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Challenge-based learning assisted by virtual reality STEAM trails at a cultural heritage museum to promote mathematical creative thinking skills

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Abstract

The 21st century requires every individual to possess creative thinking skills to face increasingly complex challenges. This skill can be developed through learning mathematics. This study aimed to determine the quality of challenge-based learning assisted by virtual reality STEAM Trails in the context of the Pekalongan Batik Museum to improve mathematical creative thinking skills. The method used in this study was design research. The participants of this study were 30 ninth-grade students at a junior high school in Pekalongan, Indonesia. The data collection techniques included validation sheets, questionnaires, and tests. Qualitative data analysis techniques were used to analyse the students' responses after learning. Quantitative data analysis techniques were used to analyse mathematical creative thinking skills based on the pretest and posttest results. Validity was analysed based on the validation results by three validators, and practicality was analysed based on the results of the practicality questionnaire by five students from the experimental group. The results of this study showed a significant increase in the pre- and post-test results. Additionally, the results of the student response questionnaire indicated high satisfaction with the learning process. Further research is needed to develop VR for other contexts.

Keywords: challenge-based learning; math trails; Pekalongan batik museum; STEAM; virtual reality

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Introduction

The rapid development of the 21st century requires the existence of competent human resources who are able to follow developments and take advantage of these advances. Education today plays an important role in preparing quality human resources that emphasize the skills, knowledge, and attitudes needed to succeed in the 21st century (Martinez, 2022). The US-based Partnership for 21st century skills identifies four skills needed in the 21st century, one of which is creative thinking (Supena et al., 2021). Creative thinking skills are also high-level thinking skills, so they are important to develop (Muttaqin & Tohir, 2021).

Creative thinking skills can be developed through mathematics learning called mathematical creative thinking skills that are honed through solving mathematical problems with more than one solution and students think fluently, flexibly, elaborate, and have originality (Maryati & Nurkayati, 2021). Isyrofinnisak et al. (2020) define mathematical creative thinking as the ability to solve mathematical problems by proposing diverse new ideas. Mathematical creative thinking skills are important to be taught because they can train complex, logical and critical thinking in solving problems (Wahyudi et al., 2021). Students who have the ability to think creatively mathematically are able to develop ideas and look at problems from different perspectives, as well as solve them in many ways (Yayuk et al., 2020).

Based on PISA data, students' creative thinking skills in Indonesia are still not optimal (Surmilasari & Usman, 2022). The results of an interview with a 9th grade mathematics teacher at a junior high school in the city of Pekalongan stated that students have not been able to solve problems in various ways and only use common methods. This is supported by the results of the initial test of mathematical creative thinking ability conducted by the researcher only obtained an average of 43 out of 100. In an effort to overcome these problems, it is necessary to collaborate well between mathematics learning models and media to improve mathematical creative thinking skills.

Challenge-based Learning (CBL) is a pedagogical approach that actively engages students in real and relevant contexts (Romero Caballero et al., 2025). Through real-life and open-ended problems, CBL encourages students to take initiative in their learning, acquire, and apply knowledge to respond to the challenges presented (Helker et al., 2024). This real-life context allows students to develop their creativity in finding solutions to a challenge (Fairazatunnisa et al., 2021). Research by Ardiansyah & Asikin (2020) shows that the implementation of challenge-based learning can improve mathematical creative thinking skills across all indicators.

Another factor that helps hone students' mathematical creative thinking skills is the use of interactive learning media (Sanusi et al., 2020). Virtual reality (VR) is one of the interactive multimedia to facilitate the delivery of content, so that it can improve the quality of effective learning (Liao, 2024). This is influenced by the advantages of virtual reality in presenting real situations for its users, so that they can feel the sensation as if they are in the environment (Yu, 2023). Therefore, VR technology can be used as a learning medium to make it easier to understand mathematical concepts through immersive and realistic experiences.

The integration of STEAM (Science, Technology, Engineering, Art, and Mathematic) in learning can be applied to improve students' creative thinking skills (Erol et al., 2023). The STEAM approach allows students to integrate various sciences, so that students get a holistic understanding of the interconnectedness of the 21st century science field (Pocalana et al., 2024). Through the STEAM approach, students are encouraged to develop their creativity in solving real problems with mathematical concepts (Tsuchiya & Gyobu, 2025; Yunianto et al., 2025). With the STEAM approach, mathematics learning becomes more relevant and contextual, so that it can develop students' creativity and innovation.

