles on perceptions of using AR for mathematical creativity

User Criteria of Augmented reality technology for mathematical creativity

Based on the use of AR for mathematical creativity, the results of a literature review from 2015 to 2023 show eight criteria for users who have implemented AR technology. User criteria based on the literature review are shown in detail in Table 4.

Based on Table 4, 19 articles show that the use of AR technology is dominated by increasing the mathematical creativity of university students. Twelve articles examine AR as the second-best for junior high school students. Six articles show that elementary school students can apply AR, and three articles show that secondary school students can apply AR to increase their creativity and comprehension. Furthermore, two articles said AR could increase infant creativity; two articles said AR helps teachers improve their learning process, and two other articles said AR is useful in everyday life. One article state that AR can develop the creativity of higher secondary school students.

Measuring tool for test the effectiveness of AR technology in increasing Mathematical creativity

Furthermore, a literature review of 66 articles on AR for mathematical creativity from 2015 to 2023 shows that 23 articles used a meta-analysis measure to identify the advantages of AR applications for mathematical creativity. Tests for increasing student creativity by AR were also carried out using various measuring instruments, 19 articles using a questionnaire, 18 articles using a test instrument, 1 article using a quiz, 7 articles using interviews, 5 articles using observation, and 4 articles using video recording. In addition, eight articles used an effectiveness test to test AR technology as an appropriate learning media for teaching mathematics and enhancing mathematical creativity (Fig. 9).

Table 4 User Criteria of Augmented reality technology for mathematical creativity

Criteria	Citations
Infant—Early childhood education	Oh et al. (2016) and Zhu et al. (2017)
K1/Kindergarten (5–6)	–
K2–K6/Primary school (6–12)/Elementary School	Albayrak et al. (2016), Cascales-Martínez et al. (2017), Chen et al. (2022), Pritami and Muhimmah (2018), Yilmaz and Goktas (2016), and Yousef (2021)
K6–K10/Junior High school/High School/Secondary School/Incomplete Secondary School/Intermediate school/middle school	Aldalalah et al. (2019), Giasiranis and Sofos (2016), Le and Ki (2017), Lin et al. (2015), Rashevska et al. (2020), Sannikov et al. (2015), Sarkar et al. (2019), Saundarajan et al. (2020), Sholikhah and Cahyono (2021), Suryanti et al. (2020), Syafril et al. (2021), and Yulianti et al. (2023)
K11–K14/Senior High School/Higher secondary school/senior secondary school/intermediate college/pre-university college	Hsu et al. (2017)
K11–K12/Secondary Schools/Senior High	Papanastasiou et al. (2018), Salinas and Pulido (2017), and Saltan and Arslan (2017)
K15–K20/Community College/Universities/Higher education/University student	Agustina et al. (2019), Arulanand et al. (2020), Buchori et al. (2017), Coimbra et al. (2015), Cui (2022), Gao et al. (2023), Hamzah et al. (2021), Herrera et al. (2019), Langer et al. (2020), Le and Ki (2017), Martin-Gutierrez (2017), Ou Yang et al. (2023), Papanastasiou et al. (2018), Raccanello et al. (2022), Raghaw et al. (2018), Salako et al. (2021), Salinas and Pulido (2017), Saltan and Arslan (2017), and Theodoropoulos and Lepouras (2021)
Teacher	Silva et al. (2019) and Tzima et al. (2019)
Others	Chandrasekera and Yoon (2018) and Rizki et al. (2023)

Evaluation method

In Fig. 10, the results of the analysis of the literature review show an evaluation method for testing the application of AR in mathematical creativity. Twenty-seven articles describe the advantages of AR through the results of the analysis of the literature review. Seventeen articles describe the role of AR as an effective product in learning. Three articles describe teachers' experiences regarding the effectiveness of using AR in their mathematics learning process. Twenty articles explain that AR can improve student academic achievement. Nine articles discussing AR can increase students' creativity and thinking skills. Ten articles mentioned that AR can increase students' motivation to learn mathematics.

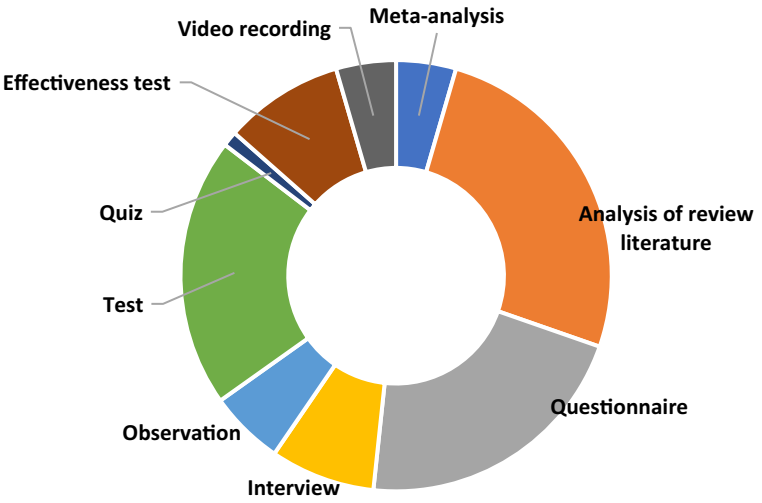

Fig. 9 Measuring tool to test the effectiveness of AR technology

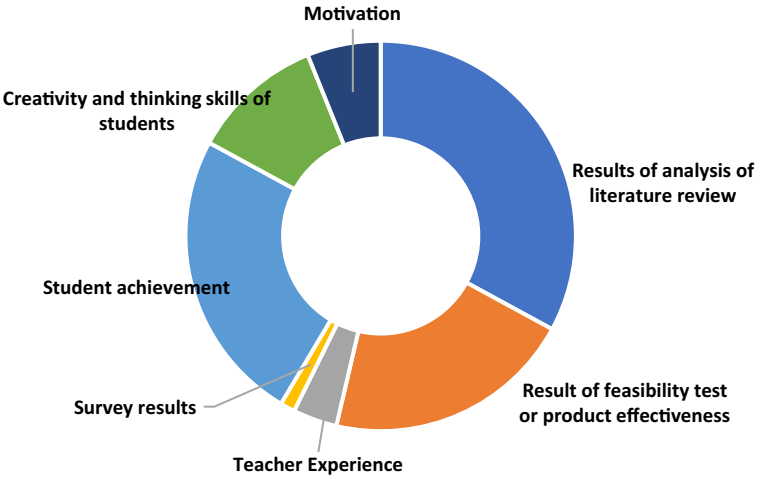

Fig. 10 Distribution for the evaluation method

Discussion, implication, and conclusions

In this section, this study informs the development of AR research to advance mathematics education and creativity in the future. This study reviewed 66 articles on the use of AR for mathematical creativity from 2015 to 2023 and then analyzed the literature review results based on three research questions. Based on the literature review analysis; the implications, features, potential, perceptions, evaluation methods, and user criteria of the use of AR for mathematical creativity are studied in more depth to enhance future studies and become a reference for educators,

researchers, stakeholders, and policy research in AR application for mathematical creativity.

