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Digital Scaffolding in Science Education: A Systematic Review

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A R T I C L E I N F O

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A B S T R A C T

This study aimed to synthesize the characteristics, implementation, use, adaptivity, and effectiveness of digital scaffolding in science education. A systematic literature review was conducted using the Scopus database and search terms related to digital scaffolding, science learning, technology-enhanced scaffolding, scientific inquiry, and online learning. The results show that digital scaffolding has been implemented through prompts, hints, feedback, digital journals, argumentation tools, search guidance, and adaptive systems based on learner modelling. Its effectiveness was associated not only with the availability of technological support, but also with the alignment of scaffolds with learners' needs, learners' attention to and actual use of the support provided, social interaction, task characteristics, design quality, and the timing of assistance. Overall, the findings indicate that digital scaffolding should be understood as a multidimensional and process-oriented support system in which technological and human assistance interact to respond to learners' emerging needs. This review provides a conceptual basis for the design and investigation of adaptive scaffolding in future science and chemistry education research.

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INTRODUCTION

The increasing integration of technology into science education has expanded opportunities to provide learners with support through various forms of digital scaffolding, particularly when they engage in complex, open-ended, and inquiry-based activities that require substantial cognitive and metacognitive engagement. In technology-enhanced learning environments, digital scaffolding is no longer limited to simple information or instructions but may include prompts, hints, feedback, sentence starters, digital journals, argumentation tools, search guidance, pedagogical agents, interactive activities, and adaptive systems based on learner modeling. This diversity indicates that digital scaffolding can support different learning processes according to learners' characteristics, task demands, and instructional goals. Shin et al. (2020) showed that technology-supported science learning cannot be understood solely in terms of digital assistance because hard scaffolding, peer scaffolding, and teacher scaffolding contribute differently to individual achievement and group performance. In genetics learning, Deep et al. (2020) demonstrated how digital scaffolding can integrate conceptual knowledge, scientific inquiry, statistical procedures, problem-solving, metacognitive reflection, and knowledge transfer. Similarly, Ustunel and Tokel (2017) showed that technology can function as part of distributed scaffolding that operates synergistically with teacher support to facilitate students' scientific argumentation. These findings suggest that digital scaffolding has evolved from relatively static technology-based assistance into a multidimensional support system embedded within broader learning processes. Consequently, its analysis should extend beyond identifying available technological features to examining the form and function of support, its source, delivery mechanism, and the learning processes it is intended to facilitate (Deep et al., 2020; Shin et al., 2020; Ustunel & Tokel, 2017).

Although these studies provide important empirical evidence, the literature remains conceptually fragmented because individual studies generally address specific dimensions of digital scaffolding. Shin et al. (2020) focused on the configuration of hard, peer, and teacher scaffolding; Deep et al. (2020) emphasized complex learning and reflection; Belland et al. (2018) examined students' actual use of computer-based scaffolding; and Johnson (2018) highlighted self-regulated learning, attention, and timing. Other perspectives include distributed scaffolding (Ustunel & Tokel, 2017), learner modeling and adaptive scaffolding (Basu et al., 2017), and strategic guidance for learner-generated content (van Dijk & Lazonder, 2013). These perspectives provide complementary insights but have not been integrated into a multidimensional framework encompassing scaffold form, pedagogical function, source of support, adaptivity, timing and contingency, actual use, social interaction, fading, and learning outcomes. Moreover, the mechanisms linking scaffold design to outcomes remain insufficiently synthesized, particularly the progression from the availability of support to learner attention, perception, actual use, cognitive or metacognitive activity, and subsequent learning outcomes. Fading and the development of learner independence have also received comparatively limited attention, as many studies emphasize

performance while support remains available rather than learners' subsequent ability to perform with reduced assistance. Differences in domains, populations, digital systems, tasks, and science learning contexts further limit straightforward generalization across studies. Therefore, a systematic synthesis is required to explain not only what forms of digital scaffolding are available but also how they are implemented and used, how support adapts to learners, and under what conditions it contributes to learning (Basu et al., 2017; Belland et al., 2018; Deep et al., 2020; Johnson, 2018; Shin et al., 2020; Ustunel & Tokel, 2017; van Dijk & Lazonder, 2013).

Based on these gaps, this study aims to develop a multidimensional synthesis connecting the design, use processes, adaptivity, and outcomes of digital scaffolding in science education. Its contribution lies not in establishing whether digital scaffolding can improve learning, as such benefits have been demonstrated in previous studies, but in integrating dimensions that have largely been investigated separately. Specifically, the review maps scaffold forms, pedagogical functions, sources of support, levels of adaptivity, timing and contingency, and fading mechanisms; examines how scaffolds are actually implemented and used in relation to learner needs, attention, responses, and interactions with teachers and peers; and synthesizes reported learning outcomes together with factors supporting or constraining their effectiveness. Accordingly, the study addresses the following research questions:

RQ1: What are the characteristics of digital scaffolding used in science education in terms of scaffold forms, pedagogical functions, sources of support, adaptivity, timing and contingency, and fading mechanisms?

RQ2: How is digital scaffolding implemented and used in science learning, particularly in relation to learner needs, actual scaffold use, interactions with teachers and peers, and the adaptation of support?