Pekalongan city which is known as a batik city in Indonesia, has a landmark called Pekalongan Batik Museum which is a proof of batik wisdom in Pekalongan city. Learning math by incorporating the context of landmarks is one of the interesting learning strategies (Cahyono & Lavicza, 2023; Nugroho et al., 2024). Pekalongan Batik Museum has mathematical elements related to geometry concepts in mathematics such as congruence, equality, line equality, flat shapes and transformation (Khalishah & Nalim, 2022). Mathematical elements can be found through the collection of batik motifs, stamped batik technology, and museum architecture (Ghoni et al., 2023). The relationship between STEAM and ethnomathematics contexts in Pekalongan Batik Museum can be used in learning mathematics related to daily practices (Rodríguez-Nieto & Alsina, 2022).

Several previous studies have shown that CBL can improve student collaboration, engagement, and creativity (Ardiansyah & Asikin, 2020; Crusat & Martínez, 2021; Beemt & MacLeod, 2021). The utilization of VR technology in learning has been shown to increase motivation, and understanding of learning materials (Akman & Çakır, 2023; Jiang & Fryer, 2024). Most of the previous CBL research is still limited to general issues and has not integrated local wisdom in learning. Meanwhile, the integration of local culture into learning has been proven to strengthen students' connection with the socio-cultural environment and can foster creativity (Suherman & Vidákovich, 2022). The novelty in this research is the integration of challenge-based learning and virtual reality with the context of Pekalongan Batik Museum as a STEAM trails setting that can be a unique way to improve mathematical creative thinking skills. Therefore, this study aims to determine the quality of challenge-based learning assisted by virtual reality STEAM Trails in the context of the Pekalongan Batik Museum to improve mathematical creative thinking skills.

Methods

This study used a design research approach because this method was appropriate for the research objectives, which placed the design of new learning such as learning activities and technology as key components in the overall research process (Bakker, 2018). This research is a development of Virtual Reality STEM Trails (Cahyono, 2024). The research was conducted in Pekalongan, Indonesia, involving local junior high schools. This study consisted of three stages, beginning with preparation and design, teaching experiment, and retrospective analysis. The stages of the study are shown in Figure 1.

