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AI AS A DIGITAL SCAFFOLD: AN INTEGRATIVE REVIEW OF VYGOTSKY'S ZONE OF PROXIMAL DEVELOPMENT IN MODERN EDUCATION

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Abstract:

This paper conducts an integrative review to synthesize current research on the intersection of Artificial Intelligence (AI), adaptive learning systems, and Vygotsky's Zone of Proximal Development (ZPD). It aims to clarify how AI functions as a "digital scaffold" and evaluate the extent to which current technologies align with the core principles of ZPD. A systematic search of academic databases was conducted for peer-reviewed literature published between 2020 and 2025. The review analyzes and synthesizes findings from these sources to identify key themes, practical applications, and research gaps. The analysis reveals that AI-powered systems operationalize ZPD primarily through three mechanisms: (1) personalized learning paths that adapt content difficulty in real-time; (2) immediate, targeted feedback that corrects misconceptions; and (3) the facilitation of self-regulated learning. Recent literature indicates a shift towards using generative AI to also support collaborative and social learning, moving beyond purely individualized instruction. The paper highlights a gap between the theoretical potential of AI in education and its practical implementation, particularly concerning equity,

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teacher preparedness, and ethical data use. It concludes by proposing a framework for designing and evaluating AI tools based on Vygotskian principles and calls for more empirical research on the effectiveness of AI as a digital scaffold in real-world classroom settings.

Keywords:

Zone of Proximal Development, Artificial Intelligence, Adaptive Learning Systems

Introduction

The educational landscape is undergoing rapid transformation, with digital technologies playing an increasingly central role in shaping how learning takes place. Among the most impactful developments is the integration of Artificial Intelligence (AI) and adaptive learning systems, which facilitate personalised learning experiences tailored to students' individual needs and levels of readiness. Central to effective learning is Vygotsky's concept of the Zone of Proximal Development (ZPD), a key element of his Sociocultural Theory (McLeod, 2024). The ZPD refers to the space between what a learner can accomplish independently and what they can achieve with appropriate guidance. This guided support, commonly referred to as "scaffolding," has traditionally been provided by teachers or peers and, in contemporary digital contexts, by intelligent technologies. While ZPD has historically been implemented in face-to-face learning environments where educators offer real-time, individualised support, the emergence of AI and adaptive technologies has expanded the possibilities for scalable, personalised scaffolding that promotes cognitive development in digital settings (Vorobyeva et al., 2025). This paper examines the potential of AI and adaptive learning systems to effectively support the ZPD in digital education. Through the integration of these technologies, educators can now offer more precise, continuous support, ensuring learners consistently operate within their ZPD for optimal growth. AI-powered platforms not only provide immediate feedback and customised content delivery but also enable real-time adjustments based on learners' ongoing performance and progress. Viewed through this lens, AI and adaptive systems play a vital role in creating responsive learning environments that scaffold and nurture learners' cognitive advancement (Akavova et al., 2023).

In light of this, the objective of this paper is to conduct an integrative review of current research addressing three central questions: (1) How do modern AI and adaptive learning systems function as "digital scaffolds" to support learners within their ZPD? (2) What are the primary benefits and challenges of using AI to operationalise ZPD in digital education? (3) What key gaps remain in the literature, and what are the most pressing directions for future inquiry? This paper will begin by outlining the methodology used for the integrative review, followed by a thematic analysis of the findings. It will then present a critical discussion of implications for educators and developers, concluding with targeted recommendations for future research.