Implications and features of using augmented reality for mathematical creativity

The implications of using AR for mathematical creativity provide a positive increase in students' abilities, performance, and learning skills. Based on the literature review above, this study shows that using AR for mathematical creativity has other implications for improving students' cognitive performance; problem-solving process; self-potential; social skills, and self-ability.

Based on the results of an in-depth review of the literature, the use of AR technology for mathematical creativity, which has implications for cognitive performance, can be broken down again, including the implications of AR for increasing student performance, student knowledge, logistics analysis; computation skills; mathematical representation. The results of the review analysis show that AR for mathematical creativity has implications for increasing student performance (Chao & Chang, 2018; Chen et al., 2022; Giasiranis & Sofos, 2016; Hsu et al., 2017; Raghaw et al., 2018). In addition, AR can have implications for the development and acquisition of knowledge (Buchori et al., 2017; Saidin et al., 2015; Saltan & Arslan, 2017; Sejzi, 2015). In building knowledge, AR supports assimilating mathematical knowledge (Cascales-Martínez et al., 2017), adding information (Chen et al., 2017), and finding appropriate and creative mathematical solutions. In finding a solution to a problem, the use of AR technology for mathematical creativity supports an increase in students' logical analysis (Le & Ki, 2017), improvement of students' computational skills (Ou Yang et al., 2023) and students' mathematical representation (Agustina et al., 2019).

Based on the implications in the problem-solving process, the implications of AR technology for mathematical creativity consist of improving comprehension; problem-solving abilities; reasoning; and interests. The application of AR to mathematical creativity also has implications for increasing the ability to solve problems that are more systematic and practical (Ahn & Choi, 2015; Buchori et al., 2017; Gao et al., 2023; Guntur et al., 2020; Isti'aroh et al., 2018; Oh et al., 2016; Papanastasiou et al., 2018; Rashevska et al., 2020; Ruhaiyem & Kei, 2019; Sarkar et al., 2019). Thus, understanding can be resolved by scaffolding from the AR application (Chui et al., 2016; Radu et al., 2015; Salinas et al., 2013; Sejzi, 2015; Yousef, 2021). With the application of AR, understanding concepts can be assisted through a realistic bridge visually (Al-Azawi et al., 2019). AR can increase students' creativity and reasoning (Isti'aroh et al., 2018; Ruhaiyem & Kei, 2019). So, AR has an impact on increasing creativity and interest in learning (Albayrak et al., 2016; Chao & Chang, 2018; Chen et al., 2017; Hamzah et al., 2021; Hsu et al., 2017; Rashevska et al., 2020; Rizki et al., 2023; Saltan & Arslan, 2017; Syafril et al., 2021).

AR's implications for creativity also influence students' self-potential development (Isti'aroh et al., 2018). AR supports the emergence of positive

perceptions (Hsu et al., 2017; Lin & Wang, 2022; Radu et al., 2015; Yulianti et al., 2023), high curiosity (Pamungkas, 2020), and learning motivation (Albayrak et al., 2016; Arulanand et al., 2020; Buchori et al., 2017; Cascales-Martínez et al., 2017; Chen et al., 2017, 2022; Giasiranis & Sofos, 2016; Guntur et al., 2020; Hamzah et al., 2021; Hsu et al., 2017; Lin & Wang, 2022; Pamungkas, 2020; Pritami & Muhimmah, 2018; Salinas & Pulido, 2017; Saltan & Arslan, 2017; Sanabria & Arámburo-Lizárraga, 2017; Sannikov et al., 2015; Silva et al., 2019; Tekederea & Göker, 2016; Theodoropoulos & Lepouras, 2021; Tzima et al., 2019; Yousef, 2021). On the other hand, AR in mathematical creativity can improve students' mathematical communication (Agustina et al., 2019; Sholikhah & Cahyono, 2021; Theodoropoulos & Lepouras, 2021), satisfaction (Saltan & Arslan, 2017), and create enjoyment of learning (Ou Yang et al., 2023).

On the other hand, AR can improve self-ability (Chao & Chang, 2018). In the aspect of self-ability, AR can develop students' critical and creative thinking (Buchori et al., 2016; Ou Yang et al., 2023; Ruhaiyem & Kei, 2019; Suryanti et al., 2020). This is supported by the opinion of Chao and Chang (2018) that AR can improve students' critical analysis in solving problems. Through the application of AR, students' learning experiences in thinking become meaningful (Al-Azawi et al., 2019; Gao et al., 2023; Hsu et al., 2017; Sholikhah & Cahyono, 2021). In the aspect of creative thinking, AR supports increasing students' intuitiveness (Le & Ki, 2017); production of novelty (Sejzi, 2015); increasing divergent thinking (Sarkar et al., 2019). In the creative process of learning mathematics, AR can increase the value of mathematics (Lin et al., 2015). AR can support students' academics (Tekederea & Göker, 2016). So through AR technology, students' academic achievement is very good (Aldalalah et al., 2019; Giasiranis & Sofos, 2016; Ou Yang et al., 2023; Saltan & Arslan, 2017).

Features of using AR for mathematical creativity. The use of head-mounted displays and personal interaction panel features in AR greatly contributes to the development of science and technology (Saidin et al., 2015). AR and 3D Visualization greatly contribute to interactive learning and education (Sannikov et al., 2015). Some of the features needed in the preparation of AR-based applications, including platforms from Unity3D (Raghaw et al., 2018) and Vuforia (Palanci & Turan, 2021); HP Reveals; Blippar; ENTiTi Creator; HD Augmented Reality; Metaio SDK (Ahmad & Junaini, 2020). The review results show that the most dominant features used in developing AR for mathematical creativity are the Unity3D tool and Vuforia.