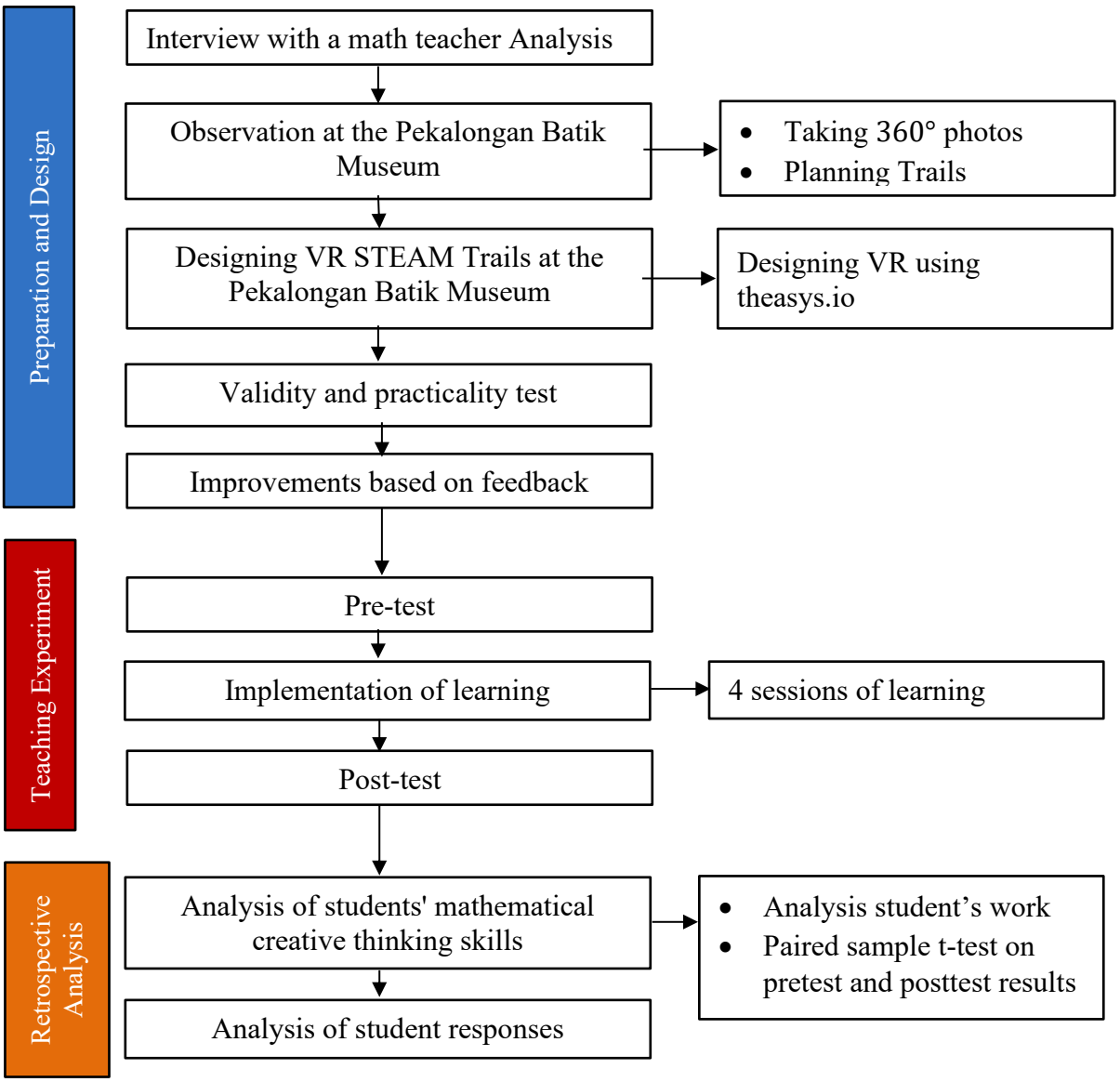


Figure 1. Research procedures

Class 9D was the experimental group, consisting of 30 students, including 17 female students and 13 male students. The researchers administered tests to measure the students' mathematical creative thinking abilities before (pretest) and after (posttest) participating in learning with challenge-based learning assisted by VR STEAM trails. The research instruments used were pretest and posttest questions and student response questionnaires.

The test questions were designed in line with indicators of mathematical creative thinking skills, which include fluency, flexibility, novelty, and elaboration (Faradillah & Maulida, 2022). The mathematical creative thinking skills test consisted of three questions, each of which contained indicators of mathematical creative thinking skills. The questions were first tested for validity and reliability. The validity test results showed an r value for each question, namely $0.8708 > 0.361$ for question 1, $0.821 > 0.361$ for question 2, and $0.8654 > 0.361$ for question 3, so it can be concluded that all three questions are valid. The reliability test results showed a calculated r value of $0.8105 > 0.32$, so it can be concluded that the test questions for mathematical creative thinking ability are reliable. The student response questionnaire

consists of 20 questions covering indicators of media quality, media operation, benefits, interest in learning, and learning support. The validity testers of the research instrument included media experts, subject matter experts, and learning experts. The practicality test was conducted on a small group of five students before being used in the experimental group.

Researchers used quantitative and qualitative data analysis techniques. Quantitative techniques analyze mathematical creative thinking abilities based on pretest and posttest results using SPSS 25. Qualitative techniques analyze student responses to challenge-based learning assisted by VR STEAM trails at the Pekalongan Batik Museum. To determine whether there are differences in pretest and posttest results for students' mathematical creative thinking abilities, researchers use a paired sample t-test.

Results

The results of the study are presented with the results of three main components of the design study, including Preparation and Design, teaching experiment, and retrospective analysis of student responses.

Preparation and design

The first thing to do is to interview the math teacher to find out the needs of students, student characteristics, student learning environment and the curriculum used. Teachers stated that students' needs tend to be interactive learning in groups, the learning environment must support learning motivation because students have characters who tend to be active but mostly dislike mathematics especially if the learning process is carried out by the lecture method and the curriculum used is the independent curriculum. Teachers stated that the use of smartphones is allowed for students if needed, so the use of virtual reality can be used during the learning process.

The researcher then designed the VR of Pekalongan Batik Museum which began with observations at the Pekalongan Batik Museum to analyze the object and plan the math trails that would be made. After the observation, the researchers designed the locations in the Pekalongan Batik Museum that will be used as VR content in learning. VR design is done by using the website https://theasys.io and Adobe Photoshop 2023 to edit the 360° image shown in Figure 2. VR mode and how to move to the next place students must point the VR center point to the button provided for three seconds as shown in Figure 3.

