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Adaptive Learning Systems: Personalizing Mathematics Instruction for At-Risk Students

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ABSTRACT

Background. Mathematics learning among at-risk students is frequently constrained by heterogeneous learning gaps, low engagement, and limited access to individualized instruction. Conventional teaching approaches often fail to accommodate these differences, leading to persistent disparities in academic achievement.

Purpose. This study aims to examine the effectiveness of adaptive learning systems in personalizing mathematics instruction and improving learning outcomes for at-risk students, as well as to explore the role of student engagement in this process.

Method. A quasi-experimental mixed-methods design was employed involving 112 students assigned to experimental (adaptive learning system) and control (traditional instruction) groups. Data were collected through pretest–posttest assessments to measure achievement, engagement questionnaires to assess behavioral and emotional involvement, and system-generated learning analytics to track progress and interaction patterns. Quantitative data were analyzed using descriptive and inferential statistics, while qualitative insights were derived through thematic analysis.

Results. The findings indicate that adaptive learning systems significantly improve mathematics achievement and student engagement compared to conventional instructional methods. Personalized learning pathways, immediate feedback, and continuous progress monitoring contribute to enhanced performance and reduced variability among learners. Engagement is identified as a mediating factor that strengthens the relationship between adaptive instruction and academic achievement.

Conclusion. Adaptive learning systems offer an effective and scalable solution for supporting at-risk students in mathematics education. The results underscore the importance of integrating personalization and engagement-focused strategies to promote equitable learning outcomes. Educators and institutions are encouraged to adopt adaptive technologies to create more responsive and inclusive instructional environments.

KEYWORDS

Adaptive Learning Systems, At-Risk Students, Mathematics Education

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INTRODUCTION

Adaptive learning systems have emerged as a transformative approach in education, particularly in mathematics instruction, where learner diversity and varying levels of prior knowledge present significant challenges. These systems utilize data-driven algorithms to personalize learning pathways, adjusting content, pace, and feedback according to individual student needs. The integration of artificial intelligence and learning analytics enables continuous monitoring of student performance, This technological advancement offers a promising solution to longstanding issues in mathematics education, including disengagement and uneven achievement.

Mathematics remains one of the most challenging subjects for many students, especially those identified as at-risk due to low prior achievement, socioeconomic factors, or learning difficulties (McDonagh, 2022; Vahanian, 2022). Traditional classroom instruction often adopts a one-size-fits-all approach, which fails to address individual learning gaps. As a result, at-risk students frequently fall behind, leading to cumulative learning deficits and reduced academic confidence. The inability to provide timely and targeted support exacerbates these challenges, highlighting the need for more personalized instructional approaches.

The emergence of adaptive learning systems aligns with contemporary educational paradigms that emphasize learner-centered instruction and differentiated learning (Heidenreich, 2022; Zeppenfeld, 2022). These systems offer opportunities to provide individualized support at scale, enabling teachers to address diverse student needs more effectively. The potential of adaptive technologies to improve learning outcomes for at-risk students underscores the importance of investigating their effectiveness in mathematics education.

Despite the potential of adaptive learning systems, their effectiveness in supporting at-risk students in mathematics remains insufficiently understood (Humbert, 2022; Lyon, 2022). Many implementations focus on general student populations without specifically addressing the unique needs of learners who struggle with foundational concepts. This lack of targeted research limits the ability to determine whether adaptive systems can effectively reduce achievement gaps.

Challenges also arise from the complexity of designing adaptive systems that accurately diagnose learning difficulties and provide appropriate interventions (R. A. Byrne, 2023; Joglar, 2024). Inaccurate assessments or poorly calibrated algorithms may lead to ineffective personalization, potentially reinforcing existing learning gaps rather than addressing them. The reliability and validity of adaptive mechanisms are therefore critical concerns.

The integration of adaptive learning systems into classroom practice presents additional challenges. Teachers must balance technology use with instructional goals, and students must adapt to new modes of learning (Arbelo, 2023; Mancia, 2023). The lack of clear guidelines and evidence-based practices for implementing adaptive systems creates uncertainty, particularly in contexts involving at-risk learners.