The potential of using Augmented Reality for mathematical creativity based on the six themes of the NCTM Principles and Standards

Based on Table 2, the group of publications with the theme of equity explains the advantages and effectiveness of AR applications in education (Hamzah et al., 2021; Tekederea & Göker, 2016). Based on the equity of AR in creativity, AR has an impact on improving the quality of teaching and learning (Albayrak et al., 2016; Buchori et al., 2016; Cui, 2022; Kiat et al., 2016; Pamungkas, 2020), integrating real

and virtual environments for meaningful learning (Chandrasekera & Yoon, 2018; Chen et al., 2017, 2022; Coimbra et al., 2015; Gao et al., 2023; Guntur et al., 2020; Hamzah et al., 2021; Herrera et al., 2019; Kiat et al., 2016; Langer et al., 2020; Lin et al., 2015; Ou Yang et al., 2023; Pritami & Muhimmah, 2018; Raghaw et al., 2018; Ruhaiyem & Kei, 2019; Sejzi, 2015), decrease in the level of mathematics anxiety (Rashevska et al., 2020; Salinas & Pulido, 2017; Sanabria & Arámburo-Lizárraga, 2017), encourage student engagement (Chao & Chang, 2018; Raghaw et al., 2018; Wittayakhom & Piriyasurawong, 2020; Yousef, 2021), and improve cognitive learning outcomes (Buchori et al., 2017; Silva et al., 2019).

A group of publications with the theme curricula explaining the potential of AR for mathematical creativity based on educational curricula. AR technology helps increase student creativity in learning geometric concepts in the educational curriculum (Yousef, 2021). Creatively situated AR learning strongly supports the educational curriculum for the effectiveness of student learning (Chen et al., 2022). Interactive AR applications that follow the educational curriculum foster creativity and provide positive learning experiences for students (Gao et al., 2023). On the other hand, the development of AR applications can overcome the limitations of the educational curriculum because 3D models support an interesting and creative learning process for students (Tzima et al., 2019). Research from Papanastasiou et al. (2018) states that integrating Virtual Reality and AR can improve the quality of the traditional curriculum for various student learning needs. Integration of AR and the web adapted to the educational curriculum improve student performance and academic achievement during school learning (Giasiranis & Sofos, 2016). Thus, research on AR applications is increasingly being studied for education (Buchner & Kerres, 2023). The application of AR in digital media is effective in improving education in the world. This confirms current research results; AR applications are very suitable for developing the quality of educational curricula. Therefore, research on AR applications will increase in the next few years. This follows the opinion of Rusli et al. (2023) that AR applications can help teachers and students improve the school education curriculum. AR applications help students understand concepts in advancing modern education (Alamsyah et al., 2023).

The publication group with the theme of mathematics teaching explains the potential of AR for mathematical creativity in a teaching process. According to NCTM (2000), effective mathematics teaching requires students' understanding to learn knowledge well. AR has implications for the effectiveness of educational teaching because AR enhances students' imagination, creativity, academic success, and motivation (Chen et al., 2022; Giasiranis & Sofos, 2016; Tekederea & Göker, 2016), student learning interest (Chao & Chang, 2018), collaborative learning (Hanid et al., 2020). AR can construct abstract concepts into visualizations in teaching mathematics and science (Zhu et al., 2017). This is also following the opinion of Langer et al. (2020), AR has the potential to increase didactic concepts in digital teaching. AR can be seen as a practical tool in teaching effectiveness for an essential understanding of knowledge (Arulanand et al., 2020; Iqbal et al., 2022). In several cases in teaching mathematics, AR tools effectively support teaching two-dimensional plane geometry (Rashevska et al., 2020). In addition, AR-based GeoGebra is an effective idea for mathematics teaching (Raccanello et al., 2022). AR applications

can also improve students' literacy, basic skills, and pedagogical practices (Cui, 2022). In this case, AR provides creative opportunities in educational lessons (Chen et al., 2017). AR application development supports increased creativity and visualization of students' thoughts in modern teaching (Hamzah et al., 2021).

Based on NCTM (2000), mathematics learning focuses on students' mathematical activities in building and understanding new knowledge from previous experience and knowledge. Based on the theme of learning mathematics, a literature review shows that AR is effective in mathematics learning (Ahmad & Junaini, 2020; Buchori et al., 2016; Cascales-Martínez et al., 2017; Chen et al., 2017; Herrera et al., 2019; Isti'aroh et al., 2018; Kiryakova et al., 2018; Palanci & Turan, 2021; Raccanello et al., 2022; Sannikov et al., 2015; Silva et al., 2019; Tekederea & Göker, 2016; Tzima et al., 2019; Zhu et al., 2017). The potential of AR in learning mathematics includes helping to learn science and mathematical principles (Albayrak et al., 2016), sharpening numeracy skills, and training children's motor nerves in mathematics learning (Pritami & Muhimmah, 2018), effective in students' understanding of digital learning (Chao & Chang, 2018).

Based on the results of the analysis of the literature review, the integration of AR technology with learning strategies can provide creative learning designs (Chen et al., 2022; Lin et al., 2015; Martin-Gutierrez, 2017; Raccanello et al., 2022). Learning strategies that are well integrated with AR include interactive learning, game-based learning, collaborative learning, and experiential learning (Hanid et al., 2020), direct Instruction Learning Strategy (Buchori et al., 2017), problem-based learning strategy (Sholikhah & Cahyono, 2021). On the other hand, the application of AR can be combined with varied and fun learning models (Isti'aroh et al., 2018), including a combination with the inquiry learning model (Saltan & Arslan, 2017; Sholikhah & Cahyono, 2021), the STEAM learning model (Ahn & Choi, 2015; Wittayakhom & Piriyasurawong, 2020; Yulianti et al., 2023), the character building learning model (Buchori et al., 2016), STEM learning model (Agustina et al., 2019; Ahmad & Junaini, 2020; Al-Azawi et al., 2019; Hsu et al., 2017; Iqbal et al., 2022; Langer et al., 2020).

The evaluation aspect of this study follows NCTM (2000), the evaluation must support mathematics learning and provide useful information for teachers and students. The results of the literature review analysis show that the development of an AR application system is evaluated to be very effective for increasing student creativity in active learning (Hamzah et al., 2021; Hanid et al., 2020). Production and evaluation of teaching materials using AR technology support student learning performance in teaching and learning (Giasiranis & Sofos, 2016). The effectiveness of implementing AR in a class is evaluated through the delivery of students' perceptions of critical and new ideas (Lin & Wang, 2022). If students can provide various perceptions to solve problems, that is the most important element in evaluating the success of creating a learning environment based on AR in creative situations (Chen et al., 2022). Developing a collaborative learning environment using AR media can evaluate students' creativity and divergent thinking with parameters of fluency, flexibility, and originality (Sarkar et al., 2019). On the other hand, positive learning experiences in using AR are also the main evaluation in measuring the effectiveness of interactive AR application designs in a lesson (Gao et al., 2023).