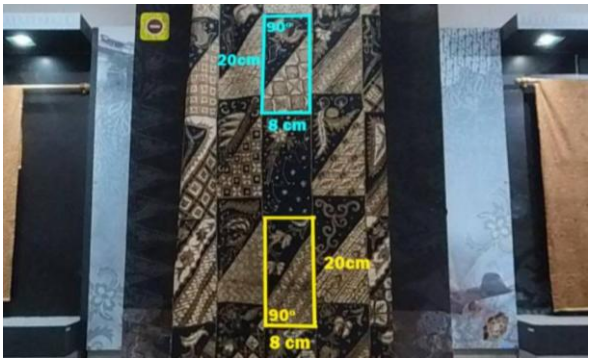


Figure 2. Display in VR

Figure 3. VR mode and a button to move locations.

The development of VR STEAM Trails in this study uses challenge-based learning because it can support student activeness in learning through solving challenges in groups according to the interactive learning needs of students at school. Learning is carried out according to the CBL framework which includes three phases, namely the investigate phase, the act phase, and the solution phase (Nichols et al., 2016). Furthermore, the researcher creates a link to access the VR that will be used by students. Here are the VR links for each meeting: the first meeting addressed issues related to Art through the link https://ths.li/rbT5jhu, the second meeting where students solve problems related to Engineering and Art through the link https://ths.li/kwrtQaW, the third meeting where students solve problems related to Science and Art https://ths.li/zVQoj3R, the fourth meeting https://ths.li/bRJ0IDk where students solve problems related to Art.

Before being used in learning, the design of challenge-based learning assisted by VR STEAM trails at Pekalongan batik museum was tested for validity and practicality. The validity test was conducted by media experts, material experts, and learning experts. Media experts validate based on aspects of software, visual communication, and design with a score of 96.4 out of 100. Material experts validated based on aspects of mathematics, construction, and language with a score of 90.3 out of 100. Learning experts validated based on aspects of learning design, operational, and learning relevance with a score of 90.3 out of 100. Suggestions and comments on the validation sheet by the experts were used as improvements.

The practicality test was carried out by testing with students in small groups of five students. Students tried the learning media and tried to work on worksheets to find out the difficulties during the trial use of the media. Finally, students were asked to fill out a media practicability questionnaire and provide suggestions and comments based on the experience of using the media during the trial. From the five students who participated in the trial, the average score of media practicality reached 86.5 out of 100.

Teaching experiment

The implementation of challenge-based learning assisted by VR STEAM Trails with the context of Pekalongan Batik Museum was carried out in one of the schools in Pekalongan with the subject of class 9D. Before learning, students were given a pretest to measure their initial mathematical creative thinking skills on congruence material. From the pretest results, an average score of 52.4 out of 100 was obtained.

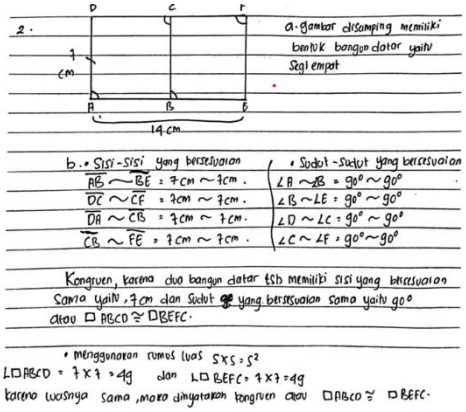
A total of 30 students followed the learning process in groups of four to five students. The time spent for learning in the study was eight hours of learning divided into four meetings by paying attention to the syntax of challenge-based learning. In the first meeting, students were first introduced to the VR media guide that would be used regarding how to access, use, and utilize it in learning. Learning begins by providing big ideas and essential questions related to the objects that students will learn. The challenge, guiding question, guiding activities and guiding resources are in virtual reality. At the end of learning, students present the results of solving the challenge given. Student activity during learning is shown in Figure 4.

Figure 4. Student learning activities

After the whole series of learning is complete, students carry out a posttest of congruence material. This test aims to measure students' final mathematical creative thinking skills after learning with challenge-based learning assisted by VR STEAM trails. The average score of the posttest results of students' mathematical creative thinking skills was 84.1 out of 100.