Literature Review

Vygotsky's ZPD in the Context of Modern Education

Lev Vygotsky's concept of the Zone of Proximal Development (ZPD) describes the gap between what a learner can accomplish independently and what they can achieve with appropriate guidance. Vygotsky asserted that learners can attain deeper understanding and more complex skills with the assistance of more knowledgeable others—such as teachers,

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peers, or even technological tools (Sætra, 2025; Strielkowski , 2025; Ali & Azamri, 2023). This guided assistance, known as scaffolding, enables learners to perform tasks they would otherwise be unable to complete on their own. As learners develop, this support is gradually withdrawn, encouraging autonomy and continuous growth. In conventional classroom settings, teachers scaffold learning by assessing each student's current level of understanding and providing just enough support to extend their capabilities (Grájeda et al., 2024; Ali & Azamri, 2023). This method ensures learners are consistently working just beyond their independent competence. As education shifts toward more student-centered models, tailoring instruction within the ZPD has become essential for enhancing learning outcomes. With the growing adoption of digital education, the application of ZPD has expanded into virtual and hybrid learning environments through AI and adaptive learning systems (Maulidiya et al., 2024). These technologies can personalise instruction by adjusting task difficulty, delivering real-time feedback, and anticipating learners' future needs based on their progress—aligning closely with the foundational principles of the ZPD.

Introduction to AI and Adaptive Learning Systems

Artificial Intelligence (AI) in education involves the use of intelligent systems that replicate aspects of human cognition, enabling machines to perform tasks that traditionally require human involvement (Sadiku et al., 2021). Technologies such as natural language processing, machine learning, and deep learning empower AI to automate and personalise learning experiences. AI-driven tools can monitor student progress, detect learning gaps, and deliver immediate feedback, thereby ensuring that instruction is continuously adapted to meet learners' changing needs (Kaledio et al., 2024; Madhu et al., 2024). Adaptive learning systems, a key application of AI in education, are designed to customise content, assessments, and instructional approaches based on individual learner profiles (Gupta et al., 2024; Capuano & Caballé, 2020). These systems utilise algorithms and data analytics to track student performance in real time, dynamically modifying the learning experience to suit each student's abilities. By offering personalised learning pathways, adaptive systems ensure that learners remain appropriately challenged, aligning with the principles of the Zone of Proximal Development (ZPD) (Er-Radi et al., 2023). For instance, when a student encounters difficulty, the system may present simpler tasks to build foundational understanding; conversely, when mastery is demonstrated, it may introduce more complex tasks—thereby fostering an optimal environment for cognitive growth.

Intersection of ZPD, AI, and Adaptive Learning

The convergence of the Zone of Proximal Development (ZPD), Artificial Intelligence (AI), and adaptive learning systems presents a powerful conceptual framework for advancing digital education. AI and adaptive technologies operationalise the principles of ZPD in digital environments by offering personalised scaffolding that continually aligns with learners' evolving capabilities. Similar to traditional ZPD-based scaffolding, where teachers evaluate students' readiness for new challenges (Priyo & Teguh, 2021), AI and adaptive systems assess learner performance in real time and dynamically adjust instructional content to maintain learners within their optimal learning zone (Gupta et al., 2024; Akavova et al., 2023).

- AI-powered tools offer consistent support and appropriately scaled challenges through features such as:
- Personalised learning paths: AI algorithms evaluate student progress and modify the difficulty level of tasks to ensure content is suitably challenging—neither too easy nor overwhelming (Gupta et al., 2024; Joshi, 2023).

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- Real-time feedback: In contrast to traditional settings, where feedback may be delayed, AI tools deliver instant feedback, allowing students to promptly recognise and address their mistakes (Jegede, 2024).
- Continuous monitoring and data analytics: AI systems track learning trajectories, identify areas requiring additional support, and make timely adjustments to ensure learners remain within their ZPD (Warden & Chen, 2020).

The Role of AI in Supporting ZPD

One of the most significant advantages of Artificial Intelligence (AI) in education is its capacity to personalise the learning experience for each student. Personalisation involves tailoring content, pacing, and instructional strategies to suit individual learners' needs (Ayeni et al., 2024). In conventional classroom settings, this level of individualisation is often constrained by time and the challenge of adapting instruction to each student's Zone of Proximal Development (ZPD). AI-powered systems, however, can dynamically adjust to learners' progress, offering tailored educational experiences that keep students engaged and appropriately challenged within their ZPD. These systems analyse various data points—such as learner performance, preferences, and learning styles—to customise learning paths (Yamijala et al., 2023). By examining student interactions with learning materials, AI can determine when a learner is ready to advance or when additional support is required. This ensures that learners consistently operate within their ZPD, engaging in tasks that are neither too simple nor too difficult, thereby maximising their learning potential. For instance, an AI-powered tutoring system may offer additional practice on concepts a student finds challenging, while presenting more advanced materials once mastery is demonstrated.