RQ3: What learning outcomes are reported from the implementation of digital scaffolding in science education, and what factors support or constrain its effectiveness across learning contexts?

These questions shift the analysis from a feature-centered perspective toward a process- and learner-centered understanding of digital scaffolding. In this perspective, the quality of scaffolding is determined not merely by the availability of digital support but by what assistance is provided, for what purpose, to whom, when and how it is delivered and used, how it interacts with human support, when it is reduced, and what learning outcomes it facilitates. The resulting synthesis is expected to provide a more coherent conceptual account of the conditions under which available digital support becomes productive, contingent, adaptive, socially integrated scaffolding that progressively supports learner independence.

THEORETICAL REVIEW

Digital scaffolding in science education

Digital scaffolding refers to technology-mediated support designed to assist learners in completing tasks or engaging in learning processes that they may not yet be able to perform independently. In science education, such support is

particularly relevant because learners are often required to integrate conceptual knowledge with scientific inquiry, problem-solving, evidence evaluation, modeling, argumentation, and self-regulation. Deep et al. (2020) showed that digital scaffolding can support several stages of complex learning, including hypothesis formulation, experimentation, statistical reasoning, evaluation, and reflection. Similarly, Belland et al. (2018) demonstrated that computer-based scaffolding can structure problem-based scientific inquiry by guiding learners through problem identification, information seeking, claim development, and evidence use.

These variations suggest that the form of a digital feature does not fully determine its pedagogical function. A prompt, for example, may facilitate scientific inquiry in one environment and self-regulated learning in another. Johnson (2018) demonstrated its regulatory function, while Belland et al. (2018) used prompts primarily to structure inquiry processes. Ustunel and Tokel (2017) further showed that prompts and sentence starters can perform an argumentative function by helping learners construct claims and supporting evidence. Therefore, digital scaffolding is more appropriately classified according to the learning process it supports rather than solely according to the technological feature used.

Sources and configurations of scaffolding

Digital scaffolding does not necessarily operate as an independent source of learning assistance. Technology-based support may interact with teacher and peer scaffolding within the same learning environment. Shin et al. (2020) distinguished among hard, peer, and teacher scaffolding in technology-enhanced science learning. Their findings showed that these sources of support were associated differently with learning performance, with hard scaffolding being more closely related to individual achievement and peer scaffolding contributing more strongly to group performance.

Peer support represents another component of the scaffolding system. Shin et al. (2020) demonstrated that peer scaffolding was particularly important for group performance. Van Dijk and Lazonder (2013) presented a different form of peer-related support through learner-generated content. In their study, students used information produced by other learners and were guided in selecting, evaluating, and integrating that information. These findings suggest that digital, teacher, and peer scaffolding can function as complementary sources of support rather than as separate or competing mechanisms.

Adaptivity, contingency, timing, and fading

A major distinction among digital scaffolding systems concerns the degree to which assistance responds to learners' changing needs. Some forms of scaffolding are designed before instruction and provide relatively similar assistance across learners. Shin et al. (2020) described this type of support as hard scaffolding embedded in a technology-enhanced learning environment. Such scaffolding can provide structure and consistency, although its responsiveness to individual learner difficulties may be limited.

The effectiveness of such assistance also depends on timing and contingency. Johnson (2018) showed that the presence of self-regulation prompts did not

necessarily ensure that learners attended to them. Some students responded to the intended regulatory processes only after facilitator intervention. This finding indicates that pedagogically appropriate content may have limited value when it does not become salient at the moment of need. Therefore, contingency involves not only providing relevant assistance but also matching that assistance to learners' current difficulties.

Fading is another important principle because scaffolding is intended to function as temporary support. Basu et al. (2017) provided the clearest example of this process by linking learner diagnosis, scaffold triggering, monitoring, and a gradual reduction of assistance as learners developed greater competence. In contrast, fading was less explicitly represented in the other reviewed studies. This pattern suggests that digital scaffolding research has paid greater attention to how assistance is provided than to how it is systematically withdrawn. Evaluating fading is important because successful scaffolding should ultimately promote greater independence rather than continued dependence on external support.

Actual use of digital scaffolding

The availability of digital scaffolding does not automatically ensure that learners use it productively. Belland et al. (2018) found that some learners ignored prompts, provided only minimal responses, adopted shortcuts when searching for information, or failed to evaluate source credibility critically. These behaviors demonstrate that the intended function of a scaffold may differ considerably from its actual use during learning.

Learner characteristics can also influence the way scaffolds are perceived and used. Johnson (2018) found that learners with lower levels of self-regulation tended to perceive digital support as more useful, whereas learners with stronger regulatory abilities sometimes considered the same support less necessary. Basu et al. (2017) addressed learner variability through a system that monitored actions and strategies before providing adaptive assistance. Belland et al. (2018) additionally identified motivation, engagement, information literacy, and group dynamics as factors that could influence the quality of scaffold use. Consequently, actual scaffold use should be treated as an important process variable linking technological design with learning outcomes.