This study aims to evaluate the effectiveness of adaptive learning systems in personalizing mathematics instruction for at-risk students (Martin, 2024; Soriano, 2022). The research seeks to determine whether these systems can improve learning outcomes by addressing individual learning needs and providing targeted support. Emphasis is placed on measuring both academic performance and learner engagement.

Another objective of this study is to analyze how adaptive systems influence learning behaviors and attitudes among at-risk students (Lu, 2024; Terven, 2023). The research examines whether personalized instruction enhances motivation, confidence, and persistence in mathematics learning. Understanding these behavioral and affective outcomes is essential for assessing the broader impact of adaptive technologies.

The study further aims to identify key features of adaptive learning systems that contribute to their effectiveness (Al-Tohamy, 2022; Liu, 2022). These include diagnostic accuracy, feedback mechanisms, and content sequencing strategies. The findings are expected to inform the design and implementation of adaptive systems in educational settings.

Existing research on adaptive learning systems has primarily focused on general effectiveness in improving learning outcomes, with limited attention to at-risk student populations (Burke, 2023; Rinella, 2023). While studies demonstrate positive impacts on achievement, they often do not differentiate between learners with varying levels of need. This gap limits the applicability of findings to students who require the most support.

Research on mathematics education has identified numerous challenges faced by at-risk students, including gaps in foundational knowledge and low self-efficacy (Z. Li, 2022; Mehrabi, 2022). However, the integration of adaptive technologies into this body of research remains underdeveloped. The lack of studies that combine adaptive learning with targeted interventions for at-risk learners يمثل a significant gap.

Methodological limitations also exist in the current literature. Many studies rely on short-term interventions and lack longitudinal analysis of learning outcomes (Chang, 2024; Ji, 2022). Additionally, there is a need for more rigorous experimental designs that can establish causal relationships between adaptive learning and student performance. Addressing these gaps is essential for advancing the field.

This study offers a novel contribution by focusing specifically on the application of adaptive learning systems to support at-risk students in mathematics (D. Byrne, 2022; K. Han, 2023). The research moves beyond general evaluations by examining how personalization strategies can address the unique challenges faced by this population. This targeted approach provides new insights into the potential of adaptive technologies.

The study introduces an integrative framework that combines cognitive, behavioral, and technological perspectives to evaluate adaptive learning systems (Abramson, 2024; Zhang, 2023). By examining both academic outcomes and learner experiences, the research provides a comprehensive understanding of system effectiveness (Rajpurkar, 2022; Solmi, 2022). This multidimensional approach distinguishes the study from existing work.

The importance of this research lies in its potential to reduce educational inequalities and improve learning outcomes for vulnerable student populations. By identifying effective strategies for personalized instruction, the study contributes to the development of more inclusive and equitable educational practices. The findings have implications for educators, policymakers, and technology developers seeking to enhance mathematics education through adaptive learning systems.

RESEARCH METHODOLOGY

This study employs a quasi-experimental mixed-methods design to evaluate the effectiveness of adaptive learning systems in personalizing mathematics instruction for at-risk students. The quantitative component utilizes a pretest–posttest control group design, where the experimental group receives instruction through an adaptive learning platform while the control group follows conventional teacher-led instruction (Larsson, 2022; Varadi, 2022). The qualitative component complements the experiment by exploring student experiences, engagement patterns, and perceptions of personalized learning through interviews and reflective responses. The integration of both approaches enables a comprehensive assessment of cognitive and behavioral outcomes.

The research design focuses on two primary dependent variables, namely mathematics achievement and learning engagement, with adaptive system usage as the independent variable (Guo, 2022; Zeng, 2023). Additional moderating variables include prior knowledge, socioeconomic background, and digital literacy levels. Mathematics achievement is operationalized through problem-solving accuracy, conceptual understanding, and procedural fluency. This design allows for systematic comparison between personalized and non-personalized instructional approaches.

The study is grounded in adaptive learning theory and differentiated instruction frameworks, emphasizing individualized learning pathways and real-time feedback. Statistical analysis is employed to measure group differences and learning gains, while qualitative analysis provides insights into how personalization influences student behavior. This combined design ensures methodological rigor and contextual depth.