AI also plays a pivotal role in mediating scaffolding within digital education. Scaffolding, a central principle of the ZPD, involves providing structured support that enables learners to complete tasks they cannot manage independently. AI technologies facilitate this process by delivering timely feedback, hints, and prompts that help learners progress without experiencing cognitive overload (Umutlu & Gursoy, 2022). These systems monitor learner performance in real time, providing just-in-time support to guide students through learning tasks. When a student struggles with a concept, the AI may supply supplementary explanations or step-by-step prompts to aid comprehension. As the learner's competence grows, the level of support is gradually reduced, promoting independence. This mirrors the concept of dynamic scaffolding, which requires continuous adjustment of assistance based on a learner's evolving capabilities (Janson, Söllner, & Leimeister, 2020). Moreover, Looi and Jia (2025) emphasise that AI tutors can simulate real-time interactions and serve as "more knowledgeable others" within digital environments. These intelligent agents model cognitive strategies, explain complex ideas, and offer learners opportunities to practice in safe, low-stakes settings. This form of AI support bridges the gap between what learners can do independently and what they can achieve with guidance, aligning directly with Vygotsky's conception of the ZPD.

A defining feature of the ZPD is the gradual transfer of responsibility from the teacher—or more knowledgeable other—to the learner. The overarching goal is to cultivate learner autonomy, enabling students to independently apply skills developed through scaffolding. AI systems are uniquely positioned to promote this autonomy by offering continuous, personalised feedback and fostering self-directed learning (Mohebbi, 2024). These tools empower students to take ownership of their educational journeys by enabling them to monitor their progress, set learning goals, and engage with content at their own pace (Huang, Lu, & Yang, 2023). Adaptive

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learning platforms, for example, give learners the flexibility to choose learning materials while still receiving support within their ZPD. This fosters a sense of control and agency, encouraging students to take an active role in their cognitive development. Additionally, Mohebbi (2024) notes that AI can support the development of metacognitive skills, which are essential for self-regulation. Through sustained interaction with AI-powered tools, learners can acquire strategies for managing their learning—such as goal-setting, progress reflection, and task adaptation. This aligns with the ultimate objective of ZPD: to promote independence while maintaining appropriate levels of support and challenge.

Several real-world applications illustrate how AI supports learners' ZPD through personalised scaffolding and autonomy development:
i. Intelligent Tutoring Systems (ITS): Platforms like Carnegie Learning and DreamBox use AI to deliver personalised mathematics instruction. These systems continuously track student progress, adjust task difficulty, and intervene when learners encounter difficulties. By modulating the pace and complexity of instruction, these systems ensure learners remain within their ZPD, receiving tailored support at each stage (Rajput, 2025).
ii. AI-Powered Writing Assistants: Tools such as Grammarly and Quillbot provide real-time feedback on grammar, structure, and clarity, helping students refine their writing skills. Radin, Mustapha, and Adam (2024) highlight how these platforms offer scaffolded support by suggesting improvements and explanations. As learners gain proficiency, the systems shift toward offering more advanced feedback, encouraging continued development within their ZPD.
iii. Language Learning Platforms: AI-driven tools like Duolingo use adaptive algorithms to personalise language instruction based on user proficiency. These platforms adjust exercise difficulty, review vocabulary, and offer instant pronunciation feedback, ensuring learners are continually challenged within their ZPD. The AI analyses learner performance and customises lessons to target specific weaknesses.

These examples demonstrate the diverse applications of AI in digital education. Each one underscores how AI facilitates personalised support and promotes autonomy, ensuring learners consistently operate within their ZPD—ultimately enhancing engagement, understanding, and long-term growth.