Retrospective analysis

The mathematical creative thinking ability test questions given to students were designed to measure all the indicators studied. In the question, it is known that there are stamped batik motifs that have two unique forms of batik patterns. The length of the stamped batik tool is 14 cm and the width is 7 cm. Points (a) what flat shape is the stamped batik made of; (b) are the two basic shapes of the stamped batik tool congruent? Based on the information provided, provide your analysis in detail in various ways. Students in this case are asked to analyze the congruence of the batik cap in detail and in various ways that they know. The students' answers will be assessed based on the indicators of mathematical creative thinking ability. The results of student work are shown in Figure 5.



Translation

(a) The picture beside has a rectangular flat shape.

(b)

The corresponding sides

$\overline{AB}$ corresponds to $\overline{BE}$ = 7 cm corresponds to 7 cm.

$\overline{DC}$ corresponds to $\overline{CF}$ = 7 cm corresponds to 7 cm.

$\overline{DA}$ corresponds to $\overline{CB}$ = 7 cm corresponds to 7 cm.

$\overline{CB}$ corresponds to $\overline{FE}$ = 7 cm corresponds to 7 cm.

The corresponding angles

$\angle A$ corresponds to $\angle B = 90°$ corresponds to 90°.

$\angle B$ corresponds to $\angle E = 90°$ corresponds to 90°.

$\angle D$ corresponds to $\angle C = 90°$ corresponds to 90°.

$\angle C$ corresponds to $\angle F = 90°$ corresponds to 90°.

Congruent, because the two flat shapes have the same corresponding side of 7cm and the same corresponding angle of 90°.

- Using area $s \times s = s^2$

Area of square ABCD $= 7 \times 7 = 49$, and

Area of square BEFC $= 7 \times 7 = 49$.

Since the areas are equal, they are congruent or square ABCD ≅ square BEFC.

Figure 5. Sample student's work

Based on Figure 5, the fluency indicator is assessed based on whether the answers given by students are correct or not. The results of the solution given by the students are declared correct as seen from the conclusion obtained which states that the shape of the batik cap is congruent. Flexibility is assessed based on the variety of solutions provided, students' answers provide two different ways to analyze the congruence of stamped batik, namely by using the corresponding angles and sides and using the flat area approach. Novelty is assessed based on the uniqueness of students' answers, the second way given by students can be said to be the uniqueness of the solution. Analysis of congruence generally uses corresponding sides or angles

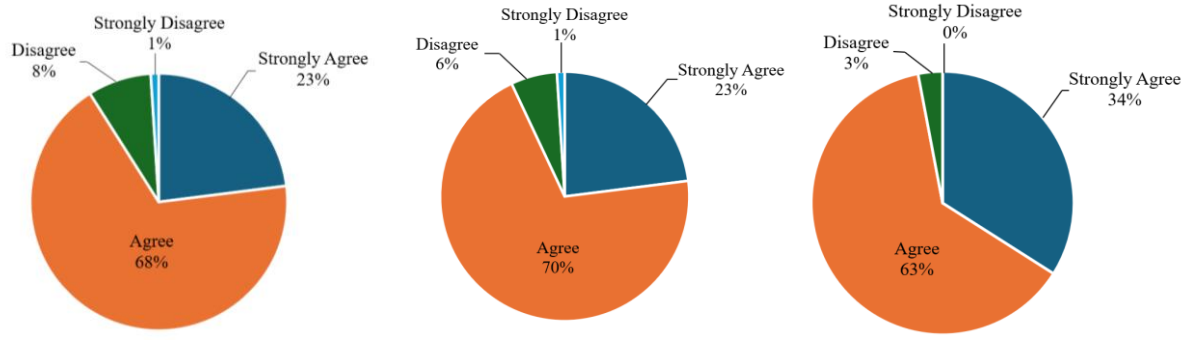
that are checked whether they are all the same or not. The batik stamp in the question is square, which is based on the first way the student obtained each side of 7 cm and all angles are 90°. The second method given by students uses the square area approach to analyze congruence, this method can only apply to a square because if a square has the same area the square can be confirmed congruent because the sides must be the same. Elaboration is assessed based on the details of the answers given by the students, these details can be seen that all angles and corresponding sides are written along with their sizes which end with a conclusion.

