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ORIGINAL ARTICLE

The Effect of Integrated Mathematical Modeling and GeoGebra on Students' Learning of Trigonometric Functions: A Mixed-Methods Study

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ABSTRACT

The present study investigated the effect of an integrative instructional intervention combining mathematical modeling activities with GeoGebra on students' performance in learning trigonometric functions. A quasi-experimental pretest–posttest design with two main groups (experimental and control) was employed. The final sample included 270 eleventh-grade students (132 in four experimental subgroups and 138 in four control subgroup). Data were collected using problem-based tests grounded in mathematical modeling and analyzed based on students' technical skills in GeoGebra and conceptual modeling levels. The experimental group received GeoGebra-based mathematical modeling instruction, whereas the control group was taught using traditional methods without technology. Quantitative analyses using one-way ANCOVA indicated significant improvements in students' performance ($p < 0.001$) with large effect sizes for digital technology ($\eta^2 = 0.715$) and mathematical modeling ($\eta^2 = 0.712$). Comparison of the two interventions showed no significant difference ($p = 0.339$), indicating the positive impact of both approaches. Qualitative findings revealed that students' active learning, group interaction, and deeper conceptual understanding were enhanced. Overall, integrating digital technology and mathematical modeling provides an effective model for interactive instruction and improving students' performance in complex mathematical topics.

KEYWORDS

Integrative Instruction, Trigonometric Modeling, GeoGebra, Student Performance, Conceptual Understanding.

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Introduction

Mathematics plays a central role in education by fostering critical thinking, problem solving, and understanding of real-world phenomena (Fard et al., 2024). However, understanding how students learn and analyzing their mathematical activities remain a major challenge in mathematics education that requires appropriate theoretical frameworks (Drijvers et al., 2013). In recent years, active and student-centered learning approaches have received increasing attention as effective strategies for improving the quality of learning (Moradi & Birnavandi, 2024).

Advances in digital technologies have created new opportunities for mathematics education. Digital tools provide visual representations, simulations, and interactive environments that can facilitate the learning of complex concepts and improve students' conceptual understanding and problem-solving abilities when used purposefully (Lee & Lee, 2024).

Alongside technology, mathematical modeling is recognized as an effective approach in mathematics education. By connecting real-world situations with mathematical concepts, modeling can enhance students' motivation and strengthen their conceptual understanding (Greefrath et al., 2022). Despite its importance, research on the combined use of modeling and digital technology in mathematics instruction remains limited (Patel & Pfannkuch, 2018).

In the secondary school curriculum, trigonometric functions are among the most important and difficult topics for many students, particularly when they are required to interpret graphs and link different mathematical representations (Bilgili & Çiltas, 2021). Although digital tools can support the understanding of these concepts, relatively few studies have examined the combined effects of technology and mathematical modeling in teaching trigonometry (Mosese & Ogbonnaya, 2021).

Therefore, the present study aims to investigate the effect of integrating mathematical modeling activities with the GeoGebra software on students' learning of trigonometric functions.

Research Questions:

Does integrated instruction using GeoGebra improve students' technical levels?

Does this approach enhance students' conceptual understanding of modeling trigonometric functions?

Do technology and modeling have a significant effect on the experimental group?

method

This study implemented an instructional intervention combining mathematical modeling and GeoGebra to teach trigonometric functions to 11th-grade students. Using a mixed-methods design with a quasi-experimental pretest–posttest structure, 270 students were divided into experimental and control groups. The experimental group completed five sessions of three-stage modeling activities in GeoGebra, while the control group received traditional instruction. Data were collected through two modeling-based assessments as well as qualitative evidence from interviews and observations, and the instruments demonstrated acceptable validity and reliability. The intervention used three real-world tasks—wave analysis, ladder-angle modeling, and window-design geometry—to strengthen students' GeoGebra skills and improve their conceptual understanding of trigonometric modeling.

Data Analysis Method

Data were analyzed using descriptive statistics and one-way ANCOVA in SPSS 26, with results reported in descriptive and inferential sections. To explore students' learning processes, twenty

semi-structured interviews and classroom observations were conducted. After coding, key themes were extracted and presented with explanations and selected quotations to illustrate students' learning and conceptual development.

Descriptive statistics

The descriptive results showed little change in the control group's performance, while the experimental group demonstrated significant improvement after the intervention, with data meeting the normality assumptions. ANCOVA results confirmed that the integrated approach using digital technology and mathematical modeling significantly improved students' technical skills and conceptual understanding. No significant difference was found between the effects of digital technology and mathematical modeling alone, indicating similar impacts. Overall, the integrated intervention substantially enhanced students' performance and understanding.

Qualitative Findings

Analysis of worksheets and interviews revealed three themes: students' interaction, their engagement with real-world modeling, and effective use of digital tools. These patterns indicated more active and coherent learning, aligning with the quantitative results.

Discussion and conclusion

The study demonstrates that integrating mathematical modeling with digital tools such as GeoGebra significantly enhances students' performance, conceptual understanding, and technical skills in trigonometry. The quantitative results, supported by ANCOVA and large effect sizes, establish a generalizable principle: technology-supported modeling creates deeper cognitive engagement and leads to higher learning outcomes. However, the study has limitations, including reliance on a specific software environment and potential variability in students' prior technological experience. The findings have both theoretical and practical implications; theoretically, they confirm the emergence of instrumental genesis, showing how GeoGebra becomes embedded in students' mathematical reasoning. Practically, they illustrate that modeling and digital technology can operate as complementary pathways for improving learning. The study concludes that integrating dynamic visualization with real-world modeling tasks strengthens problem-solving and conceptual understanding. It recommends designing trigonometry instruction with purposeful digital tools, richer modeling activities, and more interactive learning environments.

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Authors' Contribution

All authors contributed meaningfully to the development, preparation, and finalization of this manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest with any individual or organization.

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