Adaptive Learning Systems and ZPD
Adaptive learning systems are specifically designed to adjust instructional content in real time to meet individual learner needs, ensuring alignment with the Zone of Proximal Development (ZPD) (Ferguson et al., 2022). These systems monitor student performance and modify the difficulty, pacing, and presentation of learning materials based on ongoing learner interactions (Gupta et al., 2024). By leveraging algorithms and real-time data, adaptive platforms assess learners' understanding, advancing those who demonstrate mastery while offering targeted support to those encountering difficulties (Sayed et al., 2024). This continuous adjustment fosters an optimal balance between challenge and support, in line with Vygotsky's principles of scaffolding (Akavova et al., 2023).

In supporting meaningful learning within the ZPD, adaptive systems provide personalised instructional experiences that reflect each learner's unique profile (Xiao & Hew, 2024). Key features include personalised learning pathways that align content with student proficiency levels (Hicham Er-Radi et al., 2023), formative assessments that guide instructional decisions

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(Wilkinson, 2024), and adaptive content delivery tailored to diverse learning styles (Jdidou, Aammou & Er-Radi, 2023). These mechanisms ensure that learners remain appropriately supported and challenged throughout their educational journey.

Furthermore, modern adaptive learning systems increasingly incorporate collaborative components that align with Vygotsky's emphasis on social interaction and collective problem-solving within the ZPD (Gao et al., 2024; Sharma, 2024). Through features such as peer-to-peer communication, group-based challenges, and real-time interaction tools, learners engage in co-constructed knowledge building and scaffold one another's understanding. These collaborative affordances not only enhance ZPD-driven learning but also cultivate essential skills for real-world teamwork and problem-solving (Cai et al., 2024).

Examples of Adaptive Learning Systems in Practice (Dutta et al., 2024):

Carnegie Learning

Carnegie Learning provides a blended mathematics learning platform that integrates AI-driven tutoring with classroom instruction. The system delivers real-time feedback, adjusts task difficulty based on student progress, and fosters problem-solving skills through personalised guidance (Sharma, 2024). The AI engine continuously analyses student responses to identify areas of difficulty and provides targeted interventions. By adjusting the complexity of tasks and offering scaffolded support, the platform ensures learners remain within their ZPD, gradually shifting from assisted learning to independent problem-solving.

DreamBox Learning

DreamBox is an adaptive math program for students from kindergarten through eighth grade. It uses real-time data analytics to personalise both the pace and difficulty of lessons according to individual learner needs. By tracking learning behaviours, DreamBox identifies knowledge gaps and delivers immediate, focused practice. The platform supports ZPD-based instruction by presenting tasks that are suitably challenging and offering instant feedback and timely interventions to sustain learner engagement.

Smart Sparrow

Targeted primarily at higher education, Smart Sparrow enables instructors to create interactive, adaptive learning experiences—especially in subjects such as science and engineering. Its adaptive engine adjusts course content in response to learner performance, ensuring students are consistently challenged without being overwhelmed. By analysing student inputs and applying predictive analytics, the platform recommends optimal next steps and provides instructors with detailed insights into learner engagement. This data-driven scaffolding supports learners within their ZPD while promoting deeper, more autonomous learning.

Knewton

Knewton is an adaptive learning platform that customises digital course content across various disciplines, including mathematics, science, and language arts (Wiley, 2025). Its AI engine analyses student interactions to deliver lessons, assessments, and learning materials tailored to individual proficiency and pacing. By dynamically adjusting content to match each learner's capabilities, Knewton ensures that students are consistently working within their ZPD. The platform offers both targeted support and appropriately challenging tasks, supporting skill mastery and fostering learner independence.

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Methodology

This study employs an integrative review methodology to synthesize theoretical and empirical literature on the intersection of AI, adaptive learning, and ZPD. This approach allows for the combination of diverse sources to create a comprehensive understanding of the topic. A systematic search was conducted in the Google Scholar databases for literature published between January 2020 and July 2025. The search strategy used combinations of the following keywords: "*Artificial Intelligence*", "*adaptive learning*", "*Zone of Proximal Development*", "*digital scaffolding*", "*Vygotsky*", and "*educational technology*". Inclusion criteria for selected articles were: (1) peer-reviewed status, (2) direct relevance to both AI in education and ZPD, and (3) written in English. The initial search yielded over 150 articles, which were then screened for relevance, resulting in a final corpus of 45 papers that form the basis of this review. The findings were analyzed thematically to identify recurring concepts, benefits, and challenges.