After the pretest and posttest data were collected, the data were then analyzed by statistical testing to analyze students' mathematical creative thinking ability. The pretest and posttest data of students' mathematical creative thinking skills were first tested for normality. The test results showed the Sig value of the pretest data was $0.653 > 0.05$ and the Sig of the posttest data was $0.428 > 0.05$, thus the pretest and posttest data were normally distributed. Student test data were then tested with paired sample t-test. The test results in Table 1 show the results of Sig. (2-tailed) of $0.00 < 0.05$, means that there is a significant difference in students' mathematical creative thinking ability before and after learning. Thus, the challenge-based learning design assisted by VR STEAM trails at Pekalongan Batik Museum can improve students' mathematical creative thinking skills.

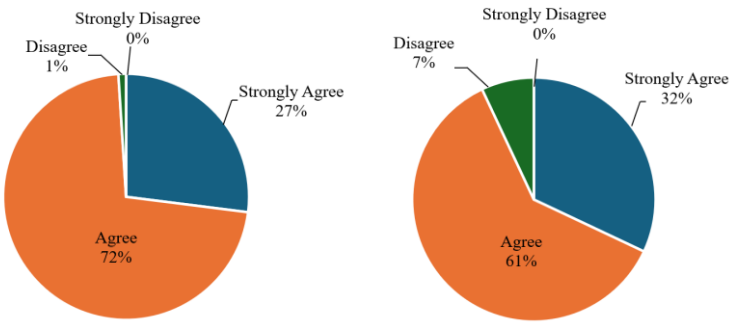
Table 1. Paired sample t-test

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	Pretest - Posttest	-31.66	10.744	1.961	-35.675	-27.651	-16.141	29	.000

After learning with challenge-based learning assisted by VR STEAM trails, students are given a questionnaire to find out student responses. The purpose of filling out this questionnaire is to find out students' satisfaction and response after learning. In line with the statement of Tang et al. (2022) that one of the ways that can be done to determine satisfaction with learning is by filling out a student response questionnaire after learning. Student responses measured include five aspects including media quality, media operation, usefulness, interest in learning, and learning support. The results of the student response questionnaire can be seen in Figure 6.



(a) (b) (c)



(d) (e)

Figure 6. Students' responses to challenge-based learning assisted by virtual reality STEAM trails at Pekalongan Batik Museum from the aspects of (a) Media Quality; (b) Media Operation; (c) Usefulness; (d) Interest in learning; (e) Supporting Learning.

Based on Figure 6, the results of student responses show that the development carried out obtained good student responses. Judging from the aspect of media quality, 68% of students agree and 23% of students strongly agree that the media makes it easier to understand mathematical materials and problems in the learning process through visualization of real situations through VR. The next aspect is media operation, 70% of students agree and 23% of students strongly agree that it is very easy to access learning media and use it in learning. Then in the usefulness aspect, 63% of students agree and 34% of students strongly agree that the media can provide additional insights and new learning experiences. On the interest to learn aspect, 72% of students agreed and 27% of students strongly agreed that the learning media can increase their interest and activeness during the learning process. The last aspect is learning support, 61% of students agree and 32% of students strongly agree that the learning media is suitable for their learning needs and characteristics. From these results, it is known that challenge-based learning assisted by VR STEAM trails at the Pekalongan Batik Museum can improve the quality of the learning process and student interest in learning. With the assisted learning process and increased student interest in learning, it is hoped that this can provide an increase in students' mathematical creative thinking skills.

Discussion

The validation process by experts aims to assess the validity of VR-assisted challenge-based learning STEAM Trails at the Pekalongan Batik Museum before it is used in learning. Validation was conducted by qualified respondents to ensure validity. The validation results indicate that the media and content aspects fall within the valid category, thereby enabling the learning tool to be utilized in the learning process. The validation and evaluation conducted demonstrate that the developed learning tool can be applied in educational settings. This aligns with Amirah & Mahartika (2025), who state that learning tools deemed valid can be applied in the learning process.

The practicality test of VR-assisted challenge-based learning STEAM Trails at the Pekalongan Batik Museum was conducted using a practicality questionnaire filled out by five students in the test group. The results showed that the learning tools developed were very

practical, covering aspects of media quality, media operation, appearance, benefits as learning aids, and interest in learning. Attractive, high-quality, and easy-to-operate media can stimulate motivation and enhance students' understanding in learning. The developed learning tool was deemed practical and can be used in learning. This aligns with the statement by Suryati et al. (2025) that practical learning tools support the smoothness of the teaching and learning process for both teachers and students without significant obstacles.