Learning outcomes and effectiveness

Digital scaffolding has been associated with a wide range of learning outcomes in science education. Shin et al. (2020) reported relationships between hard scaffolding and individual academic achievement, while peer scaffolding was more strongly associated with group performance. Deep et al. (2020) demonstrated improvements in complex learning involving genetics concepts, scientific inquiry, statistical reasoning, problem-solving, reflection, and transfer.

Other studies reported outcomes related to specific scientific practices. Ustunel and Tokel (2017) showed that technology-supported scaffolding, combined with teacher intervention, facilitated the development of scientific argumentation. Belland et al. (2018) demonstrated that scaffolding could guide problem-based scientific inquiry, although learners differed considerably in the

extent to which they used the available assistance. Johnson (2018) reported improvement in knowledge of waves, whereas changes in self-regulated learning were more limited. This difference illustrates that a single intervention may influence conceptual and regulatory outcomes differently.

Based on this literature, digital scaffolding can be conceptualized through several interconnected dimensions: scaffold form, pedagogical function, source of support, adaptivity, timing and contingency, actual use, social interaction, fading, and learning outcomes. The literature also suggests a conceptual distinction between support that is merely available and support that becomes pedagogically productive through learner attention and use. These dimensions provide the theoretical basis for the present systematic review and guide the subsequent analysis of the characteristics, implementation, adaptivity, actual use, and effectiveness of digital scaffolding in science education.

METHODOLOGY

Research design and search strategy

This study employed a systematic literature review (SLR) to systematically identify, screen, evaluate, and synthesize studies on digital scaffolding in science education. The literature search was conducted using the Scopus database. The search combined terms related to digital scaffolding, science learning, technology-enhanced scaffolding, scientific inquiry, and online learning. The search terms were organized as follows: ("digital" AND "science" AND "scaffolding") OR ("technology" AND "enhanced" AND "scaffolding") OR ("science" AND "learning" AND "scaffolding") OR ("scientific" AND "inquiry" AND "scaffolding") OR ("online" AND "learning" AND "scaffolding"). The initial search identified 101 records.

Study selection

The identified records were selected through sequential identification, screening, and eligibility stages, as presented in Figure 1. Of the 101 records initially retrieved, two duplicate records were removed. A further 29 records were excluded because they did not meet the year criterion, and 31 records did not satisfy the Q1-Q4 journal-ranking criterion. No records were excluded because of missing abstracts. Consequently, 39 records proceeded to title and abstract screening. At this stage, 27 records were excluded because their content was not relevant to digital scaffolding in science education, leaving 12 reports for full-text retrieval. Five reports could not be retrieved, and seven full-text articles were subsequently assessed for eligibility. All seven articles met the eligibility criteria and were included in the final review: Basu et al. (2017), Belland et al. (2018), Deep et al. (2020), Johnson (2018), Shin et al. (2020), Ustunel and Tokel (2017), and van Dijk and Lazonder (2013).

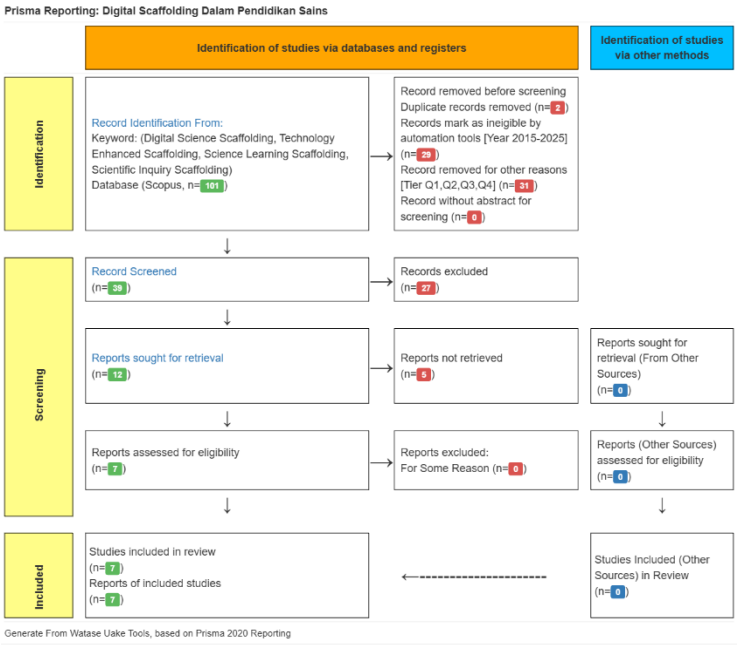


Figure 1. Study identification and selection process

Data extraction and coding

A structured data-extraction and coding sheet was developed according to the three research questions. The extracted information included study identification, research context and participants, scaffold forms, pedagogical functions, sources of support, levels of adaptivity, timing and contingency, fading mechanisms, learner needs, actual scaffold use, interactions with teachers and peers, learning outcomes, and factors supporting or constraining effectiveness. Each article was read in full, and relevant information was identified and coded according to these categories. The extracted data were subsequently organized in an analytical matrix to enable systematic comparison of the same dimensions across studies.