Research by Buchner and Kerres (2023) stated that AR applications are very effective in education and learning. However, developing a better-designed learning media between learning theory and AR application technology can become an educational gap. This is supported by Ronaghi and Ronaghi (2022), good AR applications can improve someone's interest. Therefore, a combination of AR applications and appropriate teaching methods can create a good learning environment for students. In addition, Radu et al. (2023) stated that integrating AR applications with STEM strategies can improve students' critical thinking. Thus, the number of published articles on the development of AR applications for learning can be further expanded and studied more deeply, especially the development of AR application technology for mathematical creativity.

The development of a new learning application through the integration of AR technology with other applications to increase student creativity is studied in six publications. Technology integration between AR, Virtual Learning Environment (VLE), and Mobile Learning (ML) supports the improvement of the learning process (Kiat et al., 2016), the integration of AR and the web contributes to improving student performance (Giasiranis & Sofos, 2016), and Integration of Virtual reality and AR can create a virtual environment and look real for students in the process of learning mathematics (Al-Azawi et al., 2019; Chandrasekera & Yoon, 2018; Papanastasiou et al., 2018; Sejzi, 2015). Virtual reality and AR integration is a favorite combination of publications reviewed by research from 2015 to 2019.

Perceptions of the use of Augmented Reality (AR) for mathematical creativity and its user criteria

Based on the perception of using AR for mathematical creativity, AR can encourage students to create creative solutions (Yulianti et al., 2023), AR can increase students' creative potential (Rashevska et al., 2020), creative thinking skills (Agustina et al., 2019; Oh et al., 2016; Sarkar et al., 2019), creative collaboration (Ahmad & Junaini, 2020; Papanastasiou et al., 2018; Sanabria & Arámburo-Lizárraga, 2017), development of creative research and investigation (Chen et al., 2017; Sannikov et al., 2015), AR as a creative learning media (Aditama & Setiawan, 2020; Buchori et al., 2016; Hamzah et al., 2021; Isti'aroh et al., 2018; Lin et al., 2015; Tzima et al., 2019), increasing creative comprehension (Le & Ki, 2017), supporting creative teaching strategy design (Chandrasekera & Yoon, 2018; Siddiq et al., 2020). This is also supported by Jessen et al.'s (2020) opinion that AR applications encourage creative user engagement. AR applications create simulations that represent abstract physical objects in a real environment so that students' creativity and imaginative thinking become real and unlimited (Giannopulu et al., 2022), especially in its application in the field of learning mathematics. Research from Coimbra et al. (2015) confirmed that AR applications could improve students' mathematics learning. AR applications can integrate virtual physical objects, digital technology, and mathematical creativity. Digital technology in teaching practice encourages student creativity (Bereczki & Kárpáti, 2021). Thus, this provides an excellent opportunity to

increase the number of published articles on using AR for mathematical creativity in the following year.

Based on the concept of mathematical material, AR can make learning mathematics interesting in new and creative ways to understand algebraic concepts (Saundarajan et al., 2020), the concept of two-dimensional geometry (Rashevska et al., 2020), integer (Suryanti et al., 2020), cone concept (Salinas & Pulido, 2017), complex mathematical operations (Ruhaiyem & Kei, 2019), arithmetic concepts (Cascales-Martínez et al., 2017; Papanastasiou et al., 2018). The results of the review analysis state that the use of AR is dominant for geometry learning and teaching (Aldalalah et al., 2019; Buchori et al., 2017; Chen et al., 2017; Iqbal et al., 2022; Kiryakova et al., 2018; Le & Ki, 2017; Lin et al., 2015; Radu et al., 2015; Rashevska et al., 2020; Saidin et al., 2015; Syafril et al., 2021; Tekederea & Göker, 2016; Yousef, 2021; Zhu et al., 2017). AR applications can convey accurate information for 3D objects (Alamsyah et al., 2023). In addition, AR applications involve visualizing digital models and building student understanding (Revolti et al., 2023). This article can enrich publications about implementing AR applications for education.

In the users' criteria for implementing AR, AR effectively increases students' creativity from various educational levels (Ahmad & Junaini, 2020; Ahn & Choi, 2015; Al-Azawi et al., 2019; Chen et al., 2017; Guntur et al., 2020; Hanid et al., 2020; Iqbal et al., 2022; Isti'aroh et al., 2018; Kiat et al., 2016; Palanci & Turan, 2021; Pamungkas, 2020; Ruhaiyem & Kei, 2019; Saidin et al., 2015; Sanabria & Arámburo-Lizárraga, 2017; Sejzi, 2015; Tekederea & Göker, 2016). In detail, AR has a positive impact on increasing the creativity of infants or children in early childhood education; students in elementary school (Albayrak et al., 2016; Cascales-Martínez et al., 2017; Chen et al., 2022; Pritami & Muhimmah, 2018; Yilmaz & Goktas, 2016; Yousef, 2021), students in secondary school (Aldalalah et al., 2019; Giasiranis & Sofos, 2016; Le & Ki, 2017; Lin et al., 2015; Rashevska et al., 2020; Sannikov et al., 2015; Sarkar et al., 2019; Saundarajan et al., 2020; Sholikhah & Cahyono, 2021; Suryanti et al., 2020; Syafril et al., 2021; Yulianti et al., 2023), higher secondary school students (Hsu et al., 2017), senior high school students (Papanastasiou et al., 2018; Salinas & Pulido, 2017; Saltan & Arslan, 2017), university student (Agustina et al., 2019; Arulanand et al., 2020; Buchori et al., 2017; Coimbra et al., 2015; Cui, 2022; Gao et al., 2023; Hamzah et al., 2021; Herrera et al., 2019; Langer et al., 2020; Le & Ki, 2017; Martin-Gutierrez, 2017; Ou Yang et al., 2023; Papanastasiou et al., 2018; Raccanello et al., 2022; Raghaw et al., 2018; Salako et al., 2021; Salinas & Pulido, 2017; Saltan & Arslan, 2017; Theodoropoulos & Lepouras, 2021).