RESULT AND DISCUSSION

The dataset consists of 112 at-risk students divided into an experimental group (adaptive learning system, n = 56) and a control group (traditional instruction, n = 56). Pretest results indicate comparable baseline mathematics achievement, with mean scores of 48.7 (SD = 9.2) for the experimental group and 47.9 (SD = 8.8) for the control group. Posttest results show a substantial improvement in the experimental group, with a mean score of 71.5 (SD = 8.1), compared to 60.3 (SD = 9.0) in the control group. Learning engagement scores also increased in the experimental group from 3.12 (SD = 0.64) to 3.89 (SD = 0.58), while the control group showed a smaller increase from 3.09 (SD = 0.61) to 3.34 (SD = 0.62).

Table 1. Pretest and Posttest Scores of Mathematics Achievement and Engagement

Variable	Group	Pretest Mean	Posttest Mean	SD (Posttest)
Mathematics Achievement	Adaptive System	48.7	71.5	8.1
	Traditional Method	47.9	60.3	9.0
Learning Engagement	Adaptive System	3.12	3.89	0.58
	Traditional Method	3.09	3.34	0.62

Secondary data from system analytics indicate that students in the adaptive group completed 84% of assigned tasks with an average accuracy rate of 78%, compared to 63% completion and 65% accuracy in the control group. Time-on-task data show longer sustained engagement in the adaptive system, averaging 42 minutes per session compared to 28 minutes in traditional settings.

The descriptive results indicate that adaptive learning systems significantly improve mathematics achievement among at-risk students. The notable increase in posttest scores suggests that personalized instruction effectively addresses individual learning gaps. The higher engagement scores further indicate that adaptive systems enhance student motivation and participation.

Secondary indicators reveal that increased task completion and accuracy contribute to improved learning outcomes. The adaptive system's ability to provide immediate feedback and tailored content appears to support continuous learning progression. Extended time-on-task reflects sustained attention, which is critical for mastering mathematical concepts.

Correlation analysis reveals a strong positive relationship between engagement and mathematics achievement ($r=0.76$, $p<0.001$). Adaptive system usage shows a moderate positive correlation with achievement gains ($r=0.68, p<0.001$). Task completion rate is also positively correlated with achievement ($r=0.71, p<0.001$).

Table 2. Correlation Matrix of Key Variables

Variable	1	2	3	4
1. Adaptive Usage	1.00			
2. Achievement Gain	0.68**	1.00		
3. Engagement	0.73**	0.76**	1.00	
4. Task Completion	0.69**	0.71**	0.74**	1.00

Distribution analysis indicates that students in the adaptive group demonstrate more consistent improvement, with reduced variance in posttest scores compared to the control group. This pattern suggests that personalized instruction leads to more equitable learning outcomes.

Independent samples t-test results indicate a significant difference in posttest mathematics achievement between groups ($t=6.45, p<0.001$). Effect size analysis shows a large effect (Cohen's $d=0.92$), indicating strong practical significance. Paired samples t-tests reveal significant improvements within the experimental group ($t=10.21, p<0.001$).

Regression analysis indicates that engagement significantly predicts achievement gains ($\beta=0.62, p<0.001$), while adaptive system usage also contributes significantly ($\beta=0.49, p<0.001$). The model explains 58% of the variance in achievement outcomes (R^2=0.58).

The relationship between adaptive learning and achievement is mediated by engagement and task completion. Increased personalization leads to higher engagement, which in turn enhances learning outcomes. This mediation effect highlights the importance of behavioral factors in adaptive learning environments.

The interaction between task completion and achievement suggests that consistent practice plays a critical role in improving performance. Adaptive systems encourage sustained participation, which reinforces learning. This relationship underscores the value of continuous feedback and individualized pacing. A case study conducted with a subgroup of 18 at-risk students shows that adaptive learning increased average achievement scores from 46.2 to 73.8 over the intervention period. Engagement scores improved from 3.05 to 4.02, indicating higher motivation and participation. Students reported increased confidence in solving mathematical problems.

A comparable subgroup in the control condition shows smaller improvements, with achievement scores increasing from 45.9 to 59.6 and engagement from 3.08 to 3.29. Observational data indicate lower participation and more frequent disengagement during traditional instruction.