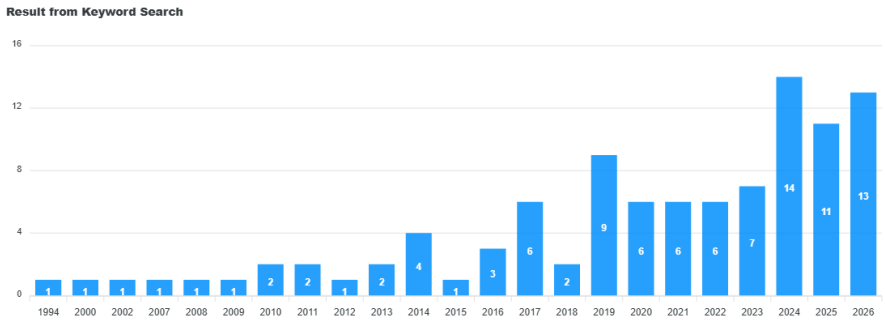


Figure 2. Data extraction and synthesis procedure

Data synthesis

The extracted data were analyzed using descriptive and thematic synthesis. Findings were first grouped according to similarities, differences, and relationships across the predefined dimensions of digital scaffolding. This procedure enabled the review to compare variations ranging from static to adaptive scaffolding, digital to distributed sources of support, and scaffold availability to actual scaffold use (Basu et al., 2017; Belland et al., 2018; Johnson,

2018; Shin et al., 2020; Ustunel & Tokel, 2017). A cross-study synthesis was then conducted to examine relationships between scaffold characteristics and implementation processes and the reported learning outcomes, including conceptual understanding, scientific inquiry, scientific argumentation, self-regulation, modeling, computational thinking, information processing, collaboration, and knowledge transfer (Deep et al., 2020; van Dijk & Lazonder, 2013). The final synthesis was used to develop a multidimensional mapping of the conditions that supported or constrained the effectiveness of digital scaffolding in science education.

RESULTS

Characteristics of the included studies

The selection process resulted in seven articles that met the eligibility criteria and constituted the final corpus for the synthesis of digital scaffolding in science education. The studies covered learning contexts involving biology and genetics, environmental science, waves and light, computational-thinking-based science, and technology-enhanced inquiry learning. The identified forms of digital scaffolding included hard scaffolding, prompts, hints, feedback, sentence starters, digital journals, argumentation tools, search guidance, pedagogical agents, interactive activities, and adaptive support based on learner modeling. Considerable variation was observed across studies in terms of scaffold forms, pedagogical functions, sources of support, levels of adaptivity, implementation mechanisms, and targeted learning outcomes.

Shin et al. (2020) examined hard, peer, and teacher scaffolding in technology-enhanced biology learning, whereas Deep et al. (2020) used Geneticus Investigatio to support complex learning in genetics. Belland et al. (2018) employed the Connection Log to structure problem-based scientific inquiry, while Johnson (2018) incorporated digital prompts into the Waves game to support conceptual learning and self-regulated learning. Ustunel and Tokel (2017) integrated WISE, student journals, hints, sentence starters, question prompts, and SenseMaker to facilitate learning about light and scientific argumentation. Basu et al. (2017) implemented CTSiM with a learner model and mentor agent that provided support according to learners' actions and strategies. Van Dijk and Lazonder (2013) employed a search guidance tool in SCY-Lab to support students in using learner-generated content. The main characteristics, implementation features, and reported outcomes of the seven studies are summarized in Table 1.

Table 1. Characteristics, implementation, and reported outcomes of digital scaffolding

Study	Digital scaffolding/environment	Main implementation features	Reported outcomes
Shin et al. (2020)	Hard scaffolding in technology-enhanced inquiry learning	Examined in combination with peer and teacher scaffolding	Hard scaffolding was associated with individual achievement, whereas peer scaffolding was

			associated with group performance
Deep et al. (2020)	Geneticus Investigatio; hints, feedback, reflection, and interactive activities	Scaffolds were embedded across several stages of genetics problem-solving	Improvements were reported in complex learning, inquiry, and knowledge transfer
Belland et al. (2018)	Connection Log and inquiry prompts	Students' actual use of scaffolds did not always correspond to the intended design	Some students followed the inquiry process, whereas others ignored or responded minimally to prompts
Johnson (2018)	Self-regulated learning prompts in the Waves game	Some self-regulatory responses emerged following facilitator guidance	Knowledge of waves improved, whereas changes in self-regulated learning were more limited
Ustunel and Tokel (2017)	WISE, SenseMaker, hints, student journals, and sentence starters	Digital scaffolds were implemented together with teacher intervention	The combined support facilitated components of scientific argumentation
Basu et al. (2017)	CTSiM, learner model, and mentor agent	Diagnosis → trigger → adaptive support → monitoring → fading	Improvements were reported in model accuracy, modeling strategies, science concepts, computational thinking, and transfer
van Dijk and Lazonder (2013)	SCY-Lab and search guidance tool	Supported information searching, evaluation, and integration	Students developed more differentiated and interconnected conceptual knowledge structures

Overall, the seven studies demonstrate substantial heterogeneity in how digital scaffolding was designed and implemented. Some studies employed relatively fixed forms of support, such as prompts, hints, or search guidance, whereas others incorporated multiple sources of assistance or adaptive mechanisms based on learner behavior. The findings also indicate that the presence of digital scaffolding did not necessarily correspond to its intended use, as actual learner engagement with the available support varied across studies. These variations provide the basis for the subsequent analysis of scaffold characteristics, implementation processes, adaptivity, and reported learning outcomes.