Based on the description above, AR applications are centered on various groups of users in educational development (Lima et al., 2022). AR applications are based on taking real pictures; physical objects can be seen virtually and real in front of the camera (Sidani et al., 2021; Wan et al., 2022). Research by Su et al. (2021) indicated that the publication of AR applications would be more successful and effective in future research and development. In addition, research by Chang et al. (2022) also analyzed 134 studies on AR applications, that AR applications for education positively impact student knowledge, responses, skills, and performance in the future. This shows that AR applications will significantly impact the world of education. This study enriches information about AR applications for education, especially

mathematical creativity. This literature review will serve as a reference for researchers, academics, and practitioners in mathematics education now and in the future.

Acknowledgements The author would like to thank the DRTPM KEMDIKBUDRISTEK Indonesia with contract number "43/UN39.14/PG.02.00.PL/VI/2023" for supporting and funding this research.

Data availability The datasets generated in this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

Ethical approval No ethical approval is required for this work.

References

Aditama, P. W., & Setiawan, I. N. A. F. (2020). Indigenous Bali on augmented reality as a creative solution in Industrial Revolution 4.0. *Journal of Physics: Conference Series, 1471*(1), 1–9. https://doi.org/10.1088/1742-6596/1471/1/012008

Agustina, W. W., Sumarto, S., & Trisno, B. (2019). Augmented reality based on stem for supporting science literacy in vocational education. *Journal of Physics: Conference Series, 1375*(1), 1–10. https://doi.org/10.1088/1742-6596/1375/1/012088

Ahmad, N. I. N., & Junaini, S. N. (2020). Augmented reality for learning mathematics: A systematic literature review. *International Journal of Emerging Technologies in Learning, 15*(16), 106–122. https://doi.org/10.3991/ijet.v15i16.14961

Ahn, H., & Choi, Y. (2015). Analysis on the effect of the augmented reality-based STEAM program on education. *Advanced Science and Technology Letters, 92*, 125–130.

Alamsyah, D. P., Parulian, J. M., & Herliana, A. (2023). Augmented reality android based: Education of modern and traditional instruments. *Procedia Computer Science, 216*, 266–273. https://doi.org/10.1016/j.procs.2022.12.136

Al-Azawi, R., Albadi, A., Moghaddas, R., & Westlake, J. (2019). Exploring the potential of using augmented reality and virtual reality for STEM education. In *International workshop on learning technology for education in cloud (LTEC 2019)*, 2019 (Vol. 1011, pp. 36–44). https://doi.org/10.1007/978-3-030-20798-4_4

Albayrak, M., Altıntaş, V., Sümen, A. M., & Şener, G. (2016). Robotics education based on augmented reality in primary schools. In *3rd International conference on advanced technology and sciences*, 2016 (pp. 1–6). https://www.researchgate.net/publication/309134652

Aldalalah, O., Ababneh, Z. W. M., Bawaneh, A. K., & Alzubi, W. M. M. (2019). Effect of augmented reality and simulation on the achievement of mathematics and visual thinking among students. *International Journal of Emerging Technologies in Learning, 14*(18), 164–185. https://doi.org/10.3991/ijet.v14i18.10748

AlFadalat, M., & Al-Azhari, W. (2022). An integrating contextual approach using architectural procedural modeling and augmented reality in residential buildings: The case of Amman City. *Heliyon, 8*(8), 1–15. https://doi.org/10.1016/j.heliyon.2022.e10040

Arulanand, N., RameshBabu, A., & Rajesh, P. K. (2020). Enriched learning experience using augmented reality framework in engineering education. *Procedia Computer Science, 172*, 937–942. https://doi.org/10.1016/j.procs.2020.05.135

Bereczki, E. O., & Kárpáti, A. (2021). Technology-enhanced creativity: A multiple case study of digital technology-integration expert teachers' beliefs and practices. *Thinking Skills and Creativity*. https://doi.org/10.1016/j.tsc.2021.100791

Buchner, J., & Kerres, M. (2023). Media comparison studies dominate comparative research on augmented reality in education. *Computers and Education, 195*, 1–12. https://doi.org/10.1016/j.compedu.2022.104711

Buchori, A., Setyosari, P., Dasna, I. W., & Ulfa, S. (2016). Developing character building learning model using mobile augmented reality on elementary school student in central Java. *Global Journal of Pure and Applied Mathematics, 12*(4), 3433–3444. http://www.ripublication.com/gjpam.htm

Buchori, A., Setyosari, P., Dasna, I. W., Ulfa, S., Degeng, I. N. S., & Sa'dijah, C. (2017). Effectiveness of direct instruction learning strategy assisted by mobile augmented reality and achievement motivation on students cognitive learning results. *Asian Social Science, 13*(9), 137–144. https://doi.org/10.5539/ass.v13n9p137

Bujak, K. R., Radu, I., Catrambone, R., MacIntyre, B., Zheng, R., & Golubski, G. (2013). A psychological perspective on augmented reality in the mathematics classroom. *Computers and Education, 68*, 536–544. https://doi.org/10.1016/j.compedu.2013.02.017

Cascales-Martínez, A., Martínez-Segura, M. J., Pérez-López, D., & Contero, M. (2017). Using an augmented reality enhanced tabletop system to promote learning of mathematics: A case study with students with special educational needs. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(2), 355–380. https://doi.org/10.12973/eurasia.2017.00621a

Chandrasekera, T., & Yoon, S.-Y. (2018). Augmented reality, virtual reality and their effect on learning style in the creative design process. *Design and Technology Education: An International Journal, 23*(1), 55–75.

Chang, H. Y., Binali, T., Liang, J. C., Chiou, G. L., Cheng, K. H., Lee, S. W. Y., & Tsai, C. C. (2022). Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact. *Computers and Education, 191*, 1–24. https://doi.org/10.1016/j.compedu.2022.104641

Chao, W.-H., & Chang, R.-C. (2018). Using augmented reality to enhance and engage students in learning mathematics. *Advances in Social Sciences Research Journal, 5*(12), 455–464. https://doi.org/10.14738/assrj.512.5900

Chen, C.-C., Chen, H.-R., & Wang, T.-Y. (2022). International forum of educational technology and society creative situated augmented reality learning for astronomy curricula. *Educational Technology and Society, 25*(2), 148–162. https://doi.org/10.2307/48660130

Chen, P., Liu, X., Cheng, W., & Huang, R. (2017). A review of using augmented reality in education from 2011 to 2016. In *Innovations in smart learning* (pp. 13–18). https://doi.org/10.1007/978-981-10-2419-1_2

Chui, T. B., Bin Ahmad, M. S., Bassim, F. B. A., & Zaimi, N. B. A. (2016). Evaluation of service quality of private higher education using service improvement matrix. *Procedia: Social and Behavioral Sciences, 224*, 132–140. https://doi.org/10.1016/j.sbspro.2016.05.417