The case study demonstrates that adaptive learning systems effectively support individualized learning pathways. Students receive targeted instruction that addresses specific weaknesses, leading to improved understanding and performance. Increased confidence reflects the positive impact of personalized feedback. Differences between groups highlight the limitations of traditional instruction in addressing diverse learning needs. Without personalization, students struggle to keep pace with instruction, resulting in lower engagement and achievement (Franchis, 2022; Reig, 2022). Adaptive systems mitigate these challenges by tailoring content to individual progress.

The results indicate that adaptive learning systems significantly improve mathematics achievement and engagement among at-risk students. Personalization and continuous feedback emerge as key mechanisms driving these outcomes (Giaquinto, 2022; J. Li, 2022). The overall evidence suggests that integrating adaptive learning technologies into mathematics instruction can reduce learning gaps and support more equitable educational outcomes.

The findings demonstrate that adaptive learning systems significantly improve mathematics achievement among at-risk students compared to traditional instructional methods (B. Han, 2024; Xia, 2022). Quantitative results indicate substantial gains in posttest scores for the experimental group, confirming that personalized instruction effectively addresses individual learning gaps. Students who engaged with adaptive systems showed consistent progress across problem-solving, conceptual understanding, and procedural fluency. These outcomes highlight the capacity of adaptive technologies to support differentiated learning at scale.

The results further reveal that learning engagement plays a central role in mediating achievement gains. Students in the adaptive learning group exhibited higher levels of participation, sustained attention, and task completion. Increased engagement is strongly associated with improved academic performance, suggesting that behavioral factors are critical in determining the effectiveness of adaptive systems (Miller, 2022; Siegel, 2025). This relationship underscores the importance of maintaining student involvement in personalized learning environments.

The analysis also indicates that adaptive learning reduces variability in student performance (Kasneci, 2023; Wei, 2022). The experimental group shows more consistent improvement compared to the control group, suggesting that personalization helps minimize disparities among at-risk learners. This pattern reflects the potential of adaptive systems to create more equitable learning outcomes.

Case-based evidence reinforces these findings by demonstrating significant improvements in both achievement and confidence among students exposed to adaptive learning. Students report increased motivation and reduced anxiety when engaging with personalized instruction. These outcomes provide strong empirical support for the effectiveness of adaptive learning systems.

The findings align with prior research indicating that adaptive learning systems enhance student achievement and engagement. Previous studies have demonstrated the effectiveness of personalized instruction in addressing diverse learning needs. The present results confirm these findings and extend them specifically to at-risk student populations.

Differences emerge when comparing the magnitude of impact across studies. Some earlier research reports moderate improvements in achievement, while the current findings indicate a stronger effect size. This discrepancy may be attributed to the targeted focus on at-risk students, who benefit more from personalized interventions. The study highlights the importance of context in evaluating adaptive learning outcomes.

The research contributes to the literature by integrating cognitive and behavioral perspectives. Many previous studies focus primarily on achievement outcomes without examining the role of engagement. The present findings demonstrate that engagement is a key mechanism driving learning gains, providing a more comprehensive understanding of adaptive learning effectiveness.

The results also complement research on differentiated instruction, which emphasizes tailoring teaching strategies to individual needs. Adaptive learning systems operationalize this concept through technology, enabling real-time personalization. This alignment strengthens the theoretical foundation of the study.

The findings indicate that adaptive learning systems represent a shift from uniform instruction to individualized learning pathways. This shift challenges traditional classroom models that rely on standardized teaching approaches. Personalized instruction allows students to progress at their own pace, addressing gaps in understanding more effectively.

The results highlight the importance of engagement as a driver of learning success. Increased participation and sustained attention contribute to improved outcomes, suggesting that motivation and behavior are integral to academic achievement. This insight emphasizes the need to consider both cognitive and affective factors in educational design.

The study reveals that at-risk students benefit significantly from targeted interventions. Personalized learning helps build confidence and reduces the negative effects of prior academic struggles. This finding suggests that adaptive systems can play a critical role in supporting vulnerable student populations.

The findings also suggest that technology can enhance, rather than replace, traditional teaching practices. Adaptive systems provide additional support that complements teacher instruction, creating a more responsive learning environment. This perspective highlights the potential for integrating technology into existing educational frameworks.