DISCUSSION

Overall, this systematic literature review indicates that digital scaffolding in science education should not be understood merely as a technological feature added to a digital learning environment. Rather, it represents a configuration of support involving scaffold forms, pedagogical functions, sources of assistance, learner characteristics, timing, actual use, social interaction, adaptivity, and

learning outcomes. The seven studies covered a continuum from pre-designed hard scaffolding, prompts, hints, and feedback to adaptive support triggered by diagnoses of learners' actions and strategies (Basu et al., 2017; Deep et al., 2020; Shin et al., 2020). Importantly, the availability of scaffolding did not necessarily result in productive learning activity. Learners could ignore prompts, pay insufficient attention to available support, or require facilitator intervention before using the scaffolds as intended (Belland et al., 2018; Johnson, 2018). Furthermore, digital support operated alongside teacher and peer assistance rather than independently from them (Shin et al., 2020; Ustunel & Tokel, 2017). These findings support a multidimensional view of digital scaffolding in which effectiveness depends not only on what support is provided but also on why, when, to whom, and how it is provided and used.

Characteristics of digital scaffolding in science education

The findings for RQ1 demonstrate that digital scaffolding can first be distinguished according to its form and pedagogical function, which are related but not equivalent dimensions. Shin et al. (2020) investigated pre-designed hard scaffolding embedded within technology-enhanced inquiry learning, whereas Deep et al. (2020) incorporated feedback, hints, reflective questions, additional resources, interactive activities, and opportunities to revise responses. Belland et al. (2018) used the Connection Log to structure processes ranging from problem identification and information seeking to claim development and evidence use. Johnson (2018) employed prompts to support planning, monitoring, strategy control, and self-reflection, while Ustunel and Tokel (2017) combined student journals, hints, sentence starters, question prompts, and SenseMaker to facilitate scientific argumentation. Basu et al. (2017) employed a different configuration in which a pedagogical agent provided support based on information generated through learner modeling, whereas van Dijk and Lazonder (2013) used search guidance to facilitate information searching, evaluation, and integration.

These variations indicate that technically different features may perform similar scaffolding functions, while the same feature, such as a prompt, may serve conceptual, strategic, metacognitive, regulatory, or argumentative purposes depending on its pedagogical design. Across the reviewed studies, scaffolding addressed conceptual understanding, procedures, strategies, metacognition, self-regulation, scientific argumentation, information processing, diagnosis, collaboration, and adaptation (Basu et al., 2017; Belland et al., 2018; Deep et al., 2020; Johnson, 2018; Ustunel & Tokel, 2017; van Dijk & Lazonder, 2013). Therefore, classifying digital scaffolding only according to the technological feature used provides an incomplete account. A more informative classification considers the learning process that the feature is intended to support. This functional perspective also enables different technologies to be compared within a common analytical framework.

A second characteristic concerns the source of scaffolding. The reviewed studies indicate that technological, teacher, and peer support may contribute differently to the learning process. Shin et al. (2020) distinguished hard, peer, and teacher scaffolding and found that hard scaffolding was more strongly associated with individual academic achievement, whereas peer scaffolding was an

important predictor of group performance. Ustunel and Tokel (2017) similarly demonstrated that technology-based scaffolding operated together with teacher intervention in supporting scientific argumentation. Belland et al. (2018) reported situations in which teacher assistance remained necessary when learners did not understand prompts or encountered difficulties interpreting information, while Johnson (2018) showed that facilitators sometimes had to direct learners' attention toward already available digital prompts. Van Dijk and Lazonder (2013) added another dimension through learner-generated content, in which products created by peers became information resources to be selected, evaluated, and integrated with the assistance of search guidance. Digital scaffolding, therefore, should not be conceptualized as an automatic substitute for teachers or peers but as one component of a broader support system.

The findings also reveal important differences in adaptivity, timing, contingency, and fading. Pre-designed hard scaffolding provides relatively consistent assistance based on anticipated learner difficulties but offers limited responsiveness to individual changes during learning (Shin et al., 2020). Other environments provide support at particular stages of an activity through hints, feedback, reflective questions, or revision opportunities (Deep et al., 2020). Johnson (2018) further showed that appropriate content alone is insufficient when a scaffold lacks sufficient salience to attract learners' attention at the relevant moment. The clearest example of adaptive and contingent support was reported by Basu et al. (2017), whose system used learner actions and strategies to diagnose difficulties and determine whether and what type of assistance should be provided. This study also provided the strongest evidence concerning fading, as scaffold requirements decreased as learners developed greater competence. By contrast, fading was not reported as explicitly across the other studies. The synthesis therefore identifies fading as an important but comparatively underexamined dimension. Digital scaffolding should consequently be evaluated not only by the content of assistance but also by whether support is responsive to learner needs, delivered at an appropriate time, and reduced as learners become increasingly capable of independent performance.