Discussion

This integrative review confirms the transformative potential of AI to function as a dynamic, responsive scaffold in digital education. The findings indicate that AI systems are moving beyond simple content delivery to provide nuanced, real-time support that aligns with the core tenets of ZPD. However, the synthesis of recent literature also highlights critical challenges that temper this optimism. A key implication is the changing role of the educator. As AI takes on more of the direct scaffolding role, teachers must become facilitators of learning and critical evaluators of AI tools. This requires significant professional development, which is currently lacking in many educational systems. Furthermore, while personalization is a clear benefit, there is a risk of creating overly individualized learning "*bubbles*" that neglect the social aspect of learning, which was central to Vygotsky's original theory. The emergence of generative AI for collaborative tasks may offer a solution, but this area remains under-researched.

Future Directions and Practical Implications

As education continues to evolve, technology—particularly in the form of digital scaffolding—has become instrumental in reshaping instructional practices. Adaptive instructional design plays a critical role in online learning environments by enhancing the ways in which technology can effectively support learners (Yang, Jiang, & Su, 2022). Moreover, emerging innovations such as artificial intelligence and virtual reality present significant opportunities to further personalise education, allowing for customised learning experiences that cater to individual learner needs (Ahmad, Umirzakova, Mujtaba, Amin, & Whangbo, 2023).

Challenges and Limitations

While the adoption of AI and adaptive learning systems offers significant benefits, it also presents several critical challenges. Equity remains a pressing concern, as students in under-resourced communities often lack reliable infrastructure and access to digital devices, thereby limiting their ability to benefit from personalised learning and exacerbating existing educational inequalities (Lata, 2024; Pawar & Khose, 2024; Joshi, Khatiwada & Pokhrel, 2024). Teacher readiness is another major issue—many educators feel unprepared to integrate AI tools into their practice or to effectively interpret data for ZPD-aligned instruction (Bowman et al., 2022; Dogan, Dogan & Celik, 2021; Arnado & Aviles, 2023; Stringer et al., 2022; Redmond et al., 2021; Cohn et al., 2025; Salas-Pilco, Xiao & Hu, 2022; Tammets & Ley, 2023). In addition, ethical concerns arise surrounding student data privacy, algorithmic bias, and the potential misuse of information collected through AI systems (Akavova, Temirkhanova

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& Lorsanova, 2023; Weber, 2020; Aquino, 2023). Finally, without careful design and implementation, adaptive learning systems risk causing cognitive overload—presenting tasks that are too difficult too quickly, failing to account for learners' emotional responses, and ultimately increasing frustration and disengagement (Akavova, Temirkhanova & Lorsanova, 2023; Ferguson et al., 2022; Wan Ismail, Awang & Mohd Pauzi, 2021; Lazarides & Chevalère, 2021).

Conclusion

This integrative review has synthesized the current state of research on the role of AI and adaptive learning systems in advancing Vygotsky's Zone of Proximal Development. The analysis confirms that these technologies can function as powerful digital scaffolds, personalizing instruction and providing timely feedback. However, the review also highlights a critical need for a more pedagogically-grounded approach to the design and implementation of these tools. The challenges of equity, teacher readiness, and ethical AI use must be addressed to ensure that the benefits of AI-enhanced learning are accessible to all. Future research should move beyond conceptual discussions and focus on empirical studies that compare the effectiveness of different AI scaffolding models in diverse classroom settings. Longitudinal studies are needed to understand the long-term effects on learner autonomy and metacognition. Finally, more work is required to explore how AI can support not just individual learning, but also the collaborative and social dimensions of ZPD, thereby creating a truly holistic and human-centered digital learning environment.

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