Coimbra, M. T., Cardoso, T., & Mateus, A. (2015). Augmented reality: An enhancer for higher education students in math's learning? *Procedia Computer Science, 67*, 332–339. https://doi.org/10.1016/j.procs.2015.09.277

Cui, K. (2022). Artificial intelligence and creativity: Piano teaching with augmented reality applications. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2022.2059520

De Lima, C. B., Walton, S., & Owen, T. (2022). A critical outlook at augmented reality and its adoption in education. *Computers and Education Open, 3*, 1–15. https://doi.org/10.1016/j.caeo.2022.100103

Fiskerstrand, A. (2022). Literature review—Parent involvement and mathematic outcome. *Educational Research Review, 37*, 1–16. https://doi.org/10.1016/j.edurev.2022.100458

Gao, S., Lu, Y., Ooi, C. H., Cai, Y., & Gunawan, P. (2023). Designing interactive augmented reality application for student's directed learning of continuous distillation process. *Computers and Chemical Engineering, 169*, 1–12. https://doi.org/10.1016/j.compchemeng.2022.108086

Giannopulu, I., Brotto, G., Lee, T. J., Frangos, A., & To, D. (2022). Synchronised neural signature of creative mental imagery in reality and augmented reality. *Heliyon, 8*(3), 1–13. https://doi.org/10.1016/j.heliyon.2022.e09017

Giasiranis, S., & Sofos, L. (2016). Production and evaluation of educational material using augmented reality for teaching the module of "representation of the information on computers" in junior high school. *Creative Education, 7*(09), 1270–1291. https://doi.org/10.4236/ce.2016.79134

Grodotzki, J., Müller, B. T., & Tekkaya, A. E. (2023). Introducing a general-purpose augmented reality platform for the use in engineering education. *Advances in Industrial and Manufacturing Engineering, 6*, 1–18. https://doi.org/10.1016/j.aime.2023.100116

Guntur, M. I. S., Setyaningrum, W., Retnawati, H., & Marsigit. (2020). Can augmented reality improve problem-solving and spatial skill? *Journal of Physics: Conference Series*. https://doi.org/10.1088/1742-6596/1581/1/012063

Hamzah, M. L., Ambiyar, A., Rizal, F., Simatupang, W., Irfan, D., & Refdinal, R. (2021). Development of augmented reality application for learning computer network device. *International Journal of Interactive Mobile Technologies, 15*(12), 47–64. https://doi.org/10.3991/ijim.v15i12.21993

Hanid, M. F. A., Said, M. N. H. B. M., & Yahaya, N. (2020). Learning strategies using augmented reality technology in education: Meta-analysis. *Universal Journal of Educational Research, 8*(5A), 51–56. https://doi.org/10.13189/ujer.2020.081908

Herrera, L. M., Pérez, J. C., & Ordóñez, S. J. (2019). Developing spatial mathematical skills through 3D tools: Augmented reality, virtual environments and 3D printing. *International Journal on Interactive Design and Manufacturing, 13*(4), 1385–1399. https://doi.org/10.1007/s12008-019-00595-2

Hincapie, M., Diaz, C., Valencia, A., Contero, M., & Güemes-Castorena, D. (2021). Educational applications of augmented reality: A bibliometric study. *Computers and Electrical Engineering, 93*, 1–11. https://doi.org/10.1016/j.compeleceng.2021.107289

Hsu, Y. S., Lin, Y. H., & Yang, B. (2017). Impact of augmented reality lessons on students' STEM interest. *Research and Practice in Technology Enhanced Learning, 12*(1), 1–14. https://doi.org/10.1186/s41039-016-0039-z

Iqbal, M. Z., Mangina, E., & Campbell, A. G. (2022). Current challenges and future research directions in augmented reality for education. *Multimodal Technologies and Interaction, 6*(9), 1–29. https://doi.org/10.3390/mti

Isti'aroh, B. I., Ismail, Z. R. W., & Falaq, F. I. (2018). The victory of culture games (VOC-games): Math-based learning media 3D and augmented reality as a conservation culture. In *Advances in social science, education and humanities research (ASSEHR)* (pp. 23–25).

Jessen, A., Hilken, T., Chylinski, M., Mahr, D., Heller, J., Keeling, D. I., & de Ruyter, K. (2020). The playground effect: How augmented reality drives creative customer engagement. *Journal of Business Research, 116*, 85–98. https://doi.org/10.1016/j.jbusres.2020.05.002

Kang, B., Crilly, N., Ning, W., & Kristensson, P. O. (2023). Prototyping to elicit user requirements for product development: Using head-mounted augmented reality when designing interactive devices. *Design Studies, 84*, 1–33. https://doi.org/10.1016/j.destud.2022.101147

Kaufmann, H., & Schmalstieg, D. (2003). Mathematics and geometry education with collaborative augmented reality. *Computers and Graphics, 27*(3), 339–345. https://doi.org/10.1016/S0097-8493(03)00028-1

Kiat, L. B., Ali, M. B., Halim, N. D. A., & Ibrahim, H. B. (2016). Augmented reality, virtual learning environment and mobile learning in education: A comparison. In *2016 IEEE conference on e-learning, e-management and e-services (IC3e)*, 2016 (pp. 23–28).

Kiryakova, G., Angelova, N., & Yordanova, L. (2018). The potential of augmented reality to transform education into Smart education. *TEM Journal, 7*(3), 556–565. https://doi.org/10.18421/TEM73-11

Langer, K., Lietze, S., Krizek, GCh., & Wien, F. T. (2020). Vector AR3-APP—A good-practice example of learning with augmented reality. *European Journal of Open, Distance and E-Learning, 23*(2), 51–64. https://doi.org/10.2478/eurodl-2020-0010

Le, H.-Q., & Ki, J.-I. (2017). An augmented reality application with hand gestures for learning 3D geometry. In *2017 IEEE international conference on big data and smart computing (BigComp)*, 2017 (pp. 34–41).