Implementation and actual use of digital scaffolding

The findings for RQ2 show that digital scaffolding was generally implemented by embedding support within the sequence of science-learning activities. Deep et al. (2020), for example, incorporated scaffolding throughout problem interpretation, hypothesis formulation, variable identification, experimental design, prediction, statistical analysis, evaluation, conclusion development, and reflection. Belland et al. (2018) embedded support across stages of problem-based scientific inquiry, while Ustunel and Tokel (2017) integrated digital assistance into inquiry and scientific argumentation activities. Johnson (2018) placed self-regulation prompts within game-based learning, and van Dijk and Lazonder (2013) introduced scaffolding during information searching and the use of learner-generated content. Basu et al. (2017) integrated assistance even more closely with learners' ongoing activity by using learner-generated action data to determine subsequent support. These findings indicate that effective

implementation begins with the learning process and the difficulties learners are expected to encounter rather than with the technological tool itself.

A particularly important finding is the distinction between scaffold availability and productive scaffold use. Belland et al. (2018) showed that access to scaffolding did not ensure that learners responded adequately to prompts, conducted sufficiently thorough information searches, evaluated source credibility, or connected evidence with claims as intended. Johnson (2018) reported a comparable pattern in which learners did not consistently attend to self-regulation prompts until facilitators directed their attention toward them. Van Dijk and Lazonder (2013) further showed that scaffold effectiveness was not necessarily reflected in access frequency because differences were more evident in the organization and quality of conceptual knowledge. These studies suggest that technical indicators such as frequency of access or the mere presence of a feature are insufficient indicators of meaningful scaffold use.

This distinction has an important methodological implication. The process connecting scaffold design with learning outcomes may involve several intermediate conditions, including exposure to support, attention, interpretation, actual use, and the cognitive or metacognitive activity elicited by that use. Shin et al. (2020) examined perceived usefulness in relation to learning outcomes, although their design did not fully capture how perceptions were translated into moment-to-moment behavior. Belland et al. (2018), in contrast, demonstrated more directly that pedagogically designed support may fail to perform its intended function when learners ignore it or respond superficially. Consequently, future evaluations of digital scaffolding should examine not only whether scaffolds are available and whether learning outcomes improve but also how learners interact with the available assistance.

Actual scaffold use also differed according to learner characteristics and social support. Johnson (2018) indicated that learners with lower self-regulation tended to perceive scaffolding as more useful, whereas those with stronger self-regulatory capacity sometimes considered the same assistance less necessary. Basu et al. (2017) addressed learner heterogeneity by monitoring actions and strategies before providing support. Deep et al. (2020) identified difficulties related to interpreting hypotheses, making predictions, using statistical procedures, and interacting with the learning system, which subsequently informed design refinement. Belland et al. (2018) additionally identified motivation, engagement, information literacy, and group dynamics as relevant to scaffold use. At the social level, teachers provided explanations, questions, guidance, and modeling when digital support alone was insufficient (Belland et al., 2018; Ustunel & Tokel, 2017), while peer scaffolding contributed particularly to group performance (Shin et al., 2020).

Taken together, these findings support a conceptual progression from scaffold design and availability to attention, actual use, learning activity, adaptation, and outcomes. However, this progression should be regarded as an analytical synthesis rather than a causal model established within a single study. Its value lies in identifying the processes that may intervene between a technological design and its reported educational outcomes. This shifts the

analytical focus from whether a scaffold exists to whether and how learners actually transform available assistance into productive learning activity.

Learning outcomes and conditions influencing effectiveness

The findings for RQ3 demonstrate that the outcomes associated with digital scaffolding are multidimensional. Shin et al. (2020) reported different relationships between scaffolding sources and individual or group performance. Deep et al. (2020) found improvements related to complex learning and the integration of genetics concepts, scientific inquiry, statistical reasoning, problem-solving, reflection, and transfer. Belland et al. (2018) showed how scaffolding could support problem-based scientific inquiry, although learners differed substantially in how they used the available support. Johnson (2018) reported improvement in knowledge of waves, whereas changes in self-regulated learning were more limited. Ustunel and Tokel (2017) reported development in components of scientific argumentation, including claims, grounds, warrants, backing, and, in some cases, rebuttals. Basu et al. (2017) identified improvements in model accuracy, modeling strategies, science understanding, computational thinking, and transfer, while van Dijk and Lazonder (2013) found more differentiated and interconnected conceptual knowledge structures among learners receiving search guidance.

These outcomes indicate that the effectiveness of digital scaffolding should be evaluated in relation to its intended pedagogical function. A scaffold designed to support scientific argumentation should be evaluated through indicators of argumentation rather than content achievement alone. Similarly, support designed to facilitate self-regulation requires measures capable of detecting changes in regulatory processes, not only conceptual knowledge. The reviewed studies collectively identified outcomes involving conceptual understanding, scientific inquiry, scientific argumentation, problem-solving, self-regulated learning, information processing, modeling, computational thinking, collaborative performance, and transfer (Basu et al., 2017; Belland et al., 2018; Deep et al., 2020; Johnson, 2018; Shin et al., 2020; Ustunel & Tokel, 2017; van Dijk & Lazonder, 2013). Thus, the question of whether digital scaffolding is effective cannot be separated from the question of what the scaffold was designed to support.