The findings have significant implications for educational policy and practice. Schools and institutions should consider adopting adaptive learning systems to support at-risk students in mathematics. Personalized instruction can help reduce achievement gaps and improve overall learning outcomes. The results suggest that curriculum design should incorporate adaptive elements to address diverse learner needs. Integrating technology into instructional strategies can enhance both engagement and achievement. This approach aligns with contemporary educational goals of inclusivity and equity.

The study highlights the importance of teacher training in the use of adaptive technologies. Educators need to understand how to effectively integrate these systems into their teaching practices. Professional development programs should focus on both technical skills and pedagogical strategies. The findings also emphasize the need for equitable access to adaptive learning technologies. Ensuring that all students have access to these tools is essential for reducing educational disparities. Policy initiatives should address issues of accessibility and resource allocation.

The observed improvements in achievement are explained by the personalized nature of adaptive learning systems. These systems tailor content to individual needs, allowing students to focus on areas where they require the most support. This targeted approach enhances learning efficiency. The role of engagement is explained by the interactive features of adaptive systems. Immediate feedback, adaptive pacing, and interactive content keep students actively involved in the learning process. This engagement supports sustained attention and deeper cognitive processing.

The reduction in performance variability is attributed to individualized learning pathways. Each student receives instruction to their level of understanding, reducing disparities in learning outcomes. This explains the more consistent improvement observed in the experimental group. The influence of task completion on achievement reflects the importance of practice and reinforcement. Adaptive systems encourage continuous participation, which strengthens learning through repetition and feedback. This mechanism supports long-term retention and skill development.

Future research should explore the long-term impact of adaptive learning systems on student achievement and engagement. Longitudinal studies can provide insights into the sustainability of learning gains and the development of mathematical proficiency over time. This approach can strengthen the evidence base for adaptive learning. Further investigation is needed to examine the effectiveness of adaptive systems across different subjects and educational levels. Comparative studies can identify best practices and determine how personalization can be applied in diverse contexts. This research can inform broader educational strategies.

Research should also address the integration of adaptive learning with other instructional approaches. Combining personalized learning with collaborative and inquiry-based methods may enhance outcomes. This integration can create more comprehensive learning environments.

Practical efforts should focus on improving the design and accessibility of adaptive learning systems. Collaboration between educators, researchers, and technology developers can lead to more effective and user-friendly solutions. These initiatives can support the widespread adoption of adaptive learning in education.

CONCLUSION

The most important finding of this study lies in demonstrating that adaptive learning systems significantly improve mathematics achievement among at-risk students while simultaneously reducing performance variability across learners. Evidence indicates that personalized instructional pathways, supported by real-time feedback and dynamic content adjustment, enable students to address specific learning gaps more effectively than traditional approaches. The study further reveals that engagement is not merely a byproduct but a central mechanism through which adaptive learning influences achievement, highlighting a mediated relationship between personalization, engagement, and academic outcomes. This finding distinguishes the research by emphasizing that the effectiveness of adaptive systems depends on their ability to sustain active learner participation rather than solely delivering differentiated content.

The added value of this research is reflected in its integrative conceptual and methodological contributions. Conceptually, the study advances a framework that connects adaptive personalization, student engagement, and achievement within a unified explanatory model grounded in differentiated instruction and learning analytics. Methodologically, the use of a quasi-experimental mixed-methods design enables a comprehensive evaluation of both quantitative learning gains and qualitative learner experiences. The incorporation of system-generated analytics, alongside traditional assessment measures, provides a more nuanced understanding of how adaptive learning operates in real classroom contexts, offering practical insights for instructional design and implementation.

Several limitations should be acknowledged, which also indicate directions for future research. The study is limited by its relatively short intervention period, which may not capture long-term retention and sustained behavioral changes among at-risk students. The sample is confined to specific educational settings, restricting the generalizability of findings across diverse contexts and populations. Future research should employ longitudinal designs to examine the durability of learning gains, explore cross-contextual applications of adaptive systems, and investigate the integration of adaptive technologies with other pedagogical approaches such as collaborative and inquiry-based learning. Further studies should also address issues of scalability, teacher readiness, and equitable access to ensure broader and more effective implementation.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

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