

Effectiveness of STEAM-Based Mathematics Learning in Enhancing Students' Mathematical Communication Skills and Creativity

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Abstract. Research on STEAM-based mathematics learning has frequently highlighted gains in creativity and problem-solving, yet its specific impact on mathematical communication skills remains underexplored. This gap is important because mathematical communication supports students in articulating ideas, constructing arguments, and representing concepts effectively. This study examines the effectiveness of STEAM-based mathematics instruction in enhancing senior high school students' mathematical communication and creativity. Using a quasi-experimental *Posttest Only Control Group* design, two randomly assigned classes participated: one received STEAM-based instruction, while the other followed conventional teaching. The results show that students in the STEAM class achieved significantly higher scores in both communication and creativity. These findings suggest that STEAM offers a relevant and effective approach for strengthening essential twenty-first-century competencies.

Keywords: STEAM-Based Learning, Mathematical Communication, Mathematical Creativity

1 Introduction

Mathematics education in the twenty-first century necessitates the cultivation of competencies that extend beyond procedural proficiency, incorporating communication skills, creativity, collaboration, and problem-solving capabilities to navigate the intricacies of contemporary social and economic contexts [1][2][3][4]. These qualities are deemed essential for equipping students to address future workplace requirements and everyday life issues.

The STEAM [Science, Technology, Engineering, Arts, Mathematics] method has developed as a pedagogical framework that amalgamates science, technology, the arts, and mathematics to foster contextual and multidisciplinary learning experiences. Current literature indicates that the integration of the arts enhances educational processes and fosters the cultivation of higher-order thinking skills [5][6][7][8]. Nonetheless, the application of STEAM in educational settings is markedly diverse, both regarding instructional design and the learning objectives prioritized [9] [10].

The capacity to communicate mathematically is an essential aspect of mathematical skill, facilitating students in articulating ideas, constructing arguments, utilizing various representations, and linking concepts to real-world contexts [11] [12]. Regrettably, conventional teaching that emphasizes procedural fluency restricts students' prospects for meaningful mathematical discourse [13], which may impede the advancement of mathematical literacy.

Pedagogical interventions that incorporate discussion, presentation, and the creation of mathematical objects have demonstrated improvements in mathematical literacy and communication abilities [14][15]. Mathematical creativity, encompassing the capacity to produce original, adaptable, and detailed ideas, represents a significant learning result and is intricately linked to mathematical communication [16][17][18]. Project-based STEAM education offers tangible environments for students to explore, refine concepts, and articulate mathematical principles through innovative outputs [19][15].

Although many STEAM studies report improvements in creativity and problem-solving, several systematic reviews emphasize that the evidence remains heterogeneous, and standardized indicators for assessing communication skills are rarely employed [1,20]. The literature further indicates that STEAM research tends to prioritize creativity and product-based outcomes, whereas quantitative assessments of mathematical communication are infrequently reported [21] [7] [6]. Moreover, only a limited number of studies simultaneously assess creativity and mathematical communication within authentic instructional settings [17].

A critical analysis indicates that assessments of mathematical communication in STEAM contexts frequently suffer from methodological inconsistencies, and the instruments employed are largely unstandardized [22]. Additional reviews highlight that the majority of STEAM research lack rigorous experimental designs featuring pretest–posttest measures or do not disclose quantitative impact sizes [23,24], thereby constraining the generalizability of their results.

This study seeks to furnish empirical data about the efficacy of STEAM-based mathematics instruction in enhancing two critical learning outcomes concurrently: students' mathematical communication and creativity. The results are anticipated to enhance the theoretical framework of STEAM literature and provide pragmatic recommendations for educators and policymakers in formulating curriculum that adequately address the competency requirements of the twenty-first century.

2 Method

This study employed a quasi-experimental approach using a Posttest-Only Control Group Design, a design commonly implemented when pretest measurements cannot be administered but causal comparison between groups is required. The design consisted of two intact classes selected randomly, namely an experimental group and a control group, each receiving different instructional treatments prior to the administration of a posttest at the end of the learning sessions.

The population comprised all 102 tenth-grade students of SMA Negeri 3 Ndosong Waning distributed across four classes. Samples were selected using a random sampling technique,

resulting in two classes being assigned as the experimental and control groups. Class XA, consisting of 26 students, served as the experimental group and received mathematics instruction using the STEAM (Science, Technology, Engineering, Art, and Mathematics) approach. Meanwhile, Class XB, consisting of 25 students, served as the control group and received conventional mathematics instruction. The random selection of classes was conducted to minimize selection bias and strengthen the causal inference of the study.

Instruction in the experimental group was designed by integrating elements of science, technology, engineering, the arts, and mathematics through project-based problem-solving activities. The instructional framework adopted an integrated STEAM model, emphasizing design-based processes, collaborative learning, and the creation of meaningful artifacts as integral components of the learning experience [5]. In contrast, the control group received conventional mathematics instruction consisting of lectures, demonstrations, and routine exercises. Both groups experienced the same instructional duration to maintain equivalence in exposure time.

Research data were collected using a mathematical communication test and a mathematical creativity test, each consisting of three open-ended items. The communication test measured students' ability to articulate ideas coherently, use mathematical representations, and construct logical arguments. Meanwhile, the creativity test assessed fluency, flexibility, and originality [17,25]. Content validity of the instruments was established through expert judgment by two mathematics education specialists, and item quality was evaluated through a pilot test before being used in the main data collection.