Effectiveness was also influenced by the alignment between learner characteristics and scaffold design. Johnson (2018) showed that scaffold needs varied according to self-regulatory capacity, whereas Belland et al. (2018) indicated that low motivation or engagement could result in scaffolds being ignored or minimally used. Deep et al. (2020) identified interface design, question interpretation, hypothesis context, and statistical procedures as factors affecting learners' interactions with the system. Johnson (2018) emphasized scaffold salience, Belland et al. (2018) documented ignored scaffolding, and van Dijk and Lazonder (2013) identified the possibility of additional regulatory demands associated with scaffold use. Basu et al. (2017) addressed potential mismatches through a diagnostic mechanism that provided assistance after patterns of learner difficulty had been identified. These findings indicate that insufficient support

may fail to address learner needs, whereas excessive or poorly integrated support may create additional demands.

The social and contextual conditions of scaffolding were similarly important. Teacher assistance complemented digital support when learners encountered difficulties that the system could not address (Belland et al., 2018; Ustunel & Tokel, 2017), and facilitator guidance sometimes activated attention toward otherwise overlooked support (Johnson, 2018). Peer scaffolding also contributed to group performance (Shin et al., 2020). However, these effects were observed across heterogeneous populations, domains, tasks, technologies, and research designs. Belland et al. (2018), for example, investigated a small credit-recovery sample, whereas Shin et al. (2020) used a larger but nonrandom design. Other studies were situated in specific learning systems and science domains (Basu et al., 2017; Deep et al., 2020; Ustunel & Tokel, 2017; van Dijk & Lazonder, 2013). Therefore, the available evidence does not support treating effectiveness as a universal property of digital scaffolding. Instead, effectiveness appears to depend on the configuration of learner characteristics, scaffold characteristics, task demands, timing, actual scaffold use, social support, and targeted learning outcomes.

The main contribution of this synthesis is therefore a shift in the unit of analysis from technology itself to the relationship among the learner, scaffold, task, social support, implementation process, and outcome. Previous studies emphasize different parts of this relationship, including scaffold sources (Shin et al., 2020), complex learning (Deep et al., 2020), actual use (Belland et al., 2018), self-regulation and timing (Johnson, 2018), distributed support (Ustunel & Tokel, 2017), adaptivity and fading (Basu et al., 2017), and strategic information guidance (van Dijk & Lazonder, 2013). Integrating these dimensions provides a framework for distinguishing available digital support from productive scaffolding. A digital feature becomes pedagogically meaningful not simply because it is present but because it addresses a relevant need, is noticed and used by the learner, elicits an appropriate learning process, interacts effectively with other sources of support, and is reduced when continued assistance is no longer necessary.

Implications for science and chemistry education

The findings have several implications for the design and evaluation of digital scaffolding. First, scaffold development should begin with the learning process and diagnosed learner needs, followed by the selection of appropriate technological support. Assistance intended for conceptual understanding, inquiry, argumentation, problem-solving, self-regulation, or information processing requires different forms of support and different indicators of success (Deep et al., 2020; Johnson, 2018; Ustunel & Tokel, 2017). Second, designers should consider the salience and timing of assistance because relevant information may have limited value when learners fail to notice it at the point of need (Johnson, 2018). Third, actual scaffold use should be examined directly because learners may ignore, bypass, or respond superficially to available assistance (Belland et al., 2018). Fourth, the amount of support should be calibrated to learner needs to avoid both insufficient assistance and unnecessary regulatory demands (van Dijk & Lazonder, 2013). Finally, teacher and peer support should be treated as complementary

components of digital learning environments rather than external influences (Belland et al., 2018; Shin et al., 2020; Ustunel & Tokel, 2017).

Adaptive systems offer one direction for achieving this alignment. Basu et al. (2017) demonstrated a mechanism involving learner diagnosis, triggering of assistance, monitoring, and subsequent reduction of support. However, adaptivity need not depend exclusively on automated systems. Teacher intervention can also provide contingent adjustment when automated diagnosis is unavailable or insufficient. Future digital scaffolding research should therefore examine both technological and human forms of adaptation and explicitly investigate whether assistance is gradually reduced as learners become more independent.

The implications for chemistry education require particular caution because none of the seven reviewed studies focused specifically on chemistry learning. The present review therefore does not provide direct empirical evidence that the identified scaffold configurations will produce equivalent effects in chemistry contexts. Its contribution to chemistry education is instead conceptual and design-oriented. The identified dimensions—scaffold form, pedagogical function, source, adaptivity, timing, contingency, actual use, social interaction, fading, and targeted outcomes—provide an analytical framework that can be empirically examined in chemistry learning environments. Functions identified across the reviewed science studies, including conceptual learning, inquiry, problem-solving, evidence evaluation, argumentation, self-regulation, modeling, information processing, and transfer, may serve as categories for designing and evaluating future digital scaffolding research in chemistry (Basu et al., 2017; Belland et al., 2018; Deep et al., 2020; Johnson, 2018; Ustunel & Tokel, 2017; van Dijk & Lazonder, 2013).