Lin, H. C. K., Chen, M. C., & Chang, C. K. (2015). Assessing the effectiveness of learning solid geometry by using an augmented reality-assisted learning system. *Interactive Learning Environments, 23*(6), 799–810. https://doi.org/10.1080/10494820.2013.817435

Lin, Y.-J., & Wang, H. (2022). Applying augmented reality in a university English class: Learners' perceptions of creativity and learning motivation. *Innovation in Language Learning and Teaching, 17*(2), 291–305. https://doi.org/10.1080/17501229.2022.2040513

Lionoa, R. A., Amandaa, N., Pratiwia, A., & Gunawan, A. A. S. (2021). A systematic literature review: Learning with visual by the help of augmented reality helps students learn better. *Procedia Computer Science, 196*, 144–152. https://doi.org/10.1016/j.procs.2021.12.019

Martin-Gutierrez, J. (2017). Learning strategies in engineering education using virtual and augmented reality technologies. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(2), 297–300. https://doi.org/10.12973/eurasia.2017.00630a

Maybury, L., Corcoran, P., & Cipcigan, L. (2022). Mathematical modelling of electric vehicle adoption: A systematic literature review. *Transportation Research, 107*, 1–20. https://doi.org/10.1016/j.trd.2022.103278

National Council of Teacher of Mathematics. (2000). *Principles and standards for school mathematics*. The National Council of Teachers of Mathematics, Inc.

Oh, Y.-J., Suh, Y.-S., & Kim, E.-K. (2016). Picture puzzle augmented reality system for infants creativity. In *2016 Eighth international conference on ubiquitous and future networks (ICUFN)*, 2016 (pp. 343–346). https://doi.org/10.1109/ICUFN.2016.7537045

Ou Yang, F.-C., Lai, H.-M., & Wang, Y.-W. (2023). Effect of augmented reality-based virtual educational robotics on programming students' enjoyment of learning, computational thinking skills, and academic achievement. *Computers and Education*. https://doi.org/10.1016/j.compedu.2022.104721

Palanci, A., & Turan, Z. (2021). How does the use of the augmented reality technology in mathematics education affect learning processes? A systematic review. *International Journal of Curriculum and Instructional Studies, 11*(1), 89–110. https://doi.org/10.31704/ijocis.2021.005

Pamungkas, T. D. (2020). Android-based augmented reality media and the curiosity about mathematics. *Journal of Physics: Conference Series, 1663*(1), 1–6. https://doi.org/10.1088/1742-6596/1663/1/012016

Papanastasiou, G., Drigas, A., Skianis, C., Lytras, M., & Papanastasiou, E. (2018). Virtual and augmented reality effects on K-12, higher and tertiary education students' twenty-first century skills. *Virtual Reality, 23*(4), 425–436. https://doi.org/10.1007/s10055-018-0363-2

Pritami, F. A., & Muhimmah, I. (2018). Digital game based learning using augmented reality for mathematics learning. In *ICSCA 2018: Proceedings of the 2018 7th international conference on software and computer applications*, 2018 (pp. 254–258). https://doi.org/10.1145/3185089.3185143

Raccanello, D., Balbontín-Alvarado, R., da Bezerra, D. S., Burro, R., Cheraghi, M., Dobrowolska, B., Fagbamigbe, A. F., Faris, M. E., França, T., González-Fernández, B., Hall, R., Inasius, F., Kar, S. K., Keržič, D., Lazányi, K., Lazăr, F., Machin-Mastromatteo, J. D., Marôco, J., Marques, B. P., …, Aristovnik, A. (2022). Higher education students' achievement emotions and their antecedents in e-learning amid COVID-19 pandemic: A multi-country survey. *Learning and Instruction, 80*, 101629. https://doi.org/10.1016/j.learninstruc.2022.101629

Radu, I., Doherty, E., Diquollo, K., Mccarthy, B., & Tiu, M. (2015). Cyberchase shape quest: Pushing geometry education boundaries with augmented reality. In *Proceedings of the 14th international conference on interaction design and children*, 2015 (pp. 430–433).

Radu, I., Yuan, J., Huang, X., & Schneider, B. (2023). Charting opportunities and guidelines for augmented reality in makerspaces through prototyping and co-design research. *Computers and Education: X Reality, 2*, 1–18. https://doi.org/10.1016/j.cexr.2023.100008

Raghaw, M., Paulose, J., & Goswami, B. (2018). Augmented reality for history education. *International Journal of Engineering and Technology, 7*(2), 121–125.

Rashevska, N. V, Semerikov, S. O., Zinonos, N. O., Tkachuk, V. V, & Shyshkina, M. P. (2020). Using augmented reality tools in the teaching of two-dimensional plane geometry. In *International workshop on augmented reality in education*, 2020 (pp. 79–90). https://doi.org/10.31812/123456789/4116

Revolti, A., Dallasega, P., Schulze, F., & Walder, A. (2023). Augmented reality to support the maintenance of urban-line infrastructures: A case study. *Procedia Computer Science, 217*, 746–755. https://doi.org/10.1016/j.procs.2022.12.271

Rizki, I. A., Saphira, H. V., Alfarizy, Y., Saputri, A. D., Ramadani, R., & Suprapto, N. (2023). Integration of adventure game and augmented reality based on Android in physics learning. *International Journal of Interactive Mobile Technologies, 17*(1), 4–21. https://doi.org/10.3991/ijim.v17i01.35211

Rohil, M. K., & Ashok, Y. (2022). Visualization of urban development 3D layout plans with augmented reality. *Results in Engineering, 14*, 1–10. https://doi.org/10.1016/j.rineng.2022.100447

Ronaghi, M. H., & Ronaghi, M. (2022). A contextualized study of the usage of the augmented reality technology in the tourism industry. *Decision Analytics Journal, 5*, 1–9. https://doi.org/10.1016/j.dajour.2022.100136

Ruhaiyem, N. I. R., & Kei, L. H. (2019). Teaching complex mathematics operation using augmented reality. In *Proceedings of the international university carnival on e-learning 2019* (pp. 10–11). http://www.zappar.com/augmented-reality/

Rusli, R., Nalanda, D. A., Tarmidi, A. D. V., Suryaningrum, K. M., & Yunanda, R. (2023). Augmented reality for studying hands on the human body for elementary school students. *Procedia Computer Science, 216*, 237–244. https://doi.org/10.1016/j.procs.2022.12.132

Saidin, N. F., Halim, N. D. A., & Yahaya, N. (2015). A review of research on augmented reality in education: Advantages and applications. *International Education Studies, 8*(13), 1–8. https://doi.org/10.5539/ies.v8n13p1

Salako, O., Ugwunna, C., Folorunso, O., & Adejimi, A. (2021). Art education post-COVID-19: Augmented reality technology application in building students' creativity skills. In *4th International conference on information technology in education and development*, 2021 (pp. 34–37).