Challenge-based learning assisted by VR STEAM trails at Pekalongan Batik Museum is able to improve mathematical creative thinking skills. This is in line with the results of statistical testing which shows a significance of 0.00 which indicates a significant difference in students' creative thinking skills before and after learning. The application of challenge-based learning in mathematics learning can improve mathematical creative thinking skills. In line with the results of research by Yang et al. (2018) which states that through challenges in mathematics learning can support student creativity in learning. The use of technology as a medium in learning can improve creativity abilities and new interesting learning experiences for students (Muthmainnah et al., 2025). Through visualization in VR, students can feel the sensation of being in a live location so that it supports them to learn mathematics better.

The STEAM approach can be applied to mathematics learning in the context of the Pekalongan Batik Museum. The museum has a diverse collection of local batik motifs for the context of Art. It also has batik-making technology such as batik stamps, canting tools, and wax heaters for basic batik motif. Furthermore, the architectural form of the Pekalongan Batik Museum can also be discussed in the context of Engineering and the application of Science in its design form or process. Research by Cahyono (2024) designed VR with replica temple objects and an artificial city with many buildings for STEM learning. Zhan et al. (2024) used wooden bridge objects as a context in mathematics education with VR tools. In these studies, the objects used were created using computer-aided digital modeling. The results of this study show real objects from specific locations captured using a 360-degree camera for VR display so that they can be used in STEAM learning.

The development of VR STEAM trails at Pekalongan Batik Museum supports learning needs with structured varied media, thus helping students understand the concept of congruence better. STEAM combined in VR has a function to visualize the state of the museum, so that students can see and feel the sensation of being in a live location from various corners of the museum (Musril et al., 2020). Math trails designed in accessible learning using VR media are systematically designed based on the sequence of congruence material and indicators of mathematical creative thinking skills. Fluency indicators are supported through challenges that require students to analyze congruence correctly, flexibility is achieved with problems that allow students to solve them in a variety of different ways, novelty in solving congruence problems is done by providing challenges that allow them to be solved in unique ways, and elaboration is found in every problem because every student's analysis must be given in detail to get the correct conclusion (Johar et al., 2023). Thus, students have met each indicator of mathematical creative thinking ability. This is in line with the statement that mathematics learning with VR media can train students' creative thinking (Chen et al., 2024).

The development that was carried out received a positive response from students. This is based on student responses in the questionnaire given after implementing challenge-based learning assisted by VR STEAM trails at the Pekalongan Batik Museum which shows the positive impact and assistance of students in learning good mathematics so as to improve mathematical creative thinking skills. This result is in accordance with the idea that learning that gets a positive response, can provide convenience during the learning process so that it has an impact on students' cognitive abilities (Jacob & Centofanti, 2024). Thus, the development of CBL assisted by VR STEAM trails at Pekalongan batik museum can be developed in the learning process.

Conclusion

The challenge-based learning assisted by VR STEAM trails at Pekalongan Batik Museum can be designed for mathematics learning. The validation results of media experts, material experts, and learning experts obtained scores of 96.4, 90.3, and 90.3 out of 100, respectively. The practicality test conducted by a group of five students obtained a practicality score of 86.5. The development carried out was able to improve mathematical creative thinking skills as seen from the significantly different pretest and posttest results. This is reinforced by good student responses to the development measured from five aspects including media quality, media operation, benefits, learning interest, and learning support.

This study is limited to the context of the Pekalongan Batik Museum and the ability measured is mathematical creative thinking. The implications of this study suggest that VR-assisted by challenge-based learning STEAM Trails can be an innovation and applied in mathematics learning. The researcher suggests teachers to integrate challenge-based learning with VR media in their mathematics learning to help students' learning process. It is expected that there will be further development and trials with different contexts and mathematical materials. In addition, research is needed on other abilities that are in line with the development in this study.

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Conflicts of Interest

In writing this article, the authors declare no conflict of interest. Furthermore, violations, plagiarism, double publishing and/or submission ethical issues, data fabrication and/or falsification, and redundancy, have been resolved by the authors.

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Author Contributions

Andy Nova Winasis: concept, writing, methodology, analysis, data curation, visualization; **Asri Rejeki:** project administration and resources; **Adi Nur Cahyono:** supervision and validation.

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