Accordingly, future chemistry education studies could move beyond asking whether a digital application improves achievement and instead examine what assistance is provided, which learner difficulty it addresses, when it is delivered, whether learners actually use it, how teacher and peer support complement it, and whether the assistance can eventually be reduced. The adaptive sequence reported by Basu et al. (2017) provides a useful conceptual basis for such studies, but its effectiveness in chemistry education remains to be tested empirically. Process data, including interaction traces, screen recordings, learner responses, and action logs, may also help distinguish scaffold availability from actual scaffold use (Basu et al., 2017; Belland et al., 2018). Such evidence would enable future research to explain not merely whether digital scaffolding works in chemistry education, but how, for whom, and under what conditions it becomes productive.

Limitations

Several limitations should be considered when interpreting this review. First, the final corpus consisted of only seven studies. Consequently, the multidimensional framework represents patterns identified within these studies and should not be assumed to encompass all possible forms of digital scaffolding in science education. Second, the review was restricted by the database and selection criteria applied in the search process, and five reports identified for full-text retrieval could not be obtained. Relevant evidence may therefore remain outside the final corpus. Third, the included studies were heterogeneous in terms

of scientific domain, population, digital environment, research design, and outcome measures. This heterogeneity supported a descriptive and thematic synthesis but did not permit direct quantitative comparison of effect sizes.

Fourth, some dimensions were reported unevenly across the reviewed studies. Fading, for example, was most explicitly represented in Basu et al. (2017), while other studies provided limited evidence concerning systematic withdrawal of assistance. Similarly, actual scaffold use was examined in greater depth in some studies than in others. Consequently, the dimensions identified in this review should not be interpreted as equally supported across the entire corpus. Fifth, none of the included studies specifically investigated chemistry education. The implications proposed for chemistry therefore represent conceptual transfer from the broader science education literature rather than direct evidence of effectiveness in chemistry learning.

Finally, the relationships among scaffold design, availability, attention, actual use, cognitive or metacognitive activity, social support, adaptation, outcomes, and fading were reconstructed by integrating evidence from different studies. They do not constitute a causal sequence empirically tested within a single investigation. Belland et al. (2018) primarily contributed evidence regarding actual scaffold use, Johnson (2018) regarding attention and self-regulation, Ustunel and Tokel (2017) regarding distributed social support, and Basu et al. (2017) regarding diagnosis, adaptation, and fading. The proposed multidimensional framework should therefore be treated as an analytical map for organizing evidence and guiding future empirical research rather than as a fully validated causal model. Further studies are required to determine whether these relationships remain consistent across science domains and, particularly, within chemistry education.

CONCLUSIONS AND RECOMMENDATIONS

This systematic literature review demonstrates that digital scaffolding in science education is a multidimensional learning support system rather than merely a collection of technological features. Across the seven reviewed studies, digital scaffolding varied in its form, pedagogical function, source of support, adaptivity, timing and contingency, actual use, social interaction, and fading mechanisms. Its effectiveness depended on the alignment between scaffold characteristics and learner needs, learners' attention to and actual use of the available support, task demands, social support, and the intended learning outcomes. The reported outcomes extended beyond conceptual understanding to scientific inquiry, argumentation, problem-solving, self-regulated learning, information processing, modeling, computational thinking, collaboration, and knowledge transfer. The main contribution of this review is therefore a multidimensional framework that shifts the analysis from feature-centered toward process- and learner-centered scaffolding, emphasizing the relationships among learners, scaffolds, tasks, contexts, social support, and learning outcomes.

Future studies should empirically examine this multidimensional framework across different science learning contexts, particularly chemistry education, which was not specifically represented in the reviewed corpus. Research should investigate not only learning outcomes but also scaffold exposure,

learner attention, actual use, cognitive and metacognitive activity, interactions with teachers and peers, adaptation of support, and fading. Process data, such as action logs, interaction records, and learner traces, may provide stronger evidence of how scaffold design is translated into actual learning behavior (Basu et al., 2017; Belland et al., 2018). Further studies should also compare static and adaptive scaffolding and determine whether the gradual withdrawal of assistance promotes independent performance and transfer after scaffolds are no longer available. Research across different science domains, educational levels, learner characteristics, and technology-enhanced environments is needed to distinguish general principles of productive digital scaffolding from context-dependent characteristics.

FURTHER STUDY

This review has several limitations that should be considered when interpreting its findings. First, the literature search was limited to the Scopus database, which may have excluded relevant studies indexed in other scientific databases. Second, only seven studies met the eligibility criteria, indicating that empirical research on digital scaffolding in science education remains limited. The small number of studies also restricts the generalizability of the identified patterns across educational levels, scientific disciplines, and learning contexts. Furthermore, differences in scaffold design, implementation, learner characteristics, and reported outcomes make direct comparisons across studies difficult. Future research should therefore expand searches to additional databases and examine digital scaffolding across broader educational contexts. Further empirical studies are also needed to investigate how adaptivity, contingency, fading, actual scaffold use, and human support interact over time and influence learning outcomes, particularly in science and chemistry education.

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