Data were analyzed using an independent samples t-test to compare the posttest results of the experimental and control groups. This test was used to determine whether statistically significant differences existed in mathematical communication and mathematical creativity as a result of implementing the STEAM approach. Prior to analysis, assumption testing—including normality and homogeneity of variance—was conducted to ensure the appropriateness of the parametric statistical procedures.

3 Results

The findings of this study reveal clear performance differences between the experimental group taught using the STEAM approach and the control group taught using conventional instruction. Based on posttest scores, students' mathematical communication skills in the experimental group achieved a mean score of 74.28, substantially higher than the control group's mean score of 56.25. The maximum–minimum score range also reflects this pattern: the highest score in the experimental group was 93.75, while the control group reached only 81.25. A similar trend was observed in mathematical creativity, with the experimental group obtaining a mean score of 78.27, significantly higher than the control group's mean of 59.10. The maximum creativity score in the experimental group reached 92.50, compared to only 85 in the control group.

Assumption testing—including the Shapiro–Wilk normality test and Fisher's homogeneity of variance test—confirmed that all posttest data for both variables were normally distributed and exhibited homogeneous variances. Having satisfied these requirements, further analysis was conducted using an independent samples t-test.

The t-test results indicate statistically significant differences between the two groups. For mathematical communication skills, the analysis yielded $t = 4.504$ with $p = 0.000$, confirming that the STEAM approach had a significant positive impact on students' communication performance. For mathematical creativity, the t-value was 5.337 with $p = 0.000$, demonstrating a similarly strong effect of the STEAM-based instruction. These findings collectively reinforce the conclusion that STEAM-based learning is more effective than conventional instruction in enhancing these two essential mathematical competencies.

4 Discussion

This study's findings affirm that the STEAM approach significantly influences students' mathematics communication skills. This corresponds with prior studies suggesting that integrative learning settings facilitate students' expression of mathematical concepts using various verbal, visual, and symbolic representations [11]. Within the STEAM framework, learners engage in contextualized projects linked to science, technology, and the arts, rather than solely executing mathematical procedures, thereby enhancing their ability to communicate and defend their mathematical thinking. This sharply contrasts with procedural-oriented traditional training, which frequently restricts opportunities for profound mathematical communication [13].

The enhancement of mathematical creativity noted in the experimental group aligns with previous studies indicating that STEAM fosters the generation of original, adaptable, and detailed ideas through activities centered on design, exploration, and contextual problem-solving [17,19]. When students engage in project-based activities that involve designing solutions, creating artistic representations, or altering geometric forms, they are prompted to provide a variety of ideas grounded in logical thinking, thus enhancing their mathematical creativity. This technique establishes creative thinking as a fundamental element of learning rather than simply a by-product of task execution.

Moreover, the incorporation of the arts within STEAM fosters diverse thinking, which underpins mathematical creativity [16]. This elucidates the markedly elevated inventiveness scores noted in the experimental group. The integration of scientific investigation with artistic expression, enhances the scope for expression and increases the variety of potential answers in mathematical situations [9].

The results further corroborate prior systematic reviews suggesting that while STEAM possesses significant potential to foster creativity, empirical evidence regarding its influence on mathematical communication is scarce and requires additional experimental research [1,20]. This study addresses this gap by presenting empirical evidence that STEAM not only fosters creativity but also improves mathematics communication among high school students—an result seldom recorded in prior research.

From an educational perspective, these findings indicate that mathematics training that includes project work, design activities, group discussions, and student presentations can foster a more intellectually stimulating learning environment. This corresponds with Roehrig's concept of authentic integrated learning, characterized by significant, multi-representational activities that embody real-world complexity [6]. This method aligns with 21st-century learning paradigms that prioritize communication, creativity, cooperation, and problem-solving [2,3].

The elevated communication and creativity ratings in the experimental group indicate that the STEAM approach effectively fosters the development of two fundamental mathematical talents vital for contemporary schooling. Simultaneously, these findings present both theoretical and practical implications for educators aiming to develop more contextualized, multidisciplinary, and innovative mathematics learning experiences.

Based on previous findings, most STEAM-related studies have predominantly emphasized creativity, problem-solving, or product-oriented outcomes, while empirical evidence on mathematical communication—especially measured quantitatively within authentic classroom settings—remains limited and fragmented. This study extends existing literature by providing experimental evidence that STEAM-based mathematics instruction simultaneously enhances students' mathematical communication and creativity. Unlike prior research that often examined these constructs separately or relied on qualitative descriptions, the present study employs a controlled quasi-experimental design with explicit assessment indicators for both competencies. Therefore, this research contributes novel empirical support to the STEAM literature by positioning mathematical communication not merely as a complementary outcome, but as a central learning achievement that can be systematically developed alongside creativity through integrated STEAM instruction.

5 Conclusions and recommendations

This study demonstrates that the STEAM approach significantly enhances high school students' mathematical communication skills and creativity compared with conventional instruction. Students who participated in STEAM-based learning were able to communicate mathematical ideas more clearly, use a wider range of representations, and produce more original and flexible solutions. These findings affirm that integrating science, technology, engineering, the arts, and mathematics into a coherent sequence of instructional activities creates a cognitively rich learning environment capable of effectively supporting 21st-century competencies.

Future research is recommended to employ pretest–posttest or longitudinal designs to more comprehensively capture changes in students' performance over time. Additionally, subsequent studies could extend the research context to include a broader range of schools or different educational levels to improve generalizability. Further exploration of related constructs—such as collaboration, higher-order problem-solving, learning motivation, or mathematics anxiety—may also provide a more holistic understanding of the impact of the STEAM approach in mathematics education.

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