Salinas, P., González-Mendívil, E., Quintero, E., Ríos, H., Ramírez, H., & Morales, S. (2013). The development of a didactic prototype for the learning of mathematics through augmented reality. *Procedia Computer Science, 25*, 62–70. https://doi.org/10.1016/j.procs.2013.11.008

Salinas, P., & Pulido, R. (2017). Understanding the conics through augmented reality. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(2), 341–354. https://doi.org/10.12973/eurasia.2017.00620a

Saltan, F., & Arslan, Ö. (2017). The use of augmented reality in formal education: A scoping review. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(2), 503–520. https://doi.org/10.12973/eurasia.2017.00628a

Sanabria, J. C., & Arámburo-Lizárraga, J. (2017). Enhancing 21st century skills with AR: Using the gradual immersion method to develop collaborative creativity. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(2), 487–501. https://doi.org/10.12973/eurasia.2017.00627a

Sannikov, S., Zhdanov, F., Chebotarev, P., & Rabinovich, P. (2015). Interactive educational content based on augmented reality and 3D visualization. *Procedia Computer Science, 66*, 720–729. https://doi.org/10.1016/j.procs.2015.11.082

Sarkar, P., Sakhardande, P., Oza, U., & Pillai, J. (2019). Study of augmented reality interaction mediums (AIMs) towards collaboratively solving open-ended problems. In *27th International conference on computers in education conference (ICCE 2019)*, 2019. https://www.researchgate.net/publication/341104400

Saundarajan, K., Osman, S., Daud, M. F., Abu, M. S., Pairan, M. R., & Kumar, J. A. (2020). Learning algebra using augmented reality. *International Journal of Emerging Technologies in Learning, 15*(16), 123–133. https://doi.org/10.3991/ijet.v15i16.10540

Sejzi, A. A. (2015). Augmented reality and virtual learning environment. *Journal of Applied Sciences Research, 11*(8), 1–5. https://www.researchgate.net/publication/277137476

Sholikhah, B. U., & Cahyono, A. N. (2021). Augmented reality student worksheets for learning mathematics during the COVID-19 pandemic. *Journal of Physics: Conference Series, 1918*(4), 1–6. https://doi.org/10.1088/1742-6596/1918/4/042063

Sidani, A., Matoseiro Dinis, F., Duarte, J., Sanhudo, L., Calvetti, D., Santos Baptista, J., Poças Martins, J., & Soeiro, A. (2021). Recent tools and techniques of BIM-based augmented reality: A systematic review. *Journal of Building Engineering, 42*, 1–13. https://doi.org/10.1016/j.jobe.2021.102500

Siddiq, F., Gochyyev, P., & Valls, O. (2020). The role of engagement and academic behavioral skills on young students' academic performance—A validation across four countries. *Studies in Educational Evaluation*. https://doi.org/10.1016/j.stueduc.2020.100880

Silva, M., Roberto, R., Radu, I., & Cavalcante, P. (2019). Why don't we see more of augmented reality in schools? In *2019 IEEE international symposium on mixed and augmented reality adjunct (ISMAR-Adjunct)*, 2019 (pp. 138–143). https://doi.org/10.1109/ISMAR-Adjunct.2019.00-61

Sommerauer, P., & Müller, O. (2014). Augmented reality in informal learning environments: A field experiment in a mathematics exhibition. *Computers and Education, 79*, 59–68. https://doi.org/10.1016/j.compedu.2014.07.013

Su, W. H., Chen, K. Y., Lu, L. Y. Y., & Huang, Y. C. (2021). Identification of technology diffusion by citation and main paths analysis: The possibility of measuring open innovation. *Journal of Open Innovation: Technology, Market, and Complexity, 7*(1), 1–22. https://doi.org/10.3390/JOITMC7010104

Suryanti, S., Arifani, Y., & Sutaji, D. (2020). Augmented reality for integer learning: Investigating its potential on students' critical thinking. *Journal of Physics: Conference Series, 1613*(1), 1–10. https://doi.org/10.1088/1742-6596/1613/1/012041

Syafril, S., Asril, Z., Engkizar, E., Zafirah, A., Agusti, F. A., & Sugiharta, I. (2021). Designing prototype model of virtual geometry in mathematics learning using augmented reality. *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1742-6596/1796/1/012035

Tekederea, H., & Göker, H. (2016). Examining the effectiveness of augmented reality applications in education: A meta-analysis. *International Journal of Environmental and Science Education, 11*(16), 9469–9481.

Theodoropoulos, A., & Lepouras, G. (2021). Augmented reality and programming education: A systematic review. *International Journal of Child–Computer Interaction, 30*, 1–16. https://doi.org/10.1016/j.ijcci.2021.100335

Tzima, S., Styliaras, G., & Bassounas, A. (2019). Augmented reality applications in education: Teachers point of view. *Education Sciences, 9*(2), 1–18. https://doi.org/10.3390/educsci9020099

Wan, X., Shen, L., Fang, Z., Dong, S., Zhang, S., & Lin, C. (2022). A novel motionless calibration method for augmented reality surgery navigation system based on optical tracker. *Heliyon, 8*(12), 1–9. https://doi.org/10.1016/j.heliyon.2022.e12115

Wittayakhom, N., & Piriyasurawong, P. (2020). Learning management STEAM model on massive open online courses using augmented reality to enhance creativity and innovation. *Higher Education Studies, 10*(4), 44–53. https://doi.org/10.5539/hes.v10n4p44

Yilmaz, R. M., & Goktas, Y. (2016). Using augmented reality technology in storytelling activities: Examining elementary students' narrative skill and creativity. *Virtual Reality, 21*(2), 75–89. https://doi.org/10.1007/s10055-016-0300-1

Yousef, A. M. F. (2021). Augmented reality assisted learning achievement, motivation, and creativity for children of low-grade in primary school. *Journal of Computer Assisted Learning, 37*(4), 966–977. https://doi.org/10.1111/jcal.12536

Yulianti, E., Mustikasari, V. R., Muhlisin, N., Rahman, N. F. A., & Phang, F. A. (2023). An augmented reality-based science book for junior high school students: Case study on environmental pollution and global warming topics. *AIP Conference Proceedings*. https://doi.org/10.1063/5.0112204

Zhu, Y., Yang, X., & Wang, S. J. (2017). Augmented reality meets tangibility: A new approach for early childhood education. *EAI Endorsed Transactions on Creative Technologies, 4*(11), 1–8. https://doi.org/10.4108/eai.5-9-2017.153059

Flavia Aurelia Hidajat is a Dr. from the Department of Mathematics Education, Universitas Negeri Jakarta. Her research interests include digital technology learning, creativity, self-regulated learning, and mathematics education.